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Probabilistic Structural Analysis of Adaptive/Smart/Intelligent Space Structures

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Probabilistic Structural Analysis of Adaptive/Smart/Intelligent Space Structures

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ABSTRACT

A three-bay, space, cantilever truss is probabilistically evaluated for adaptive/smart/intelligent behavior. For each behavior the scatter (ranges) in buckling loads, vibration frequencies and member axial forces are probabilistically determined. Sensitivities associated with uncertainties in the structural, material and load variables that describe the truss are determined for different probabilities. The relative magnitude of these sensitivities are used to identify significant truss variables that control/classify its behavior to respond as an adaptive/smart/intelligent structure. Results show that the probabilistic buckling loads and vibration frequencies increase for each truss classification, with a substantial increase for intelligent trusses. Similarly, the probabilistic member axial forces reduce for adaptive and intelligent trusses and increase for smart trusses.

INTRODUCTION

Aerospace structures and spacecraft are a complex assemblage of structural components that are subjected to a variety of complex, cyclic, and transient loading conditions. All of these introduce significant uncertainties. The inherent randomness of material properties and the fabrication processes introduce additional uncertainties. Therefore, it is becoming increasingly evident that to assure the structural performance/reliability of these structures, all these uncertainties have to be quantified in order to ascertain that the structural response will be within the acceptable limits during the life of the structure. Probabilistic structural analysis provides a formal way to properly account for all these uncertainties.

A Probabilistic Structural Analysis Method (PSAM) is being developed at NASA Lewis Research Center (ref. 1) which uses different distributions such as the Weibull, normal, log-normal, etc. to describe the uncertainties in the structural and load parameters, herein referred to as primitive variables. PSAM assesses the effects of these uncertainties on the scatter of structural responses member forces (buckling loads, frequencies). Thus, PSAM provides a formal and systematic way to reliably evaluate structural performance and durability. PSAM is embedded in a computer code NESSUS (Numerical Evaluation of Stochastic Structures Under Stress) (refs. 2 and 3).

In the recent past, NESSUS has been used to computationally simulate and probabilistically evaluate a three-dimensional, three-bay cantilever truss (fig. 1) typical for space type structures and to quantify the uncertainties in the structural responses (displacements, member axial forces, and vibration frequencies) (ref. 4). Furthermore, a methodology has been developed to perform probabilistic progressive buckling assessment of space type trusses using the NESSUS computer code (ref. 5). In this methodology, the deterministic analysis indicated that axial forces in some members were sufficiently high to cause local buckling in these members. The subsequent probabilistic analysis showed that the scatter in the spacial geometry (variations in the nodal coordinates) has very significant impact on the probabilistic buckling load.

The objective of this paper is to adapt PSAM to determine uncertainties in ranges associated with sizing devices to control adaptive and smart structures and structures made from intelligent materials where these are defined as described below. It is assumed in the computational simulation that (1) when local instability is imminent, the length of that member is suitably controlled to prevent instability. Herein this is referred to as "adaptive structure." (2) when local instability is imminent, a redundant member engages in load sharing without weight penalty. This is referred to as "smart structure." (3) when local instability is imminent as exhibited by bowing, the material induces a local restoring moment. This is referred to as "intelligent structure" through the corresponding restoring action of the intelligent material. In this paper, each of these structures are probabilistically evaluated for the respective changes to prevent instabilities. In addition, the uncertainties associated with the primitive variables which influence these changes and their respective sensitivities are evaluated with respect to structural responses (buckling load, vibration frequency and member force).

FUNDAMENTAL APPROACH AND CONSIDERATIONS

One of the major problems encountered in the analysis of space type trusses is to come up with a stable and optimum configuration for given loading conditions and to be able to probabilistically analyze them to take into account the probable uncertainties in the primitive variables typical for space environment conditions. In addition, local sensors and suitable devices, local stress concentrators, etc. are used to reduce the degree of local instability thereby, improving the overall performance of the space trusses at desired reliability levels. The presently available methods/programs do not easily allow us to identify any local instability in any of the internal members of the truss during probabilistic analysis. Therefore using the NESSUS code, methodologies for the probabilistic structural analysis of adaptive/smart/intelligent space structures are developed and are described hereafter.

FINITE ELEMENT MODEL

A three-dimensional, three-bay cantilever truss is computationally simulated using a linear isoparametric beam element based on the Timoshenko beam equations. The element is idealized as a two-noded line segment in three-dimensional space. The cantilever truss is assumed to be made from hollow circular pipe members. The members are made up of wrought aluminum alloy (616-W) with modulus of elasticity (E) equal to 10 Mpsi. The outer and inner radii (r_o and r_i) of the tube, are 0.5 and 0.4375 in., respectively. All 6 degrees of freedom are restrained at the fixed end (left side) nodes. Each bay of the truss is 5 ft wide, 8 ft long, and 6 ft high (fig. 1). The overall length of the truss is 24 ft. Six vertical and two longitudinal loads are applied. In addition, twisting moments are applied at the truss-end nodes. The directions of the forces and moments are shown in figure 1 and mean values are given in table I. The applied loads and moments are selected to represent anticipated loading conditions for a typical space truss.

PROBABILISTIC MODEL

The following primitive variables are considered in the probabilistic analysis:

(1) Nodal coordinates (X,Y,Z—spacial locations of truss panel points)
(2) Modulus of elasticity (E)
(3) Outer radius of the tube (r_o)
(4) Inner radius of the tube (r_i)
(5) Vertical loads (V)
(6) Longitudinal loads (H)
(7) Twisting moments (M)

It is possible that the above primitive variables will vary continuously and simultaneously due to extreme changes in the environment when such trusses are used in upper Earth orbit for space station type structures. The normal distribution is used to represent the uncertainties in E, r_o, r_i, and X,Y,Z coordinates. The applied loads and moments are selected to represent an anticipated loading for a typical space truss. The scatter in these are represented by log-normal distributions. Initially, the NESSUS/FEM (Finite Element Methods) module is used to deterministically analyze the truss for mean values of each of these primitive variables. In the subsequent probabilistic analyses, each primitive variable is perturbed independently and by a different amount. Usually, the perturbed value of the primitive variable is obtained by a certain factor of the standard deviation on either side of the mean value.

