41st AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference and Exhibit
Atlanta, GA 3-6 April 2000

A00-24605

AIAA-2000-1663

AUTOMATED OPTIMUM DESIGN OF SHELLS OF REVOLUTION WITH APPLICATION TO RING-STIFFENED CYLINDRICAL SHELLS WITH WAVY WALLS

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ABSTRACT

GENOPT, a program that writes user-friendly optimization code, and BOSOR4, a program for stress, buckling, and vibration analysis of segmented, branched, stiffened shells of revolution, are combined to create a capability to optimize specific classes of shells of revolution. GENOPT and BOSOR4 and recent improvements to them are described. An example is provided of an aluminum cylindrical shell with a wavy wall and with ring stiffeners. In the example the objective of the optimization is minimum weight and the design constraints include stress, buckling and modal vibration. In the report from which this paper is condensed an Appendix is provided in which a very simple example is employed to demonstrate in detail how a user can create a capability to optimize any shell of revolution.

1.0 INTRODUCTION

This paper is condensed from a much longer report [26] that contains several additional examples, including one in which the shell is made of laminated composite material. Figures and tables in [26] are referred to frequently here, and the interested reader is urged to obtain a copy of [26] for more details about this project.

About 10 years ago Cohen and Haftka [1] took a step toward creating a capability for automated design of shells of revolution. In this paper a further step is taken by combination of two computer program systems, GENOPT [2] and BOSOR4 [3]. GENOPT and BOSOR4 are combined to permit optimization of a certain class of shells of revolution, called here "WAVYCYL". This class includes ring-stiffened cylindrical shells with a "wavy" wall. The waviness is in the axial direction, that is the cylindrical shell is corrugated with the axis of the corrugations running around the circumference. This "wavy" cylindrical shell, if perfect, is axisymmetric. The rings may be rectangular or Tee-shaped, external or internal. They are modeled as consisting of little shell segments, as in [4].

1.1 Configurations in the class, WAVYCYL

Figure 1a shows the example studied intensively here, and Figs. 1(b-f) display additional members of the class called "WAVYCYL". Classical simple support or clamping is imposed at the right end of the models (z = 0). Prebuckling symmetry and

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buckling symmetry or antisymmetry are imposed at the left of the models (z=AXIAL/2), which represents the midlength of the entire cylindrical tube of length, AXIAL. In the computer models the material stiffness and density of the ring at the symmetry plane, if any, are half those of the rings elsewhere in the models.

In the models shown in Figs. 1(a-c) the wavy portion is a multi-segmented model consisting entirely of joined toroidal frustra, that is, segments within each of which the meridional curvature is constant and fixed by the amplitude, AMPLIT, and axial halfwavelength, WAVLEN, of the waviness. The meridional slope is continuous at junctions between adjacent toroidal frustra, for example at the junction between Segment i and Segment i+1 in Fig. 2. Each of the little toroidal segments has the same number of nodal points, NMESHC, in the discretized BOSOR4 model.

Figure 2 shows an expanded view of the configuration depicted in Fig. 1a in the neighborhood of one of the rings. The decision variables of the optimization problem, THICK, BRINGS, TWEB, HWEB, TFLANG, HFLANG, WAVLEN, and AMPLIT, are identified. If the wall of the cylindrical shell is laminated composite, the ply thicknesses and possibly also layup angles may be decision variables. In ring-stiffened configurations all of the rings are identical.

In the model shown in Fig. 1d the wavy portion consists of very, very short toroidal segments connected by little conical segments. The model depicted in Fig. 1e is of the same class as that in Fig. 1d. The "little conical segments" have become annular segments. The model shown in Fig. 1f is an ordinary ring-stiffened cylindrical shell.

1.2 Models with "smeared" waviness

Note that the models shown in Figs. 1(a-e) all have a straight cylindrical segment near the right end. This is Segment 1 of the multi-segmented BOSOR4 model. Its wall properties are derived by a "smearing" of the waviness as described in Item 10 of Section 5 in [26].

Figure 3 displays a comparison of predictions of general buckling (Figs. 5a,b), local buckling (Figs. 5c,d), and modal vibration (Figs. 5e,f) for an optimized configuration with rings of rectangular (blade) cross section with waviness smeared (Figs. 5a,c,e) and explicit (Figs. 5b,d,f). The smeared model is too stiff for adequate prediction of local buckling but not too far off for prediction of general buckling and fundamental modal vibration, especially for the purpose of obtaining reasonable preliminary designs. Final optimum designs are always obtained with use of the BOSOR4 models with explicit waviness such as shown in Figs. 5b,d,f.

As shown in Fig. 1c, for example, the BOSOR4 model generally consists of two regions, one in which the generator is straight (smeared waviness) and the other in which the waviness is explicit. One of the input data defined by the GENOPT user is called "MAXDOF" (maximum allowable number of degrees of freedom in the BOSOR4 model). The WAVYCYL system uses this datum, MAXDOF, to determine the axial extent of the explicitly wavy portion of the model. The user can do initial optimizations setting MAXDOF to a relatively low number, such as 1500 - 3000. In such a model there may be a relatively long straight segment, such as is shown in Fig. 1c, for which MAXDOF was set equal to 1500 and NMESHC was set equal to 21.

The results obtained with use of a BOSOR4 model generated from a low value of MAXDOF are approximate because a significant part of the total axial length of the BOSOR4 model consists of smeared waviness and the behavior of this straight segment (Fig. 1c) only approximates the behavior of the actual wavy shell, as seen from the results displayed in Fig. 3. After optimizing with the "rough" model, the WAVYCYL user can increase

MAXDOF and re-optimize. This strategy was used in the studies reported here and in [26] to determine that the best ring stiffeners have no outstanding flanges, given the applied loading and lower bounds of 10 inches on ring spacing and 0.03 inches on the thickness of the wavy wall in the particular case explored in this paper (Table 4.7).

Note that, given MAXDOF, the extent of the wavy portion of the BOSOR4 model depends on the axial halfwavelength, WAVLEN, of the waviness and on how many nodal points, NMESHC, are used in each of the little toroidal segments that form the explicitly wavy part of the BOSOR4 model. Some results from a convergence study with respect to MAXDOF are shown in Fig. 4. Predictions of the convergence of general and local buckling load factors and modal vibration frequencies are given later with respect to both MAXDOF and NMESHC.

1.3 Loading

The WAVYCYL models can be loaded by arbitrary combinations of axisymmetric axial load, N_x, uniform internal or external pressure, p, lateral and axial accelerations, g(lateral) and g(axial), and random lateral excitation of the support at axial station, z = 0 (right-hand ends of the BOSOR4 models shown in Figs. 1, 3 and 4).

1.4 Summary

In this paper the capabilities of GENOPT and BOSOR4 are summarized, with details given where these computer programs have been modified from the versions described in [2] and [3]. Then instructions are given on the use of GENOPT and on the use of the system of computer programs created by GENOPT, called "WAVYCYL". The flow of computations for each design evaluation is described in [26]. Finally, numerical results are given.

An appendix is provided in [26] in which a simple example is used to demonstrate how a GENOPT user can set up a user-friendly system of programs to optimize any shell of revolution. The interested reader is urged to obtain a copy of [26].

2.0 GENOPT (GENeral OPTimization)

2.1 Summary of capabilities and properties of GENOPT [2]

The purpose of GENOPT [2] is to enable an engineer to create a user-friendly system of computer programs for analyzing and/or optimizing anything. The application of GENOPT is not limited to the field of structural mechanics. In [2] the purpose, properties and operational details of GENOPT are described. The reader is advised to read [2] and [26] in order to obtain a better understanding of the work described in this paper. GENOPT is executed via the following commands:

GENOPTLOG (The GENOPT command set is activiated.)

GENTEXT (The GENOPT user responds interactively to GENOPT prompts in order to provide names, definitions, and roles of variables to be used during execution of the user-friendly system of programs described next.)

GENPROGRAMS (GENOPT compiles and creates executable elements, BEGIN, DECIDE, OPTIMIZE, CHOOSEPLOT, CHANGE, AUTOCHANGE, described next.)

During the execution of "GENTEXT", GENOPT creates a system of computer programs consisting of the following independently executable processors:

BEGIN (The user supplies starting design, material properties, loads, allowables, factors of safety, etc.)

DECIDE (The user chooses decision variables, lower and upper bounds, linked variables, inequality constraints.)