In general, the finite element equation for motion is written as:

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} = F(t) \tag{1}$$

where $[M]$, $[C]$, and $[K]$ denote the mass, damping, and stiffness matrices respectively. It is important to note that these matrices are calculated probabilistically in the NESSUS code. Furthermore, $\{\ddot{u}\}$, $\{\dot{u}\}$, and $\{u\}$ are the acceleration, velocity and displacement vectors at each node, respectively. The forcing function vector, $\{F(t)\}$, is time independent at each node.

In this paper, the static case is considered by setting the mass and damping matrices to zero and considering the forcing function being independent of time in equation (1) such that

$$[K]\{u\} = \{F\} \tag{2}$$

It is important to note that in the NESSUS code, a linear buckling analysis is carried out by making use of the subspace iteration technique to evaluate the probabilistic buckling load. The matrix equation for the buckling (eigenvalue) analysis for a linear elastic structure is as follows:

$$\left\{[K] - \lambda[K_g]\right\} \{\phi\} = 0 \tag{3}$$

In the above equation, $[K]$ is the standard stiffness matrix, $[K_g]$ is the geometric stiffness matrix, λ is the eigenvalue, and ϕ are the eigenvectors.

Furthermore, the vibration frequency analysis is also carried by setting only the damping matrix to zero and using the following equation:

$$\left\{[K] - \lambda^2[M]\right\}\{\phi\} = 0 \tag{4}$$

Finally, the NESSUS/FPI (Fast Probability Integration) module extracts the response variables (buckling loads, vibration frequencies and member axial forces) to calculate respective probabilistic distributions and respective sensitivities associated with the corresponding uncertainties in the primitive variables. The mean, distribution type and percentage variation for each of the primitive variables are given in Table I.

ADAPTIVE/SMART/INTELLIGENT STRUCTURES

NASA space missions have been advocating the use of adaptive/smart/intelligent structures for their spacecraft. These materials have great impact on the functioning of precision segmented reflectors, the controlling of large space truss structures, manufacturing of robotic assemblies/space cranes/manipulators and isolating vibration frequencies. These materials also have a larger role in improving the performance of aircraft and other commercial structures. However, the terminology, such as "adaptive," "smart" and "intelligent" is being used loosely and interchangeably in the research community (ref. 6).

Ahmad (ref. 6) defines the intelligent/smart materials and systems as "that have built in or intrinsic sensors, processors, control mechanisms, or actuators making it capable of sensing a stimulus, processing the information, and then responding in a predetermined manner and extent in a short/appropriate time and reverting to its original state as soon as stimulus is removed." Thus, the smart structures consist of sensors, controllers and actuators. Furthermore, the intelligent materials usually respond quickly to environmental changes at the optimum conditions and modify their own functions according to the changes. Therefore, the intelligent truss structures are usually designed with active members early in the design process. In many instances the trusses are designed with both active and passive members using an integrated design optimization procedure (7). Finally, Wada (ref. 8) describes adaptive structures "as a structural system whose geometric and inherent structural characteristics can be beneficially changed to meet mission requirements either through remote commands and/or automatically in response to external stimulations." It is important to note that these structures have an in-built capability to geometrically relocate critical points of the structure, when in space, to the desired positions through actuation of active members. Therefore, the configurations of such structures should have greater flexibility to move the critical locations.

The concepts discussed above are used for probabilistic structural analysis of adaptive/smart/intelligent structures typical for space type trusses using the NESSUS computer code. The individual analysis technique and respective results are discussed.

DISCUSSION OF RESULTS

Adaptive Structure

The deterministic analysis (ref. 5) indicated the first sign of local buckling in the first bay front diagonal (fig. 1). Since buckling varies as the length squared, decrease in length should prevent buckling at that load. Therefore, a suitable devise or sensor can be attached to this truss member that will not only sense the local buckling in the member due to significantly high axial force but also will automatically reduce the overall length of the member by predetermined increment. Thus, this member acts like an adaptive member whereby its geometrical parameters were changed accordingly.

Figures 2 to 7 show the cumulative distribution functions (CDF) and corresponding sensitivities of the probabilistic buckling loads and vibration frequencies of the truss and axial forces in the diagonal (member). By reducing the length of the member by 6 in., the probabilistic buckling loads increased by 6 percent (fig. 2). The sensitivity factors from figure 3 show that the uncertainties in the bay height (Z-coordinate) had the highest impact on the probabilistic buckling loads. The probabilistic vibration frequencies increased by 25 to 35 percent for lower probability levels (fig. 4). The scatter in the tube radii had equally significant impact on the probabilistic vibration frequencies (fig. 5). The magnitude of the probabilistic member axial forces decreased by 5 percent (fig. 6) and the scatter in bay length had the highest impact on the probabilistic member axial forces followed by bay height (fig. 7). Thus, the adaptive structures are effective in increasing the buckling loads and vibration frequencies as well as controlling the member axial forces.

Smart Structure

As mentioned earlier, in the case of smart structure the original single hollow member (diagonal) was replaced with two hollow tubes. Once again the outer tube was made up of wrought aluminum alloy (616-W) and the outer and inner radii of the tube were 0.5 and 0.468755 in., respectively. However, the inlet (inner) tube was modeled using high modulus fiber-intermediate modulus matrix composite with 60 percent fiber-volume ratio. For this tube the modulus of elasticity was equal to 36 Mpsi with 0.421875 and 0.384375 in. outer and inner radii, respectively. It was assumed that the inner composite tube can be inserted inside the outer tube without affecting the details of the member end connections. It is important to note that the composite tube not only reduces the overall weight of the truss, but also increases the stiffness and it is assumed that this tube was made with tight tolerance. Therefore, the scatter in E and tube radii are not considered in the probabilistic analysis. In addition, the aluminum tube is also useful in protecting the composite tube from possible damage from orbital environmental debris.

Figure 8 shows that, the probabilistic buckling loads increased by almost 30 percent at several probability levels. The sensitivity factors show that the uncertainties in the bay height had the highest impact on the probabilistic buckling loads (fig. 9). The probabilistic frequencies increased by 15 percent (fig. 10). The scatter in the inner tube radii had equally significant impact on the probabilistic frequencies (fig. 11). Similarly, the magnitude of the probabilistic member forces increased (fig. 12) and the scatter in the bay length and height had equally significant impact on the probabilistic member axial forces (fig. 13). Once again, the smart structures can also be used to increase the probabilistic buckling loads and frequencies and in controlling the forces in the member.

Intelligent Structure

It is important to note that all the truss members were assumed to be initially perfectly straight and when any member buckled it would yield (ref. 5). Therefore, the maximum eccentricity at which the yielding in the member (first bay front diagonal) will take place due to the combined effects of axial and in-plane bending moments was calculated. Furthermore, this member (first bay front diagonal) was modeled to represent the buckled configuration of the member at which yielding will take place, using a parabolic distribution with increased eccentricities. At the center of this diagonal (original shape) localized stress concentrators can be attached which will detect the local instability in the member and will get activated whereby a restoring moment of 15 lb-in. will be automatically applied at the center of this diagonal. Thus, this diagonal acts like an intelligent structural member due to the action of intelligent material and the loading parameters will be changed accordingly.

It can be concluded that, the probabilistic buckling loads increased by 50 percent (fig. 14) and the scatter in the bay height had the highest impact on the probabilistic buckling loads (fig. 15). The probabilistic buckling frequencies increased by 20 percent only for lower probability levels (fig. 16). Therefore, the level of scatter in the primitive variables did not increase the probabilistic frequencies at higher probability levels. The variations in the member radii had equally significant impact on the probabilistic vibration frequencies (fig. 17). The magnitude of the probabilistic member axial forces decreased by 40 percent (fig. 18) and the uncertainties in both bay length and bay height had very significant impact on the probabilistic member forces (fig. 19). Finally, the intelligent structures with the help of in-built intelligent material is very useful in increasing the probabilistic buckling loads and decreasing the member axial forces.

Finally, the above discussed methodologies can be applied for more than one member at the same time, if the situation demands, and the probabilistic analysis can be carried to evaluate various CDF's and determine the structural performance and durability of the truss.

CONCLUSIONS

The computational simulation of probabilistic evaluation for adaptive/smart/intelligent behavior of truss structures is demonstrated using the NESSUS computer code and step-by-step procedures are outlined. Scatter of the probabilistic buckling loads, vibration frequencies and member axial forces are evaluated and the sensitivities associated with the uncertainties in the primitive variables are determined. The results indicate that (1) the probabilistic buckling loads and vibration frequencies increase for each truss classification. However, they increase significantly for the case of intelligent structure; (2) the magnitude of the probabilistic member axial forces increase for smart structure and decrease for both adaptive and intelligent structures, with considerable decrease for intelligent structure; (3) for each structure the scatter in the bay height have the highest impact on the probabilistic buckling loads; (4) the scatter in member area parameters have equally significant impact on the probabilistic frequencies; (5) the uncertainties in the bay length/height have equally significant effects on the probabilistic member forces. Collectively, the results indicate that all three structures can be used to increase the probabilistic buckling loads. However, the intelligent structure gives the highest increase. Furthermore, both adaptive and smart structures are recommended for controlling the frequencies, but not true for intelligent structures. Finally, the adaptive/smart/intelligent structures are recommended for controlling the member axial forces.

REFERENCES

1. Chamis, C.C.: Probabilistic Structural Analysis Methods for Space Propulsion System Components. Space System Technology Conference, San Diego, California, June 9-12, 1986, Technical Papers, AIAA, New York, 1986, pp. 133-144.

2. Dias, J.B.; Nagtegaal, J.C.; and Nakazawa, S.: Iterative Perturbation Algorithms in Probabilistic Finite Analysis. Computational Mechanics of Probabilistic and Reliability Analysis, W.K. Liu and Belytschko, eds., ELME PRESS International, Lusanne, Switzerland, 1989, pp. 211-230.

3. Wu, Y.T.: Demonstration of New, Fast Probability Integration Method for Reliability Analysis. Advances in Aerospace Structural Analysis; Proceedings of the Winter Annual Meeting, Miami Beach, FL, Nov, 17-22, 1985, O.M. Burnside, ed., ASME, 1985, pp. 63-73.

4. Pai, S.S.: Probabilistic Structural Analysis of a Truss Typical for Space Station, NASA TM-103277, 1990.

5. Pai, S.S.; Chamis, C.C.: Probabilistic Progressive Buckling of Trusses. NASA TM-105162, 1991.

6. Ahmad, I.: U.S. - Japan Workshop on Smart/Intelligent Materials and Systems. ONRASIA SCI INFO BUL 15 (4), 1990, pp. 67-75.

7. Manning, R.A.: Optimum Design of Intelligent Truss Structures. 32nd Structures, Structural Dynamics and Materials Conference, Part 1, AIAA, 1991, pp. 528-533.

8. Wada, B.K.: Adaptive Structures. 30th Structures, Structural Dynamics and Materials Conference, Part 1, AIAA, 1989, pp. 1-11.

TABLE I - PRIMITIVE VARIABLES AND UNCERTAINTIES FOR PROBABILISTIC STRUCTURAL ANALYSIS OF A SPACE TRUSS

[Random input data.]

Primitive variables		Distribution type	Mean value	Scatter, ±percent
Geometry	Width	Normal	60 in.	0.5
	Length	Normal	96 in.	0.1
			192 in.	0.1
			288 in.	0.1
	Height	Normal	72 in.	0.2
Loads	Vertical	Lognormal	20 lb	6.3
	Longitudinal	Lognormal	20 lb	2.5
	Twisting moment	Lognormal	50 lb-in.	6.3
Material property	Modulus	Normal	10 Mpsi	7.5
Tube radii	Outer radius	Normal	0.5 in.	7.5
	Inner radius	Normal	0.44 in.	7.5

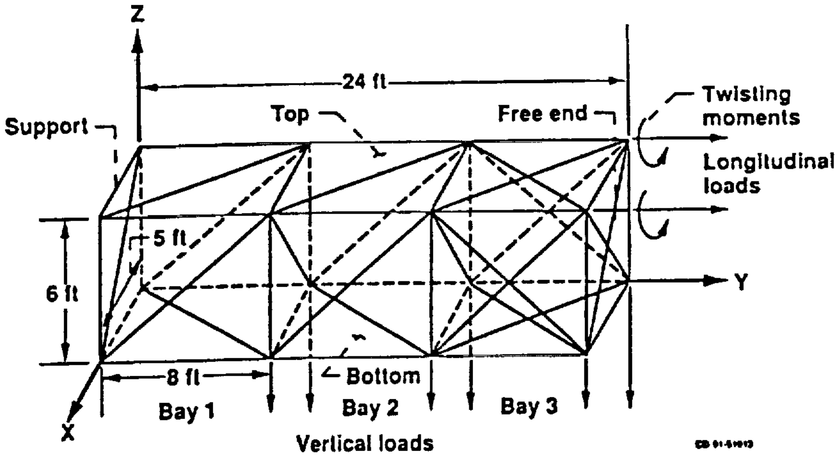

FIG. 1. - SOLAR ARRAY PANELS MAST - TYPICAL TRUSS.