MAINSETUP (The user chooses analysis type: fixed design, optimization, design sensitivity, and which design constraints to ignore during program execution.)

OPTIMIZE (The program system performs the analysis type specified by the user in MAINSETUP.)

SUPEROPT (The program system attempts to find a global optimum design.)

CHOOSEPLOT (The user chooses which variables to plot vs design iterations or vs value of design sensitivity variable.)

DIPLOT (The user obtains plots of objective, margins, decision variables vs design iterations or vs design sensitivity variable.)

CHANGE (The user changes selected problem variables.)

AUTOCHANGE (The program system changes all decision variables randomly, in a manner consistent with user-specified bounds, equality constraints, and inequality constraints.)

Certain parts of some of these processors (BEGIN, OPTIMIZE, CHANGE) are written by the GENOPT program system during the interactive "GENTEXT" execution. For example, certain subroutines called by the processor OPTIMIZE are partly written by GENOPT. These subroutines are named SUBROUTINE STRUCT, SUBROUTINE BEHXi, i = 1, 2, 3..., and SUBROUTINE OBJECT. As written by GENOPT, these subroutines are "skeletons": they have argument lists, labelled common blocks, and "RETURN" and "END" statements. The labelled common blocks contain all the variables that define the class of objects to be optimized. The body of each of the "skeletal" subroutines must be supplied by the GENOPT user. See [2] and [26] for examples of how this is done.

SUBROUTINE STRUCT calls SUBROUTINE BEHXi, i=1, 2, 3,... and SUBROUTINE OBJECT. SUBROUTINE BEHXi, i = 1, 2, 3, when completed by the GENOPT user, yield values of "behaviors" (responses such as maximum stress, critical buckling load factor, modal vibration frequency, maximum displacement, etc.). SUBROUTINE OBJECT computes the objective function.

In the rather complex example in the class, "WAVYCYL", to be described later, there are 18 "behavior" subroutines, BEHXi, i = 1, 18. In the much simpler example provided in the appendix of [26], called "CYLINDER", there are only four "behavior" subroutines, BEHXi, i = 1,4. It might be best for the reader to gain a clear understanding of how GENOPT works by first reading [2] and the appendix of [26]

During each optimization cycle, SUBROUTINE STRUCT is called to evaluate the "current" design and each "perturbed" design. A "perturbed" design is the same as the "current" design except that one of the decision variables has been perturbed a small amount in order to obtain gradients of responses, which are needed by the optimization software embedded in the GENOPT system.

The optimizer embedded in GENOPT is ADS, written many years ago by Vanderplaats and his colleagues [5,6]. As installed in GENOPT, the ADS software is "hardwired" in the "0-5-7" mode, which is the modified-method-of-feasible-directions branch of this widely used code. ADS is a gradient-based optimizer, that is, the objective and design constraints are considered to be continuous, differentiable functions.

There are two types of user referred to in [2] and in this paper:

1. the GENOPT user

2. the "end" user (in this paper called the "WAVYCYL" user and in the appendix of [26]

called the "CYLINDER" user)

The roles of the two types of user are defined in [2]. In brief, the GENOPT user "sets up" the processors just listed (BEGIN, DECIDE, OPTIMIZE, CHANGE, etc.) for the "end" user to use. The "end" user (called "WAVYCYL user" here and "CYLINDER user" in the appendix of [26] because "WAVYCYL" and "CYLINDER" are the names of the program systems created by the GENOPT user in the particular examples explored here and in the appendix of [26]) establishes the starting design, decision variables and bounds, and analysis type for the class (WAVYCYL, CYLINDER) of object to be optimized. Then the "WAVYCYL user" or "CYLINDER user" performs the optimization.

2.2 Recent improvements to GENOPT

In 1998 and 1999 the GENOPT system was improved as follows:

1. A new process (script) called SUPEROPT was introduced. SUPEROPT, a process that attempts to find a GLOBAL optimum design, is described in [7]. In the GENOPT environment it consists of multiple automatic executions of the OPTIMIZE and AUTOCHANGE processors as follows:

OPTIMIZE(Perform several design iterations)
OPTIMIZE (Perform several more iterations)
OPTIMIZE (Perform several more iterations)
OPTIMIZE (Perform several more iterations)
OPTIMIZE (Perform several more iterations)

AUTOCHANGE (Obtain a new "starting" design by randomly changing all of the decision variables.)

OPTIMIZE(Perform several design iterations)
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AUTOCHANGE (Obtain new "starting" design.)

OPTIMIZE (Perform several iterations.)
OPTIMIZE(Perform several more iterations.)

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and so on, until a total of about 275 design iterations have been executed. The new processor, AUTOCHANGE, described in [7], obtains a new starting design by a random process in which ALL of the decision variables are changed in a manner consistent with user-specified bounds, equality constraints, and inequality constraints. The WAVYCYL user chooses how many "OPTIMIZEs" to perform for each "AUTOCHANGE".

2. A new control index, IBEHV(i,j) has been introduced that can "turn off" execution of any SUBROUTINE BEHXi for any load set j. This new flexibility is especially useful in the WAVYCYL example because so much computer time is required for execution of some of the software and many of the "behaviors" are seldom critical or are almost always less critical than others. One can first perform optimization with the less critical of the SUBROUTINE BEHXi "turned off". Then, after an optimum design has been obtained, one can turn them on for a fixed design analysis to make sure that the formerly "turned off" responses do not create any significantly negative margins for the configuration that represents the optimum design. In order to obtain BOSOR4 plots of the types shown in Figs. 3 and 4, for examples, the WAVYCYL user must execute MAINSETUP and OPTIMIZE for a fixed design (ITYPE = 2) with all "behaviors" turned off except one.

3.0 BOSOR4 PROGRAM

3.1 Summary of capabilities of BOSOR4

BOSOR4 [3] is a program for the static and dynamic analysis of any shell of revolution. The shell may be loaded axisymetrically or non-axisymetrically by line loads, distributed loads, temperature, and acceleration. BOSOR4 computes static equilibrium states, buckling, modal vibration, and response to base excitation.

In BOSOR4 a complex, branched, stiffened shell of revolution is treated as an assemblage of shell segments or branches, each with its own geometry (flat, conical, cylindrical, spherical, toroidal, etc.), loading, wall construction, and linear elastic material properties. The user of BOSOR4 provides input data in an interactive mode on a segment-by-segment basis. These input data are automatically stored in a fully annotated file, one input datum and a phrase defining it on each record of the file. (See Table A.7 in the appendix of [26] for an example of such a file.) The meridian of each segment is discretized. Variation in the circumferential coordinate direction is assumed to be trigonometric, For more details about BOSOR4 see [3].

In BOSOR4 the type of analysis to be performed is controlled by an index called INDIC, as follows:

INDIC =

-2= stability determinant calculated for increasing load,

-1= bifurcation buckling with nonlinear axisymmetric prebuckling analysis,

0= nonlinear axisymmetric stress (and collapse) analysis,

1= bifurcation buckling with "linear" axisymmetric prebuckling analysis, (Actually the prebuckling analysis is the same as for INDIC = -1. However, the applied load is never changed during a case. Linear behavior is exhibited as long as the user applies a load that is very small compared to the design load.)

2= modal vibration with axisymmetric nonlinear prestress,

3= linear axisymmetric and non-axisymmetric stress analysis,

4= bifurcation buckling with linear non-axisymmetric prebuckling. The INDIC=4 branch is a combination of the INDIC=3 and INDIC=1 branches. INDIC=3 computations are first executed, followed by INDIC=1 computations. In the INDIC=4 branch the user selects the circumferential coordinate of the meridian and BOSOR4 uses the prebuckled stress state along that meridian in a bifurcation buckling analysis that is identical to the INDIC = 1 branch, that is, the fact that the prebuckled state is non-axisymmetric is ignored. This is usually a conservative approximation provided the user has chosen the meridian for which the prebuckling state is most destabilizing.

BOSOR4 will also compute peak response to loads that vary either harmonically or randomly in time. Buckling under harmonic or random base excitation can also be calculated. The capability of BOSOR4 to compute response to random base excitation, developed in 1984, has never been published. It is described briefly below and in more detail in [26].

BOSOR4 will also calculate body forces corresponding to rigid body dynamics of free-free complex shell structures subjected to non-self-equilibrating loads. These body forces are automatically included in Load Sets A ("eigenvalue" loads) and B ("constant prestress" loads) if the user indicates that rigid body motions are possible under the boundary conditions supplied.