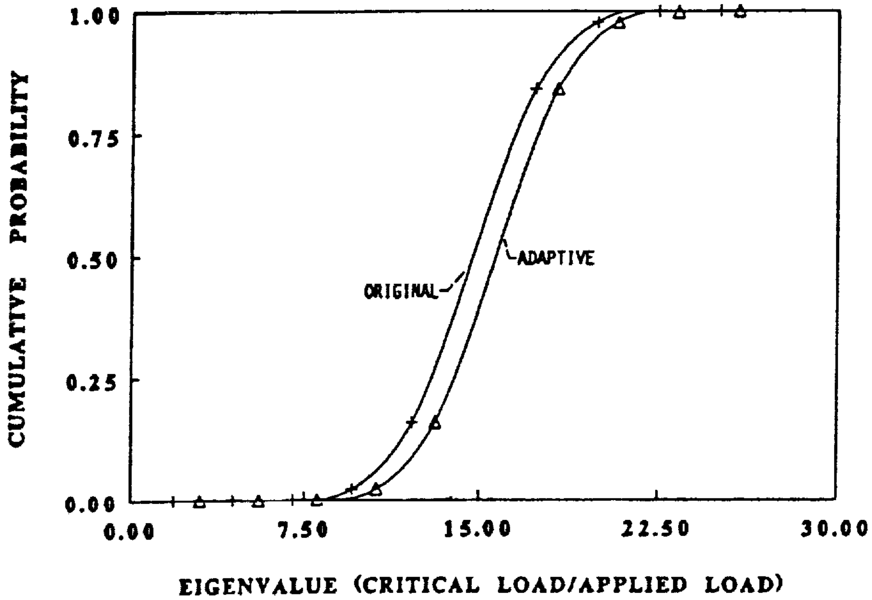

FIG. 2. - PROBABILISTIC BUCKLING LOAD FOR ADAPTIVE STRUCTURE.

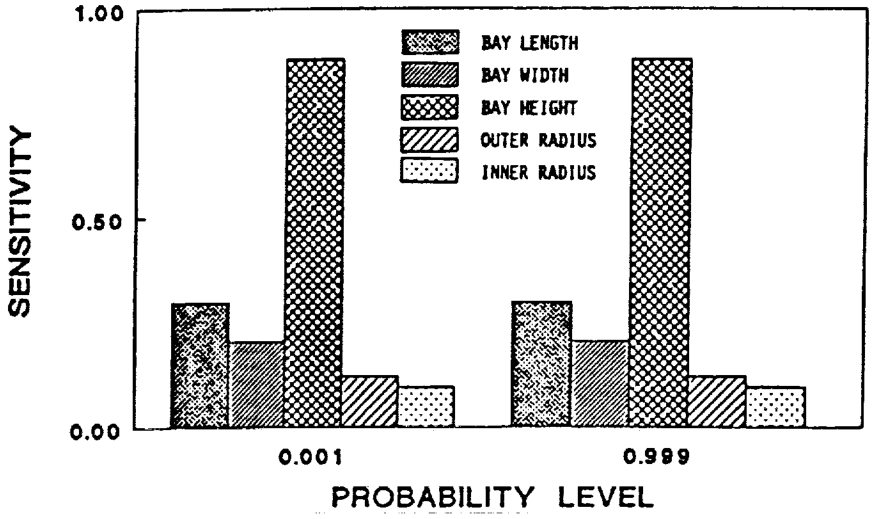

FIG. 3. - PROBABILISTIC BUCKLING LOAD SENSITIVITIES FOR ADAPTIVE STRUCTURE

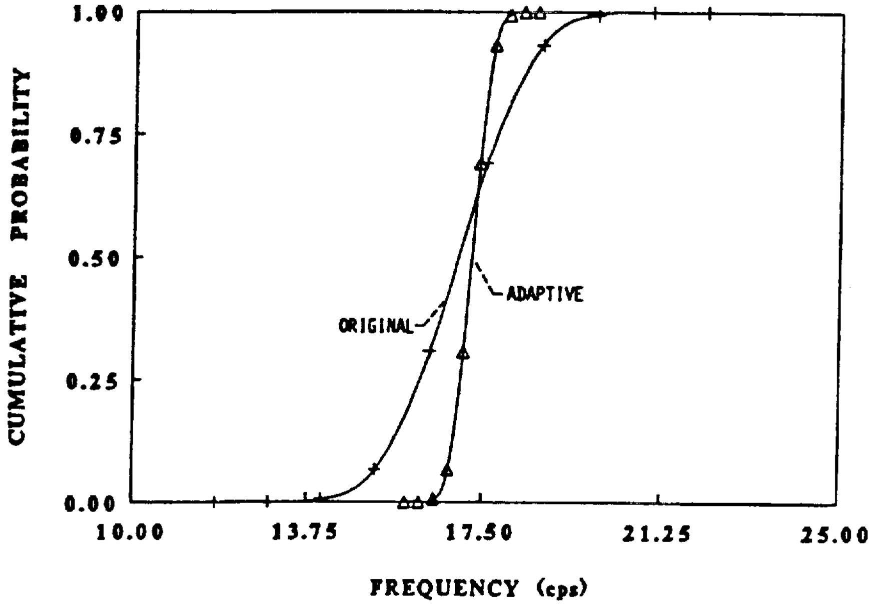

Fig. 4. - Probabilistic vibration frequency for adaptive structure.

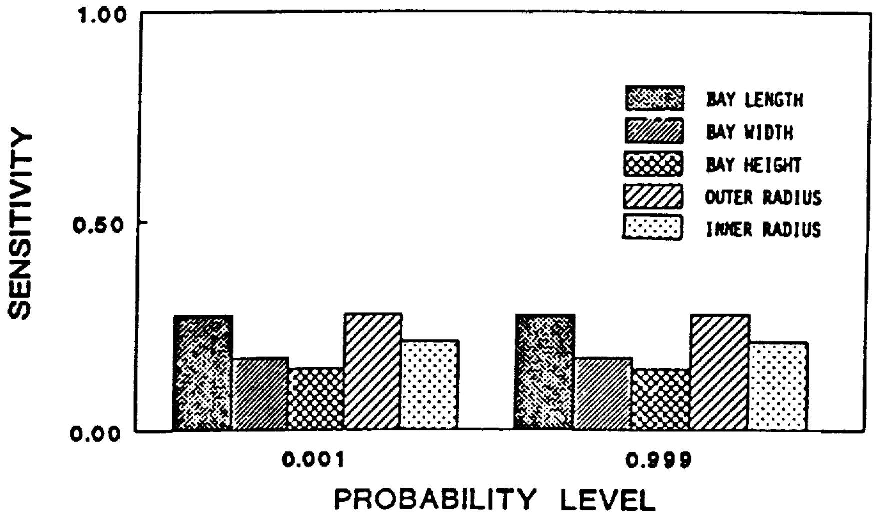

Fig. 5. - Probabilistic frequency sensitivities for adaptive structure.

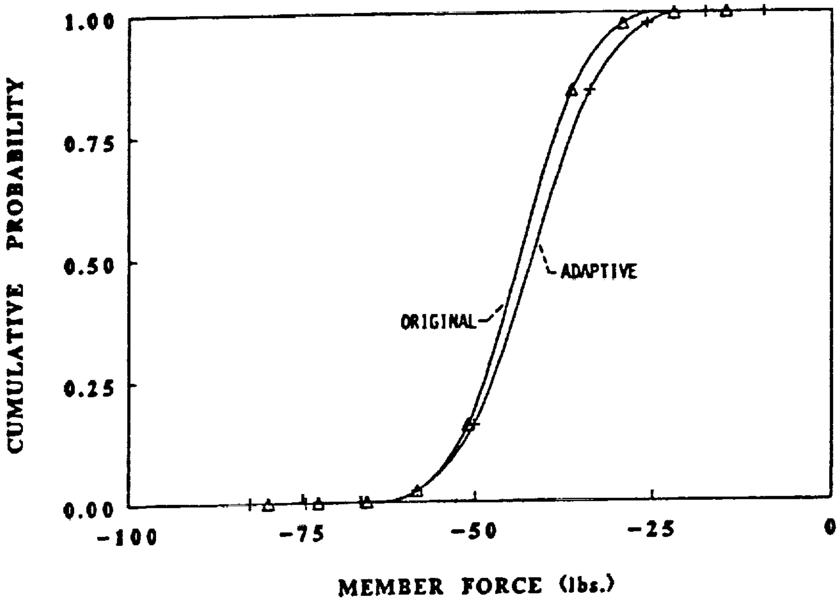

FIG. 6. - PROBABILISTIC MEMBER FORCE FOR ADAPTIVE STRUCTURE.

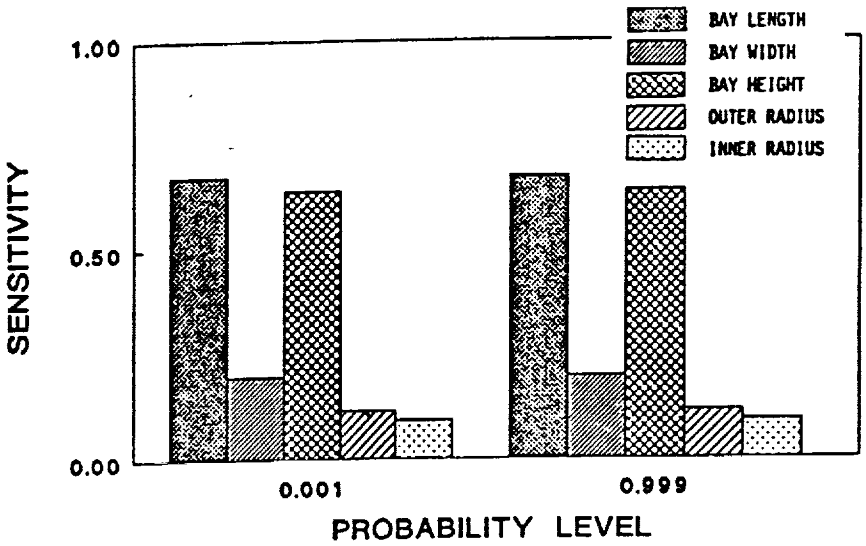

FIG. 7. - PROBABILISTIC MEMBER FORCE SENSITIVITIES FOR ADAPTIVE STRUCTURE.

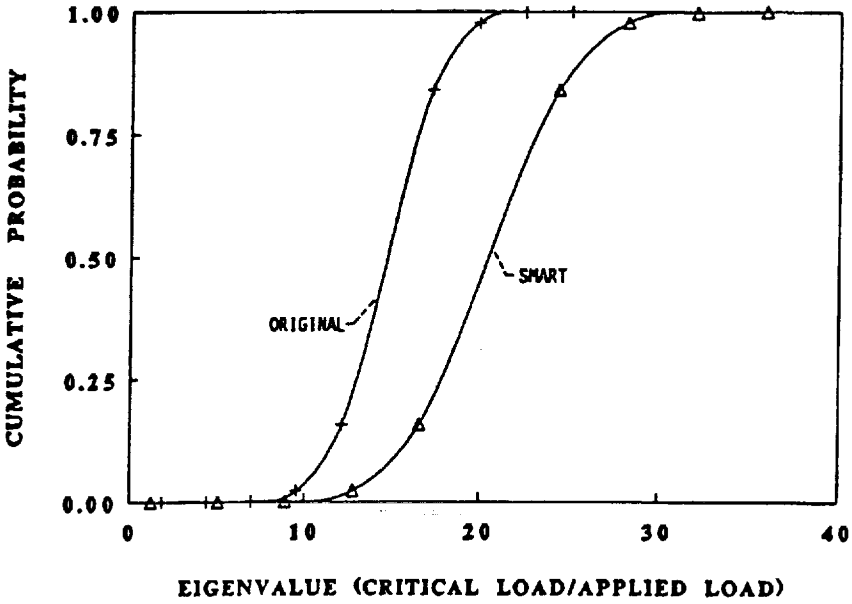

FIG. 8. - PROBABILISTIC BUCKLING LOAD FOR SMART STRUCTURE.