3.2 Modification of BOSOR4 software to yield correct predictions for buckling and modal vibration for a bellows-type ("wavy") cylindrical shell

The shell equations (Sanders type [8]) on which the BOSOR4 computer program is based [3] are not adequate to predict buckling of a bellows-type of cylindrical shell, that is, a shell that is very, very soft in the axial direction compared to the hoop direction so that it buckles like a column (n=1 circumferential wave). This type of buckling of bellows and springs is called "squirm" [9-15]. Marlowe [16] developed general equations, that when modified for application to shells of revolution, yield the correct bifurcation loads for bellows-type cylindrical shells under internal or external pressure. In particular the expressions for work done by the prebuckling stress field during buckling modal deformations and the work done by normal pressure during buckling modal deformations were changed as described next.

3.2.1 Work done by prebuckling stress resultants during buckling

For shells of revolution Marlowe [16] gives the following relationships for reference surface strains:

$$
\begin{aligned}
e_s &= \gamma_s + \frac{1}{2}\left(\gamma_s^2 + \chi^2 + \gamma_{ys}^2\right) \\
e_y &= \gamma_y + \frac{1}{2}\left(\gamma_y^2 + \psi^2 + \gamma_{sy}^2\right) \\
e_{sy} &= \frac{1}{2}\left(\gamma_{sy} + \gamma_{ys}\right) + \frac{1}{2}\left(\gamma_y\gamma_{ys} + \gamma_s\gamma_{sy} + \chi\psi\right)
\end{aligned}
\qquad (3.1)
$$

in which

$$
\begin{aligned}
\gamma_s &= u,_s + w/R_1 \\
\gamma_y &= v,_y + w/R_2 + ur,_s/r \\
\chi &= w,_s - u/R_1 \\
\psi &= w,_y - v/R_2 \\
\gamma_{sy} &= u,_s - vr,_s/r \\
\gamma_{ys} &= v,_s
\end{aligned}
\qquad (3.2)
$$

where s is the coordinate along the meridian of the shell of revolution and y is the circumferential coordinate and $()_{,s}$ and $()_{,y}$ denote differentiation of () with respect to s and y, respectively. Subscripts s and y signify "meridional" and "circumferential" and subscripts sy and ys signify in-plane shear or component of rotation about a normal to the shell surface. The buckling modal displacement components, u, v, and w, are meridional, circumferential, and outward normal, respectively, and r is the radius of the parallel circle at the reference surface at the coordinate s. The quantities R_1 and R_2 are the meridional and normal circumferential radii of curvature of the shell of revolution.

Corresponding to Eqs. (3.1), the integrand of the energy expression for bifurcation buckling of axisymmetrically loaded shells of revolution with zero prebuckling torque contains the terms

$$
\frac{N_{s0}}{2}\left(\gamma_s^2 + \chi^2 + \gamma_{ys}^2\right) + \frac{N_{y0}}{2}\left(\gamma_y^2 + \psi^2 + \gamma_{sy}^2\right) \qquad (3.3)
$$

These terms represent the work done by the prebuckling meridional and circumferential stress resultants, N_{s0}, N_{y0}, during the buckling process. The analogous terms for a buckling analysis based on Sanders' equations [8] are

$$
\frac{N_{s0}}{2}\left(\chi^2 + \gamma^2\right) + \frac{N_{y0}}{2}\left(\psi^2 + \gamma^2\right) \qquad (3.4)
$$

in which γ, the "average" rotation about the normal to the shell surface, is defined as

$$
\gamma = \left(\gamma_{sy} + \gamma_{ys}\right)/2 \qquad (3.5)
$$

3.2.2 Effect of uniform normal pressure acting on shell surface

Marlowe [17] gives

$$
W = \iint_{ys} p\left\{w(1 + \gamma_s/2 + \gamma_y/2) - (u\chi + v\psi)/2\right\} ds dy \qquad (3.6)
$$

for the work done by the uniform normal pressure during the buckling process. Equation (3.6) is to be compared with an analogous expression given by Cohen [18], which for uniform pressure simplifies to

$$W = \iint_{ys} p \left\{ \begin{array}{l} w(1+\gamma_s+\gamma_y) \\ -w^2(1/R_1+1/R_2)/2 \\ +(u^2/R_1+v^2/R_2)/2 \end{array} \right\} dsdy \qquad (3.7)$$

Use in BOSOR4 [3] of expressions (3.4) and (3.7) yields incorrect values for the buckling load of a very, very long cylindrical shell loaded by internal pressure acting on the curved wall only (not acting on the ends in such a way as to create prebuckling axial tension). For example, a cylinder with modulus $E = 10^7$ psi, Poisson ratio $\mu = 0.3$, thickness $t = 1.0$ in., radius $R = 10$ in. and length $L = 600$ in. should buckle at $p_{cr} =$ 2741 psi, according to Euler's formula,

$$\pi r^2 p_{cr} = P_{cr} = \pi^2 EI / L^2$$

$$p_{cr} = \pi^2 ERt / L^2 \qquad (3.8)$$

The BOSOR4 program, as based on Eqs. (3.4) and (3.7), yields p_{cr}=-6.9 psi for this problem. After modification of BOSOR4 such that the analysis is based on Eqs. (3.3) and (3.6), the predicted critical pressure is 2739 psi.

3.3 Modification of BOSOR4 software to compute response to base excitation and buckling due to base excitation

This capability was added in 1984 to BOSOR4 but never before published. The following description occurs in the file, "bosor4.news", which is distributed with the BOSOR4 computer program:

BOSOR4 computes the response to base excitation as follows:

(i) harmonic excitation at a series of natural frequencies

(ii) random excitation

(iii) shock excitation

Depending on which analysis type, i, ii, or iii, the user is asked by the BOSOR4 system to provide load factors, damping factors, and spectral densities as functions of the frequency. Details are listed in Table 3.1 of [26]

3.4 Modification of BOSOR4 software to work in the context of automated optimization

The version of BOSOR4 that has been widely distributed consists of a number of processors that are separate computer programs executed in a prescribed sequence, as described in [3] (preprocessor, B4READ, mainprocessor, B4MAIN, postprocessor, B4POST). This software was modified by conversion of the BOSOR4 "main programs" into subroutines that are called from SUBROUTINE STRUCT and SUBROUTINEs BEHXi, i = 1,...18. All of the FORTRAN statements dealing with the opening and closing of files were moved to SUBROUTINES OPNGEN, RWDGEN, and CLSGEN, which open, rewind, and close the various files needed for execution of BOSOR4. The "GASP" routines, which transfer data to and from random access mass storage, were modified by Frank Weiler (see Acknowledgments) in order to avoid unlimited expansion of the random access file size as optimization cycles proceed.

New subroutines were written by means of which the GENOPT data (dimensions, loads, material properties, boundary and junction conditions between segments, etc.) are used to generate input files that the BOSOR4 software can process. These new subroutines are called PUTWAV and BOSDEC. The output of SUBROUTINE BOSDEC is a standard input file for BOSOR4. (See the appendix of [26] for an example of a relatively simple BOSDEC routine. In the simple example used there is no need of a "PUTWAV" routine.)

3.5 Increase of maximum problem size that can be handled by BOSOR4

Previously, the maximum number of segments in a BOSOR4 model had to be less than or equal to 95, and the maximum number of degrees of freedom had to be less than 3000. These limits have been raised to 195 and 15000, respectively, in the version of BOSOR4 used for optimization.

4.0 INSTRUCTIONS FOR THE USE OF GENOPT/WAVYCYL

In the following it is assumed that GENOPT is being applied to problems involving a certain class of ring-stiffened shells of revolution called "WAVYCYL". However, it is emphasized that the GENOPT system can be applied to any field, not just that of structural analysis and not just that involving shells of revolution such as "WAVYCYL". For more details see [2] and the appendix supplied in [26].