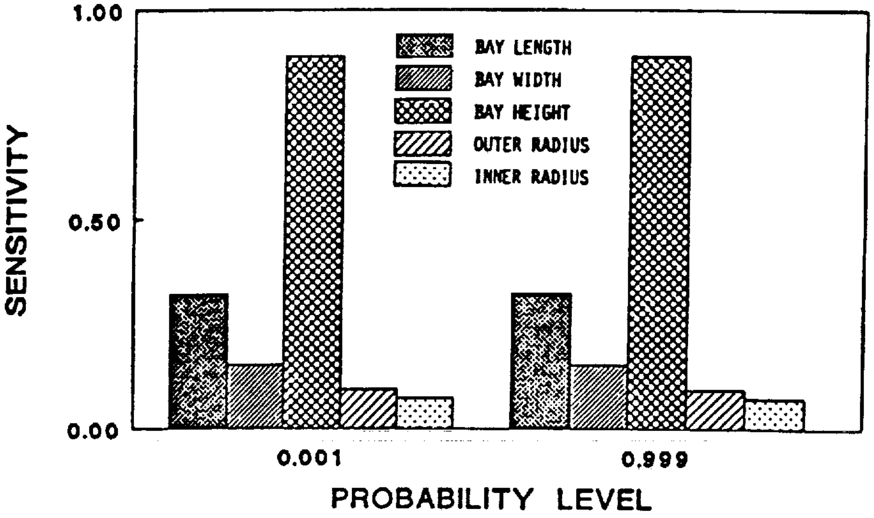

FIG. 9. - PROBABILISTIC BUCKLING LOAD SENSITIVITIES FOR SMART STRUCTURE.

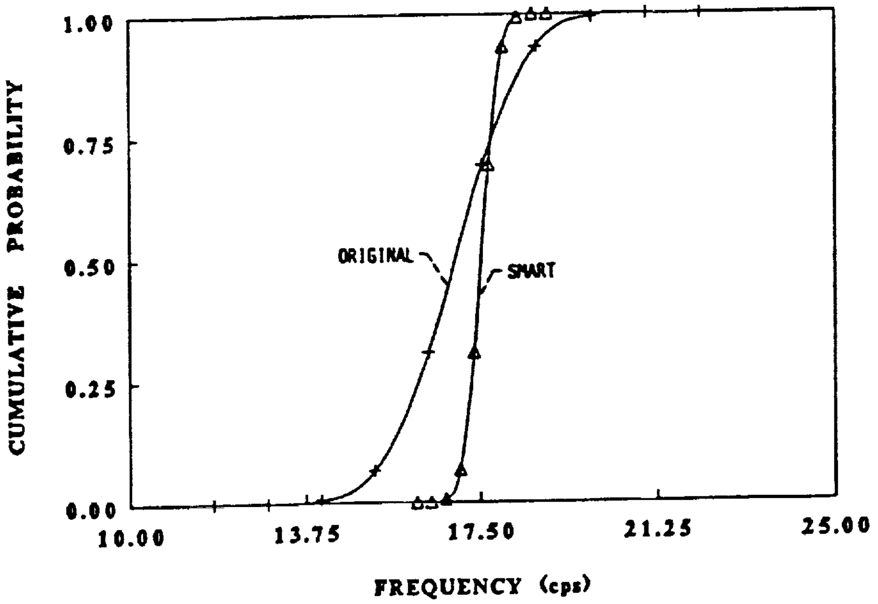

Fig. 10. - Probabilistic vibration frequency for smart structure.

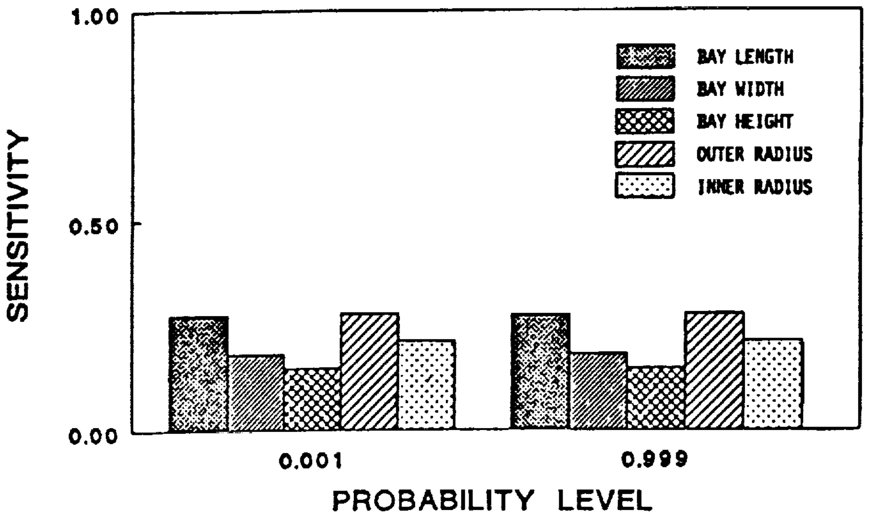

Fig. 11. - Probabilistic frequency sensitivities for smart structure.

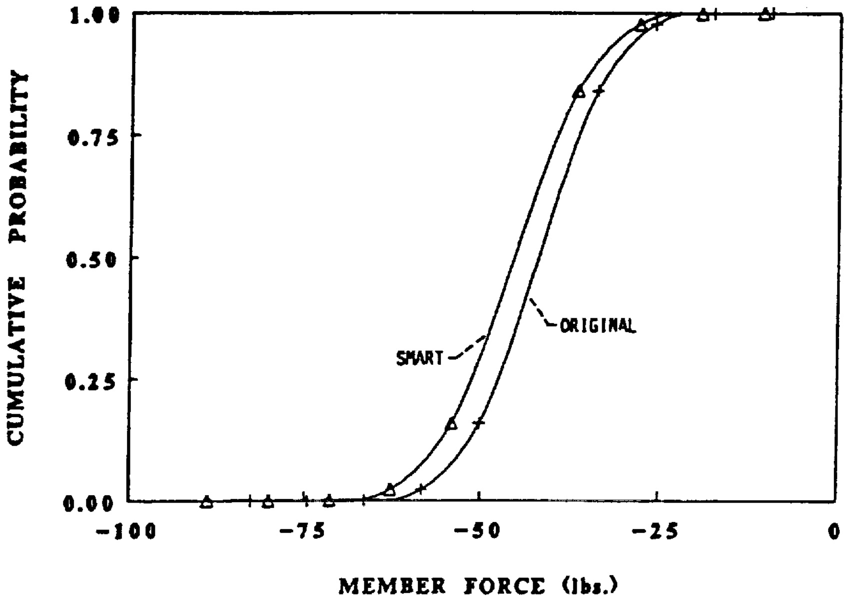

FIG. 12. - PROBABILISTIC MEMBER FORCE FOR SMART STRUCTURE.