4.1 Things for the GENOPT user to do before working with the computer

a. The GENOPT user must decide what shell of revolution or class of shells of revolution he or she wants to optimize. Questions such as the following must be answered by the GENOPT user:

1 Is the shell wall stiffened?

2 What types of shell wall are to be included (e.g. isotropic, laminated composite)?

3 What boundary conditions are to be used?

4 What are the loadings? Are there multiple load sets? Do both Load Set A and Load Set B exist?

b. The GENOPT user must identify what computer coding (presumably already written and working) he or she will need to perform the various structural analyses that will be "looped through" during optimization cycles. In this example the structural analysis coding is a modified form of the BOSOR4 computer program [3] plus translators called PUTWAV and BOSDEC that convert "WAVYCYL" input for a specific class of shells of revolution to standard BOSOR4 input data. (See the appendix of [26] for a simpler case for which PUTWAV is not needed).

c. The GENOPT user must identify various models of the structure to be used in his/her application:

1 global models

2 local models

3 Are rings to be modelled as branched shell segments?

d. The GENOPT user must decide what the objective is:

1 minimum weight

2 minimum cost

3 other

e. The GENOPT user must identify what behaviors may constrain the design:

1 stress

2 displacement

3 buckling

i. local buckling

ii. general buckling

4 modal frequency

5 thermal expansion

6 clearances

7 other

f. The GENOPT user must identify all variables in the problem, think of names for these variables (6 characters or less), think of user-friendly one-line definitions (less than 60 characters in length) for each of the variables, and think of possible supporting "HELP" paragraphs for each of the variables. The one-line definitions are especially important because they appear in the output data and therefore should be easy to understand. They are what make the system of programs created by GENOPT "user friendly".

As described in [2], GENOPT requires that each of the variables be categorized as one of the following types:

f.1 a possible decision variable for optimization, typically a dimension of a structure.

f.2 a constant parameter (cannot vary as design evolves), typically a control integer or material property, but not a load, allowable, or factor of safety, which are asked for later. For examples, a table of material properties vs temperature or a table of knockdown factors for buckling loads vs amplitude of initial imperfection would fit into this category.

f.3 a parameter characterizing the environment, such as a load component or a temperature.

f.4 a quantity that describes the response of the structure, (e.g. stress, buckling load, modal frequency)

f.5 an allowable, such as maximum allowable stress, minimum allowable frequency, etc.

f.6 a factor of safety

f.7 the quantity that is to be minimized or maximized, called the "objective function" (e.g. weight).

NOTE 1: Variables of types 4, 5, 6 are always "bundled" together. For example, if the GENOPT user selects a variable of Type 4 (for example, call it STMAX for "maximum stress") he/she will next be asked to provide information about STMAX (maximum actual stress), STMAXA (maximum allowable stress), and STMAXF (factor of safety for stress). STMAX, STMAXA and STMAXF are names that the GENOPT user chooses. All "responses" (often called "behaviors"), such as stress, buckling, displacement, etc., are treated in this manner.(See pages 2 and 3 of Table 4.4.)

NOTE 2: GENOPT requires the user to provide all input relative to variables of Types 1 and 2 before variables of Type 3. All variables of Type 3 must be provided before variables of Types 4. 5, 6. All "4, 5, 6" "bundles" must be provided before the objective (Type 7).

4.2 Things for the GENOPT user to do on the computer

a. Execute GENTEXT. "GENTEXT" is the command that causes execution of the GENOPT program called GENPROMPT. The "GENTEXT" command initiates the interactive session in which the GENOPT user is asked to provide the information just described in Section 4.1f. During this interactive session the GENOPT system writes FORTRAN code fragments that it later inserts into processors called BEGIN and CHANGE and subroutine libraries called STRUCT, BEHAVIOR, and STOGET. These entities, plus others (processors called DECIDE, MAINSETUP, OPTIMIZE, AUTOCHANGE, STORE, CHOOSEPLOT, and subroutine libraries called CONMAN, ADS, PROMPTER, and UTIL, which are NOT modified by GENOPT) constitute the computer program system by means of which ordinary "fixed design" structural analyses, such as an ordinary BOSOR4 analysis, are automatically converted into a computer program system that can optimize something, such as "WAVYCYL". (NOTE: as mentioned above, GENOPT is not restricted to the field of structural analysis.) In this paper the computer program system created by GENOPT and the GENOPT user is called "WAVYCYL". In the much simpler example featured in the appendix of [26] the computer program system created by GENOPT and the GENOPT user is called "CYLINDER".

b. It will usually happen sometime after the GENOPT user has completed a possibly very long "GENTEXT" interactive session, or even after the "end" user (WAVYCYL user) has made several optimization runs, that the GENOPT user will think of additional variables that must be included. Since GENOPT demands that the various classes of variables listed in Section 4.1f be supplied in a certain order, this seems to require that the GENOPT user start over from the beginning. However, the GENOPT system contains a processor called INSERT by means of which the GENOPT user can easily supply additional variables in any of the categories listed in Section 4.1f except f.7, the objective.

c. The subroutine libraries called STRUCT and BEHAVIOR are "shells" that contain places for the GENOPT user to insert computer coding that performs the structural analysis for each optimization cycle in which the design constraints (e.g. stress, buckling, displacement, natural frequency) and objective (e.g. weight) are computed and in which the gradients of the design constraints and objective with respect to each of the decision variables are computed. By far most of the effort in generating a working optimization tool for the class of problem selected by the GENOPT user (in this case the optimization tool called "WAVYCYL" and in the appendix of [26] the optimization tool called "CYLINDER") is the derivation of completed subroutine libraries STRUCT and BEHAVIOR and the many modifications to them that will doubtless be required before a final working and thoroughly checked version of "WAVYCYL" or "CYLINDER" (or other system) exists.

Table 4.1 summarizes the activities of the GENOPT user and the "end" ("WAVYCYL", "CYLINDER") user that lead to the capability to optimize any of a class of objects.

Tables 4.2 - 4.4 list information that is created by the GENOPT user for the "WAVYCYL" class of shells and organized by the GENOPT system.

Table 4.2 lists the first several lines of the wavycyl.INP file, generated during the first part of the interactive "GENTEXT" session. This file contains input data for "GENTEXT" provided by the GENOPT user. In this complex example the entire wavycyl.INP file is too long to be listed in its entirety here.

Table 4.3 lists the first part of the prompt file, wavycyl.PRO, which is automatically created as the GENOPT user proceeds with the interactive "GENTEXT" session. The part of the wavycyl.PRO file listed in Table 4.3 corresponds to the part of the wavycyl.INP file listed in Table 4.2. The appendix of [26] includes tables that list, for the simple case called "CYLINDER", the complete cylinder.INP and cylinder.PRO files.

Table 4.4 is part of the wavycyl.DEF file, created by the GENOPT system upon completion of the "GENTEXT" interactive session. (For more about the *.DEF file, see [2].) In this rather complex example, the GENOPT user established 18 "behaviors" (responses) that can possibly constrain the optimum design. These 18 "behaviors" are identified starting with the variable, STRMAX, on page 2 of Table 4.4.

Table 4.5, which is part of the output listed in the file *.OPM (see Table 5.2; in this case "*" = "testnew6".) after execution of OPTIMIZE, gives more complete definitions of each of the 18 "behaviors". The values listed under the heading, "CURRENT VALUE", correspond to a particular optimized configuration. "Behaviors" with values 1.000E+10 and 1.000E-10 were "turned off" during the execution of OPTIMIZE in this particular case and therefore retain extreme values automatically preset by the GENOPT system.

Table 4.6 lists design margins that correspond to the "behaviors" listed in Table 4.5. Note that the "MARGIN NO." (column 1 of Table 4.6) does not correspond to the "BEH. NO." in Table 4.5 because margins larger than a certain value are automatically discregarded by the GENOPT system in order to save computer time. In this particular case margins corresponding to "behaviors" 2, 3, and 16 and 17 are omitted from the list in Table 4.6. Table 4.6 reveals how

(a) the values of the "behavior",

(b) the allowable corresponding to that behavior, and

(c) the factor of safety corresponding to that behavior

are used to generate design margins. The design constraints, which are used by the optimizer ADS, are equal to the margins plus unity.

Table 4.5 of [26] lists the labelled common blocks created by GENOPT during the interactive "GENTEXT" session. These common blocks contain all the data that characterize the class, "wavycyl". The labelled common blocks appear in the skeletal STRUCT and BEHXi and OBJECT subroutines, which must be "fleshed out" by the GENOPT user. See [2] and [26] for examples of how this is done.

Tables 4.6 - 4.8 of [26] list input data, provided by the WAVYCYL user for the specific case called "testnew6", for the WAVYCYL processors, BEGIN, DECIDE, and MAINSETUP/OPTIMIZE, respectively. The data in Tables 4.6 - 4.8 of [26] and repeated in condensed form in Table 4.7 of this paper, correspond to the starting design depicted in Fig. 1a.