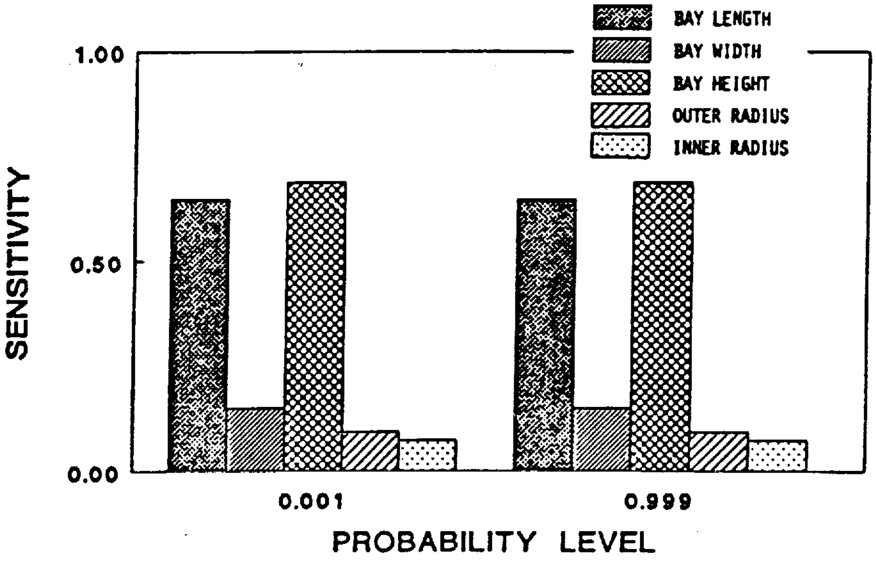

FIG. 13. - PROBABILISTIC MEMBER FORCE SENSITIVITIES FOR SMART STRUCTURE.

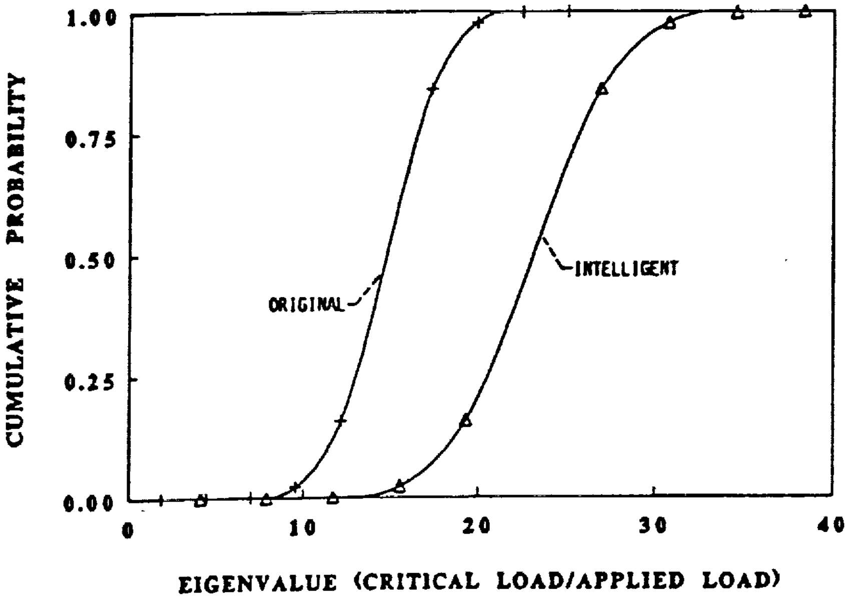

FIG. 14. - PROBABILISTIC BUCKLING LOAD FOR INTELLIGENT STRUCTURE.

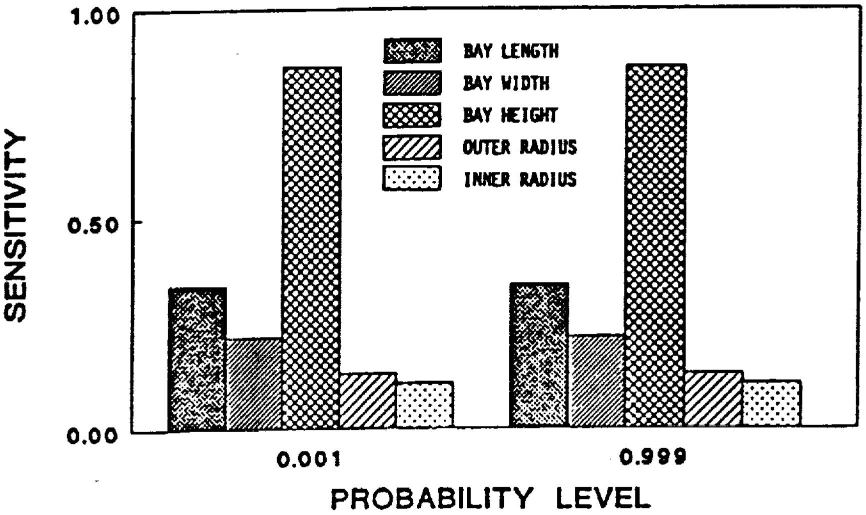

FIG. 15. - PROBABILISTIC BUCKLING LOAD SENSITIVITIES FOR INTELLIGENT STRUCTURE.