Details of the flow of computations in SUBROUTINE STRUCT and in the SUBROUTINEs BEHXi, i = 1, 18, as "fleshed out" by the GENOPT user (the writer in this case) are given in Sections 5 and 6 of [26]. Section 5 of [26] describes in detail how the "effective" wall properties, that is, the 6x6 matrix of coefficients, C(i,j), is generated for the structural segment in the BOSOR4 model (Segment 1) in which the "waviness" is "smeared". Section 6 of [26] describes briefly the flow of computations in each of the SUBROUTINES BEHXi, i = 1, 2, ...18.

5.0 NUMERICAL RESULTS: ALUMINUM WAVY CYLINDRICAL SHELL WITH RINGS

5.1 Summary

Results pertaining to the wavy cylindrical shell with external rings are listed in Tables 5.1 - 5.3 and plotted in Figs. 3 - 16. Table 4.7 lists the starting design, material properties, loading, etc. The name assigned to the case by the WAVYCYL user (the writer) is "testnew6". Optimization is conducted with "behaviors" 1, 2, 3, 9, 10, 11, 12, 13, 15, 16, 17, and 18 "turned off". (See Table 4.5 for a complete list of "behaviors".)

The wavy cylindrical shell has an initial imperfection in the form of the general buckling mode with amplitude, W_0 = 0.05*RADIUS, which corresponds to the "ASME one per cent rule", that is, the largest and smallest diameter of the imperfect cylindrical shell differ by one per cent.

This section contains descriptions of an initial optimization, the final runstream used for development of the final optimum design, results from convergence studies with respect to the maximum allowable number of degrees of freedom, MAXDOF, in the BOSOR4 model and with respect to the number of nodal points, NMESHC, used in each small toroidal segment of the wavy portion of the model, and design sensitivity studies at the optimum design with respect to all of the decision variables used during optimization.

5.2 Initial optimization of "testnew6" with the WAVYCYL system

The maximum number of degrees of freedom, MAXDOF, was initially set to 3000, not 15000 as listed in Table 4.7. The following WAVYCYL runstream was executed:

GENOPTLOG (activate the GENOPT/WAVYCYL command set)

BEGIN (establish a starting design, etc.; input file = testnew6.BEG; Table 4.6 of [26])

DECIDE (choose decision variables, bounds: input file = testnew6.DEC; Table 4.7 of [26])

MAINSETUP (choose "behaviors", analysis type; input file = testnew6.OPT; Table 4.8 of [26])

SUPEROPT (launch "global" optimizer; see Section 2.2 for description)

CHOOSEPLOT (choose what to plot vs design iterations during SUPEROPT)

DIPLOT (get postscript files of plots, testnew6.i.ps, i = 3, 4, 5)

The SUPEROPT run required about 60 hours of computer time on a very fast SGI workstation. The run was especially long because there were eight decision variables, as identified in Fig. 2.

The initial optimization run for the configuration with the Tee-shaped rings, such as shown in Fig. 1a, demonstrated that the size of the outstanding flange of the ring dwindled to small lower bounds. Therefore, further investigations were made only with rectangular rings rather than with Tee-shaped rings. The input data for "BEGIN" (Table 4.6 of [26] and Table 4.7 here) was modified by setting the thickness and width of the outstanding flange, TFLANG and HFLANG, respectively, to zero and by not choosing TFLANG and HFLANG as decision variables in "DECIDE".

Because of the long computer time required for execution of SUPEROPT, a decision was made to use PANDA2 [7, 19-22] to determine optimum values for the ring spacing, BRINGS, and the thickness and height, TWEB and HWEB, of the now rectangular rings.

5.3 A more refined run stream to develop the optimum design.

A typical run stream leading to an optimum design follows. PANDA2 is first used to obtain optimum values for the ring spacing, BRINGS, and ring thickness and height, TWEB and HWEB, respectively. Then the WAVYCYL system is used to obtain the thickness, THICK, of the wavy wall of the cylindrical shell, the axial halfwavelength, WAVLEN, and the amplitude, AMPLIT, of the waviness. The run stream is:

------ begin optimization with PANDA2. The PANDA2 case name is "cyl" --------

PANDA2LOG (activate the command set for PANDA2 [7, 19-22])

BEGIN (provide starting design for PANDA2 execution, Table 7.1 of [26] = cyl.BEG)

SETUP (PANDA2 system sets up matrix templates [22])

DECIDE (choose decision variables, bounds, inequality constraints, Table 7.2 of [26]. Inequality constraint: the ring thickness, TWEB cannot be less than one tenth the ring height, HWEB; file=cyl.DEC)

MAINSETUP (provide loading, imperfections, strategy parameters, type of analysis, etc., Table 7.3 of [26] = cyl.OPT)

SUPEROPT (launch "global" optimizer [7]. Execution of SUPEROPT required about 20 minutes of computer time on the super-fast SGI workstation. output=cyl.OPP)

CHOOSEPLOT (choose what to plot vs design iterations during SUPEROPT)

DIPLOT (obtain postscript plots for PANDA2 phase of optimization; see Fig. 5)

(See Table 5.1 for output from PANDA2 corresponding to the optimized design. The optimum ring spacing is 10 in.; the ring thickness and height are 0.067398 and 0.67398 inches, respectively.)

--- end of optimization with PANDA2 ---

--- begin optimization with WAVYYCL ---

GENOPTLOG (activate the WAVYCYL system command set)

BEGIN (provide starting design for WAVYCYL optimization, Table 4.7 with BRINGS = 10 in., TWEB = 0.067398 in., HWEB = 0.67398 in., TFLANG = 0, HFLANG = 0; upper bound of WAVLEN = 3.0 in.; input = testnew6.BEG)

DECIDE (choose decision variables and bounds. Only THICK, WAVLEN, and AMPLIT are now decision variables. See Table 7.5 of [26]= testnew6.DEC)

MAINSETUP (choose "behaviors", analysis type; Table 4.8 of [26] = testnew6.OPT)

SUPEROPT (launch "global" optimizer; output file = testnew6.OPP)

CHOOSEPLOT (choose what to plot vs design iterations during SUPEROPT)

DIPLOT (get postscript files of plots, testnew6.i.ps, i = 3, 4, 5; see Fig. 6)

--- end of first SUPEROPT optimization ---

(Reduce upper bound of WAVLEN in Table 7.5 of [26] from 3.0 to 0.8 in.)

DECIDE (run DECIDE with updated file, input = testnew6.DEC [Table 7.5 of [26] with upper bound of WAVLEN reduced from 3.0 to 0.8 in.])

SUPEROPT (launch "global" optimizer; output = testnew6.OPP)

CHOOSEPLOT (choose what to plot vs design iterations during SUPEROPT)

DIPLOT (get postscript files of plots, testnew6.i.ps, i = 3, 4, 5; see Figs. 7,8)

--- end of 2nd SUPEROPT optimization ---

(Find out why the objective (Fig. 7) and the margins (Fig. 8) are so "jumpy" during optimization cycles. To do this, run a design sensitivity analysis [ITYPE=3 in MAINSETUP; see Table 7.6 of [26]]. Use very "tight" starting and ending values of WAVLEN, with the value from the optimum design near the center of the range, 0.545 in. < WAVLEN < 0.564 in.)

MAINSETUP (choose "behaviors" and use analysis type ITYPE=3; Table 7.6 of [26])

OPTIMIZE (run the WAVYCYL processor OPTIMIZE in the design sensitivity mode [ITYPE=3])

CHOOSEPLOT (select which margins to plot for 0.545 < WAVLEN < 0.564 in.)

DIPLOT (get postscript file of plot, testnew6.3.ps [margins v WAVLEN]; see Fig. 23 of [26])

---- end of design sensitivity run with respect to WAVLEN -----

(get plots of critical buckling modes corresponding to the minimum and maximum design margins for BUC0 and B0ANTI, which occur at WAVLEN = 0.55060 in. and WAVLEN = 0.55555 in., respectively, as can be seen from Fig. 23 of [26].)

(first, get critical buckling mode corresponding to WAVLEN=0.55060)

CHANGE (change WAVLEN to 0.5506 in.)

MAINSETUP (choose all behaviors "turned off" except for Behavior no. 7 [B0ANTI = antisymmetric low-n buckling at θ=0 deg.; choose analysis type, ITYPE = 2 [fixed design analysis])

OPTIMIZE (perform the fixed design analysis to obtain output corresponding to WAVLEN = 0.55060 and THICK and AMPLIT = values obtained after the 2nd SUPEROPT run. This run yields a file called testnew6.PLT2, which is a standard BOSOR4 file, legal for input to the BOSOR4 procesor called BOSORPLOT.)