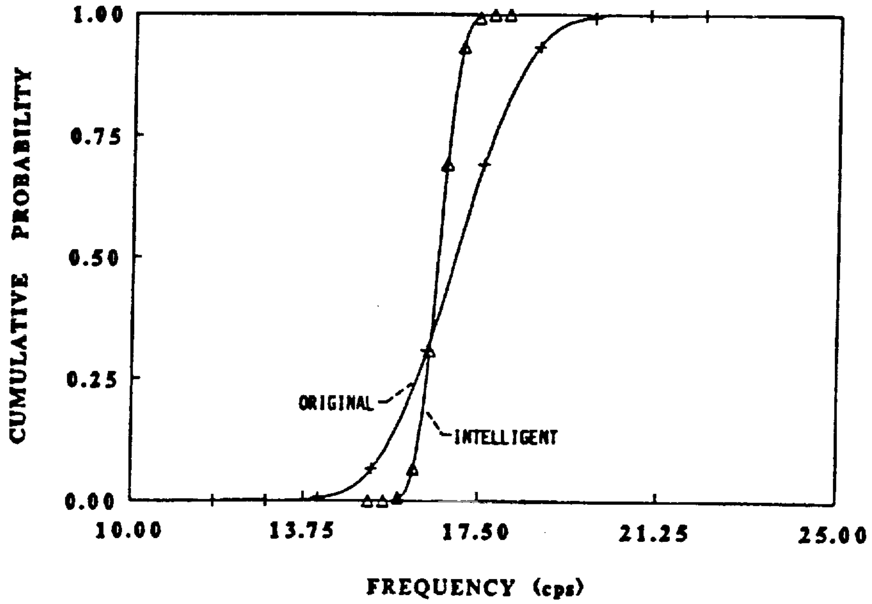

FIG. 16. - PROBABILISTIC VIBRATION FREQUENCY FOR INTELLIGENT STRUCTURE.

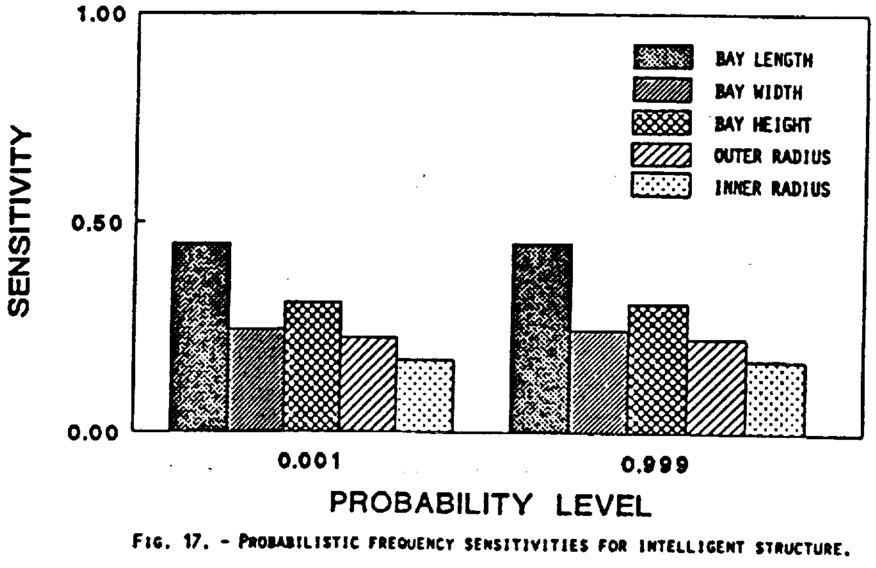

FIG. 17. - PROBABILISTIC FREQUENCY SENSITIVITIES FOR INTELLIGENT STRUCTURE.

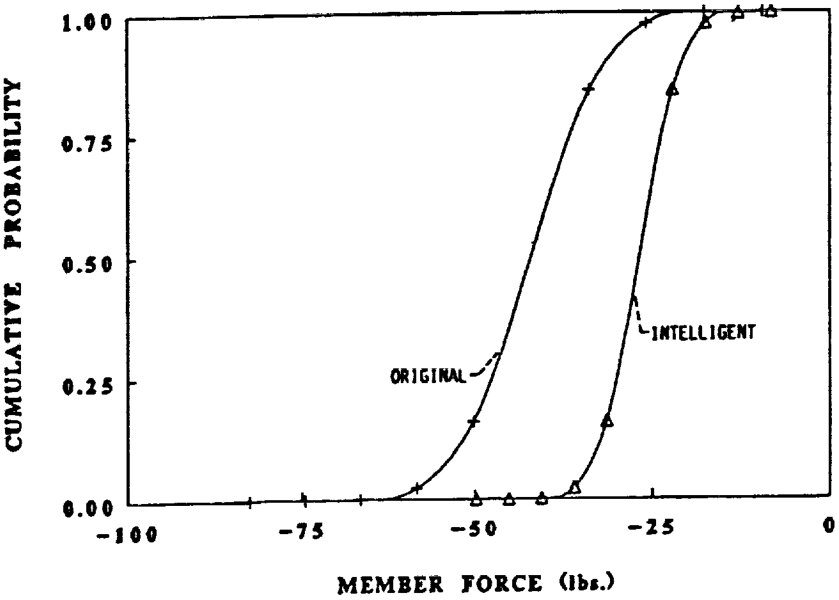

FIG. 18. - PROBABILISTIC MEMBER FORCE FOR INTELLIGENT STRUCTURE.

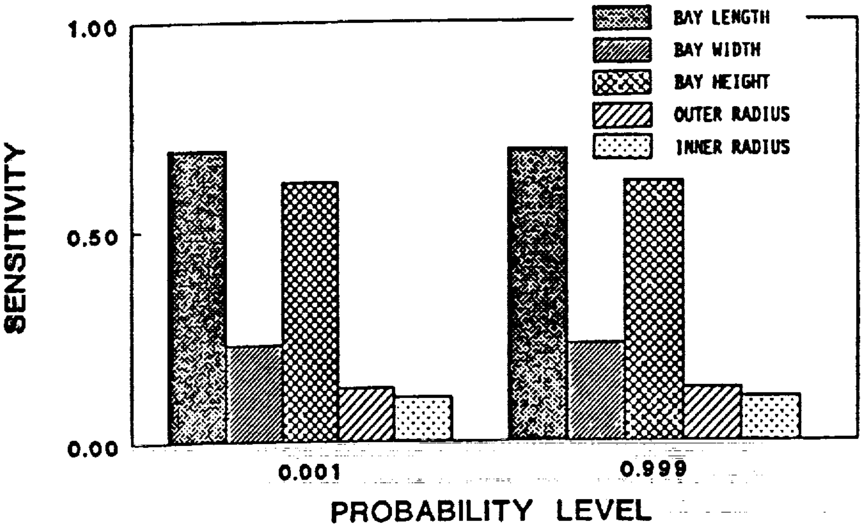

FIG. 19. - PROBABILISTIC MEMBER FORCE SENSITIVITIES FOR INTELLIGENT STRUCTURE.

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