BOSOR4LOG (activate the BOSOR4 command set)

BOSORPLOT (obtain postscript file for plotting the critical buckling mode, see Fig. 24 of [26])

(next, get critical buckling mode corresponding to WAVLEN=0.55555)

GENOPTLOG (activate the WAVYCYL system command set)

CHANGE (change WAVLEN to 0.55555 in.)

MAINSETUP (choose all behaviors "turned off" except for Behavior no. 7 [B0ANTI = antisymmetric low-n buckling at θ=0 deg.; choose analysis type, ITYPE = 2 [fixed design analysis])

OPTIMIZE (perform the fixed design analysis to obtain output corresponding to WAVLEN = 0.55555 and THICK and AMPLIT = values obtained after the 2nd SUPEROPT run. This run yields a file called testnew6.PLT2, which is a standard BOSOR4 file, legal for input to the BOSOR4 procesor called BOSORPLOT.)

BOSOR4LOG (activate the BOSOR4 command set)

BOSORPLOT (obtain postscript file for plotting the critical buckling mode, see Fig. 25 of [26])

----- end of fixed design WAVYCYL runs and BOSOR4 runs for mode shapes -----

(next, do more optimizing. From the last use of CHANGE, the axial halfwavelength of waviness, WAVLEN, is now set to 0.55555 in., which corresponds to the maxima of BUC0 and B0ANTI vs WAVLEN in the range 0.545 < WAVLEN < 0.564 in. as plotted in Fig. 23 of [26]. Maintain WAVLEN=0.55555 in. and remove WAVLEN from the list of decision variables; optimize with respect to THICK and AMPLIT only. See Table 7.7 of [26])

DECIDE (choose as decision variables only THICK and AMPLIT [Table 7.7] of [26])

MAINSETUP (use the input in Table 4.8 of [26] again.)

OPTIMIZE (perform optimization. Only one "OPTIMIZE" is enough to get the global optimum design now, since we are so close to it from all the previous computations. output = testnew6.OPP)

------ end of final optimization -----

------ beginning of fixed design analysis of optimized design ------------

MAINSETUP (input is same as Table 4.8 of [26], except analysis type, ITYPE = 2, that is, fixed design analysis and fewer "behaviors" are turned off. [See the beginning of Table 5.2 for testnew6.OPT])

OPTIMIZE (perform fixed design analysis with fewer "behaviors" turned off. The results from this run, stored in the file, testnew6.OPM, are listed in Table 5.2)

------- end of fixed design analysis of optimized design --------

5.4 Discussion about optimization of wavy cylindrical shell with rings

5.4.1 PANDA2 optimization

Tables 7.1 - 7.3 of [26] list the input files, cyl.BEG, cyl.DEC, cyl.OPT, for the PANDA2 processors, BEGIN, DECIDE, and MAINSETUP/PANDAOPT, respectively. The shell optimized with PANDA2 has a general buckling modal imperfection of amplitude, W_0 = 0.005*RADIUS = 0.045 in.

PANDA2 handles complete (360 degree) cylindrical shells as simply supported panels that span 180 degrees. The loading in the PANDA2 model is uniform axial compression and external pressure only. (The hoop resultant, N_y = p*R = -106.2 lb/in). PANDA2 cannot handle nonuniform loading, such as occurs with lateral g-loading, for example. Therefore, the loading in the PANDA2 model is slightly different from that imposed in the WAVYCYL model. Also, PANDA2 cannot account for the waviness in the wall of the cylindrical shell. In spite of these shortcomings, it is felt that for the cases studied here the similarity in capabilities of PANDA2 and WAVYCYL justify the use of PANDA2 as a "shortcut" for obtaining optimum values of ring spacing, BRINGS, ring thickness, TWEB, and ring height, HWEB. If one wants, one can re-introduce BRINGS, TWEB, HWEB as decision variables in other WAVYCYL optimizations. (However, that is not done in this paper.)

The SUPEROPT processor in the PANDA2 system of programs is used to obtain the optimum design. This processor, by means of which a global optimum design can be obtained, is described in [7]. It works in a manner completely analogous to that described for the SUPEROPT processor in the WAVYCYL system of programs, a brief description of which appears in Section 2.2.

Figure 5 and Table 5.1 show results from the PANDA2 SUPEROPT execution. At the initiation of the SUPEROPT run the user chose the option of 6 PANDAOPTs per AUTOCHANGE. (PANDAOPT is the name of PANDA2's main processor, analogous to the processor called OPTIMIZE in the WAVYCYL system) The spikes in Fig. 5 correspond to iterations for which a new starting design is generated randomly by automatic execution of the PANDA2 processor called AUTOCHANGE [7] (similar but not the same as the WAVYCYL system processor also called AUTOCHANGE). For all of the 11 random "restarts" (re-executions of AUTOCHANGE) that permitted the full six successive executions of PANDAOPT before the next execution of AUTOCHANGE, PANDA2 yields the same optimum design. (The 12th random "restart", at Iteration No. 269 approximately, was not permitted to converge to an optimum design because the SUPEROPT process reached the specified maximum permitted total number of design iterations first.) It can be concluded, therefore, that the optimum design is very likely to be the global optimum design. As will be seen later, the SUPEROPT process used with the WAVYCYL model does not usually lead to such "clean" plots.

As seen from Figs. 10 and 11 of [26] and Table 5.1 here, the most critical margins are general buckling, inter-ring buckling, rolling with local buckling (same as inter-ring buckling, just a different model of the same phenomenon), and the geometrical (inequality-condition-based) constraint, Margin No. 5 in SUBCASE 1 in Table 5.1, by means of which the thickness of the ring must be greater than one tenth the height of the ring if the design is to be feasible.

The best optimized design obtained by PANDA2 during the approximately 275 iterations is listed in Table 5.1.

NOTE: It is emphasized that with use of a SUPEROPT process the best, that is, lightest design is rarely the last design obtained during the total number of iterations. During the SUPEROPT process, PANDA2 keeps track of the best design obtained for all iterations since the beginning of the SUPEROPT process. The user can perform multiple SUPEROPT optimizations provided he/she executes at least one CHOOSEPLOT/DIPLOT between successive SUPEROPTs. These characteristics also hold for the SUPEROPT process in the WAVYCYL system of programs or in any system of programs created via GENOPT.

It was necessary to modify PANDA2 in a significant way in order to obtain the results plotted in Fig. 5 and listed in Table 5.1. In cases such as this, for which the lower bound on ring spacing (10 inches in this case) is much greater than would naturally occur if the rings were free to approach eachother more closely during design iterations, it is necessary to account for the fact that the "effective length" of cylindrical shell working efficiently with each ring during buckling modal deformation is much shorter than the ring spacing. Until now no "effective length" strategy had been introduced into PANDA2. In the present case, for a perfect shell, without any "effective length" strategy, PANDA2 yielded a general instability load factor of 1.25, whereas BOSOR4 [3] yielded a general instability load factor of 0.79 for the same ring-stiffened shell and loading. Now a new "effective length" strategy has been introduced into PANDA2 for ring-stiffened shells. It is described fully in ITEM 509 of the file, ...panda2/doc/panda2.news [25], which is a log of all PANDA2 modifications since 1987 and which is distributed with the PANDA2 program system. A brief summary is given next.

The new "effective length" strategy in PANDA2 introduces a new knockdown factor, RNGKNK = EIG(discrete)/EIG(smeared), in which RNGKNK is the knockdown factor, EIG(discrete) is the general buckling modal load factor (eigenvalue) obtained from a single discretized skin-ring module [20] permitted to buckle like a ring (see Fig. 33e on p. 345 of [20], for example), and EIG(smeared) is the buckling load of a ring with certain hoop bending stiffness, "EI". EIG(smeared) is given by:

EIG(smeared)

$$= \left(3EI/R^3\right)/p = \left(3(C_{s55} - C_{s25}^2/C_{s22})/R^3\right)/p \qquad (5.1)$$

in which C_{s22} is the hoop extensional stiffness, C_{s55} is the hoop bending stiffness, and C_{s25} is the hoop bending-stretching coupling for the cylindrical shell with rings smeared as prescribed by Baruch and Singer [23]. Eq. (5.1) is valid if the reference surface is the middle surface of the skin of the cylindrical shell. The new knockdown factor, RNGKNK, is used to reduce the buckling load factor computed in PANDA2 from what is called "the PANDA-type" model, that is, the model in which the buckling load factors are given in "closed form" by Eq. (57) in [21]. With the new "effective length" strategy in place the predictions of PANDA2 and BOSOR4 are now in good agreement for this case.

5.4.2 WAVYCYL optimization

The optimum ring spacing, BRINGS = 10 in., and optimum ring thickness, TWEB = 0.067398 in. and ring height, HWEB = 0.67398 in., determined from applcation of PANDA2, are fixed during the WAVYCYL optimization. The amplitude of the initial general buckling modal imperfection is W_0=0.005*RADIUS = 0.045 in. The upper bound on axial halfwavelength of the waviness, WAVLEN, is equal to 3.0 inches. Figure 6 shows the results of the first SUPEROPT run conducted with use of the maximum allowable number of degrees of freedom, MAXDOF, set at its largest possible value, 15000. (A previous SUPEROPT, the results from which are not included in this paper, had been executed with MAXDOF = 3000). Figure 6 is analogous to Fig. 5. Notice that, unlike the results from the PANDA2 SUPEROPT run, the objective does not return consistently to the same minimum-weight design. In fact, as design iterations proceed, the SUPEROPT process never finds a design as good as that determined during the first approximately 35 iterations, that is, before the first execution of AUTOCHANGE. This phenomenon, explained in more detail in [26], is caused by the extremely "noisy" shape of the boundary between feasible and unfeasible regions in design space. A hint of this "noisiness" is provided by plots of the design margins vs iterations shown in Fig. 8. The buckling margins for BUCO, BOANTI, and BUCOMD are especially "spiky".

Figure 17 of [26] shows the evolution of axial halfwavelength, WAVLEN during the SUPEROPT run. The general tendency is for WAVLEN to approach its upper bound, 3.0 in., in this case.

After completion of the first SUPEROPT run and execution of CHOOSEPLOT/ DIPLOT in order to obtain plots, the input file for "DECIDE" (testnew6.DEC; Table 7.5 of [26]) was edited to reduce drastically the upper bound of WAVLEN from 3.0 to 0.8 in. The WAVYCYL processors, DECIDE, SUPEROPT, CHOOSEPLOT and DIPLOT were executed again. With restriction on the possible excursions of axial halfwavelength, WAVLEN, Figure 7 shows much more consistent behavior than that depicted in Fig. 6. However, the objective is still much, much more jagged than that from the optimization with PANDA2, displayed in Fig. 5. The "spikiness" of the margins (Fig. 8), especially those for BUCO and BOANTI, remains. The WAVYCYL SUPEROPT process does not seem to be able to determine a consistent value for the axial halfwavelength, WAVLEN (Fig. 21 of [26]) at all, and the amplitude of the waviness, AMPLIT, wanders in the region from 0.6 to 0.8 inches, as one can see from Fig. 22 of [26]. An explanation of this behavior is given next.

In the WAVYCYL/GENOPT system design sensitivity can be determined with respect to any user-selected decision variable. This is done here. The decision variable, WAVLEN, is chosen as the independent variable because intuition tells us that there may be an important interaction between the ring spacing, BRINGS, and the axial halfwavelength, WAVLEN, of the waviness. New input data for MAINSETUP/OPTIMIZE are generated (Table 7.6 of [26]). A very small range, 0.545 < WAVLEN < 0.564, is chosen, with the center of the range corresponding to the value obtained as optimum after the second SUPEROPT run. The values of wavy wall thickness, THICK, and amplitude of the waviness, AMPLIT, are held at the optimum values obtained after the second SUPEROPT run.

Figure 23 of [26] (similar to Fig. 14 in this paper) shows the results of this design sensitivity analysis. As can be seen from the plots in Fig. 14, the margins for BUCO (low-circumferential-wave symmetric buckling at θ=0 degrees) and for BOANTI (low-circumferential-wave antisymmetric buckling at θ=0 degrees), are especially sensitive to small changes in WAVLEN. This explains, from a mathematical point of view, why the results from execution of SUPEROPT tend to wander. Very small changes in WAVLEN lead to very large changes in the gradients of the BUCO and BOANTI margins with respect to WAVLEN. We still need an explanation from a physical point of view of why these particular margins "oscillate" so much with very small changes in WAVLEN.

In order to determine the cause of the extreme sensitivity of the critical buckling load factors, BUCO and BOANTI, to changes in WAVLEN in the neighborhood of WAVLEN = 0.55 in., we wish to obtain plots of the configuration and the critical buckling modes corresponding to the minimum and maximum values of the BUCO and BOANTI margins in Fig. 23 of [26]. Therefore, we must do two "fixed design" analyses (ITYPE = 2 in Table 4.8 of [26], for example): the first with the value of WAVLEN set at 0.55060 in.(minimum BUCO and BOANTI margins in Fig. 23 of [26]) and the second with the value of WAVLEN set at 0.55555 in. (maximum BUCO and BOANTI margins in Fig. 23 of [26]). Each of these two "fixed design" analyses is performed with only the Behavior No. 7 "turned on" in the testnew6.OPT file (MAINSETUP). Behavior No. 7 is low-circumferential-wave buckling antisymmetric with respect to the cylindrical shell midlength. After each WAVYCYL "fixed design" analysis is complete, we copy the testnew6.PLT2 file to a directory from which BOSOR4 processors are generally executed. Then we activate the BOSOR4 command set (BOSOR4LOG) and execute the BOSOR4 plotting processor, BOSORPLOT. These operations lead to Figs. 24 and 25 of [26].

Figure 24 of [26] shows the critical buckling mode shape corresponding to WAVLEN = 0.55060 in.. The buckling load factor (eigenvalue) is 1.1397. (Remember, the factor of safety for all kind of buckling in this study is 1.25, as listed in Table 4.6 of [26] and in Table 4.4 here. Therefore, the buckling load factor of 1.1397 leads to a negative margin as shown in Fig. 23 of [26] for WAVLEN = 0.55060.)

Figure 25 of [26] shows the critical buckling mode corresponding to WAVLEN = 0.55555 in. The buckling load factor is 1.3894, about 18 per cent higher than that for WAVLEN = 0.55060 in., which is less than one per cent different from 0.55555 in. Both buckling modes correspond to general instability.

Close inspection of the plots of the undeformed meridians reveals why there is such a big difference in the buckling load factors. With WAVLEN = 0.55555 in. (Fig. 25 of [26]) the root of every ring corresponds to the outward-directed peak of a wave in the cylindrical shell. Since the ring spacing is 10 inches and the axial halfwavelength of the waviness, WAVLEN, is 0.55555 inches, there are exactly 18 halfwaves of waviness between rings, with the ring at the plane of symmetry, z = 90 in. being located at an outward-directed peak "by definition", that is in all wavy models. With the very slightly lower value, WAVLEN = 0.55060 in., several of the rings located in the bottom half of the shell depicted in Fig. 24 of [26] have their roots in "valleys" rather than peaks of the waviness. The effective overall circumferential bending stiffness for general instability is therefore considerably greater with WAVLEN = 0.55555 in. than is the case with WAVLEN = 0.55060 in, leading to the significantly higher general buckling load factor.

One might well ask, "Why not ALWAYS place the rings at outward-directed peaks in the waviness and make that part of the definition of the structure to be optimized?" It is true that the WAVYCYL system could have been constructed in this way. However, such a system would work well only in cases for which the axial halfwavelength of the waviness, WAVLEN, is small compared to the ring spacing, BRINGS.

As listed near the end of the run stream, a final optimization was conducted with WAVLEN fixed at its optimum value, 0.55555 in., and with only the thickness, THICK, of the wavy wall and the amplitude, AMPLIT, of the waviness, permitted to change during optimization cycles. In this case SUPEROPT was not needed. A single execution of OPTIMIZE was adequate to yield the final optimum design, which is listed in Table 5.2.

5.4.3 Discussion of output listed in Table 5.2

Table 5.2 lists results corresponding to the ring-stiffened cylindrical shell with a wavy wall, optimized as described in the run stream listed above. These results were obtained by "turning on" additional behaviors (9 - 13) for the "fixed design" analysis option, ITYPE = 2, that were previously "turned off" during the optimization process (ITYPE = 1). As seen from the echo of the input file, testnew6.OPT, listed at the beginning of Table 5.2, only behaviors 2 and 3 (nonlinear buckling analysis of the shell without rings) and behaviors 15 - 18 (random response behaviors) were "turned off" in the "fixed design" run leading to Table 5.2.

Table 5.2 represents an edited version of the testnew6.OPM file produced by the execution of OPTIMIZE with analysis type ITYPE = 2. Annotations have been added primarily on the right-hand side of the table to give further explanation of the meaning of the WAVYCYL output.

The dimensions of the optimized design are listed near the beginning of Table 5.2. In SUBROUTINEs BEHX6, BEHX7, and BEHX14, buckling load factors (BEHX6, BEHX7) and modal vibration frequencies (BEHX14) are listed for two models, the first in which the axial waviness of the wall is included explicitly, such as shown in Fig. 4e, and the second in which the axial waviness is "smeared out" in the manner described in Item 10 of Section 5.3 of [26], such as shown in Fig. 4a.

The "smeared waviness" models are not used during optimization. They are included in the "fixed design" analysis option (ITYPE=2) because they convey an idea of the quality of the "smeared waviness" model used for the straight portion of the "explicitly" wavy cylindrical shell such as that shown in the right-hand portion of Fig. 1c. As one can see from Table 5.2, the "smeared waviness" model provides a good estimate of general instability corresponding to n = 2 circumferential waves (p. 4 of Table 5.2) and modal vibration with n = 1 circumferential wave (p. 7 of Table 5.2). As one would expect, the "smeared waviness" model is not nearly as good for predicting local (inter-ring) buckling, which corresponds to n = 4 or 5 circumferential waves in this case (p. 4 of Table 5.2).

Figure 9 shows the starting design and the following BOSOR4 plots corresponding to the optimized design: prebuckling deflected meridian at circumferential coordinate $\theta = 0$ degrees, general buckling mode (n = 2 circumferential waves), local buckling mode with antisymmetry imposed at the midlength of the wavy tube (n = 5 circumferential waves), and fundamental modal vibration mode (n = 1 circumferential wave).

5.5 Convergence studies

5.5.1 Introduction

Table 5.3 and Fig. 4 in this paper and Figures 26 - 32 of [26] give the results of convergence studies with respect to MAXDOF, the user-specified maximum allowable number of degrees of freedom in the BOSOR4 model, and NMESHC, the user-specified number of nodal points in each of the little toroidal segments in the BOSOR4 model (Fig. 2).

The WAVYCYL model works as follows: For all stress, buckling, and vibration models except those in BEHX1 (nonlinear axisymmetric stress analysis, rings and boundary conditions neglected, that is, an infinite wavy tube), BEHX2 (low-circumferential-wave nonlinear buckling with rings and boundary conditions neglected), and BEHX3 (high-circumferential-wave nonlinear buckling with rings and boundary conditions neglected), the WAVYCYL system computes twice the number of axial halfwaves to appear explicitly in the BOSOR4 model, NWAVES, as:

NWAVES = minimum of

[(0.9*AXIAL/WAVLEN),

(value that corresponds to d.o.f.= MAXDOF)]

(5.2)

in which AXIAL is the axial length of the cylindrical tube (twice the axial length shown in Figs. 1, 3 and 4), WAVLEN is the axial halfwavelength of the waviness, and "d.o.f." denotes the actual number of degrees of freedom in the BOSOR4 model. Figures 1a and 1b show examples in which the number of axial halfwaves in the BOSOR4 model is governed by the first element, 0.9*AXIAL/WAVLEN, and Fig. 1c shows a model in which the number of axial halfwaves is governed by the second element, MAXDOF. (MAXDOF corresponding to Fig. 1c was set to a lower number than that corresponding to Fig. 1b.) In general, if the second element in Eq. (5.2) governs, the number of degrees of freedom in the BOSOR4 model, d.o.f., is not exactly equal to the user-specified MAXDOF, but is a per cent or so less than MAXDOF. The number of axial halfwaves computed from Eq.(5.2) depends on how many nodal points, NMESHC, are specified by the WAVYCYL user to exist for each of the little toroidal segments in the BOSOR4 model, how many nodal points, NMESH1, are to be used in Segment 1 (the straight segment with "smeared" waviness), and the number of mesh points NMESHR to be used in each segment of each ring. As mentioned in Section 3, in order to accommodate models with many, many axial waves the capacity of the BOSOR4 program to handle large problems was increased by a factor of 5 over that reported in [3].

5.5.2 Results from convergence studies

Figures 26 - 32 of [26] show the prebuckling deflected shape, symmetric and antisymmetric general and local buckling modes, and the fundamental vibration mode corresponding to several BOSOR4 models with increasing values of the user-specified maximum allowable number of degrees of freedom, MAXDOF, and the number of nodal points, NMESHC, used in each of the little toroidal segments in the explicitly wavy part of the BOSOR4 model. All results are for a PERFECT tube that has been optimized via SUPEROPT (dimensions slightly different from those listed near the beginning of Table 5.2).

Figures 3a,c,e display results from a BOSOR4 model in which the axial waviness has been "smeared" over the entire length of the cylindrical shell. For this model the local (inter-ring) buckling load factors are overestimated by about 35 per cent (1.79 vs the converged value of about 1.33 for n = 5 circumferential waves; compare Figs. 3c and 3d).

Figures 4b-d show results for user-specified MAXDOF = 3000, 6000, 9000, and 15000, respectively. All of these figures were produced from a model in which the number of nodal points in each little toroidal segment is NMESHC = 21. One can see that the higher the value of MAXDOF, the more little waves exist in the BOSOR4 model.

Figures 31 and 32 of [26] depict the critical local buckling modes for MAXDOF = 9000 and NMESHC = 11 and 5, respectively. Even though the mode shapes are identical for all practical purposes, the buckling load factors, 1.3039 and 1.1792 (Table 5.3), are quite different. The corresponding buckling load factor for NMESHC = 21 is 1.3271. This is probably very close to a converged value.

Table 5.3 Lists results from the convergence models shown in Figs. 26 - 32 of [26].

5.6 Design sensitivity studies at the optimum design

Figures 10 - 16 display the results of design sensitivity studies with respect to all of the decision variables used for the wavy cylindrical shell with ring stiffeners. The nominal design is the optimum design obtained for the IMPERFECT shell (See Table 5.2), and all of the design sensitivity studies reported here are for the IMPERFECT shell.

In each figure notice that for the value on the abscissa corresponding to the optimum for that decision variable, there exists a cluster of critical design margins. This characteristic is typical for optimized designs. An exception appears to occur in Fig. 15. However, the apparently negative margins corresponding to the optimum ring spacing, BRINGS = 10 in, is merely an artifact of the relatively sparse spacing of the computed points on the abscissa. Figure 16 shows how the margins look when plotted for very closely spaced values of BRINGS in the immediate neighborhood of the optimum value, BRINGS = 10 in. The relatively sparse spacing of points on the BRINGS axis in Fig. 15 is insufficient to capture the true variation of buckling margins corresponding to BUC0 (low-circumferential-wave symmetric buckling along the meridian at circumferential coordinate, $\theta = 0$ degrees) and B0ANTI (low-circumferential-wave antisymmetric buckling along the meridian at $\theta = 0$ degrees).

In Figs. 11 and 12 the plots of maximum effective stress at circumferential coordinates, $\theta = 0$ and 180 degrees, curve steeply downward for the weaker (sub-optimal) structures (smaller values of TWEB, and HWEB) because the IMPERFECT shell experiences stresses that approach infinity as the buckling load factor corresponding to general instability approaches unity. Because all the factors of safety for the various types of buckling were set equal to 1.25, a buckling load factor of unity corresponds to a design margin of -0.2 in this case.

In Figure 10 the lowest buckling load factors (small triangles and small crosses) correspond to local buckling, not general instability. Therefore, the curves for stress margin are less steep in the neighborhood of margin = -0.2 in Fig. 10 than in Figs. 11 and 12, for which the lowest buckling curves correspond to general instability, not local buckling in that neighborhood of margin.

Notice the extreme sensitivity of margin gradient to variation of WAVLEN and BRINGS in the neighborhood of the optimum value. This phenomenon has already been discussed. The optimum value of WAVLEN and BRINGS corresponds to each of the rings occurring at an outward "peak" in the axial waviness.

6.0 CONCLUSIONS

Two computer programs, GENOPT [2] and BOSOR4 [3], have been combined to create a capability to optimize classes of shells of revolution. One class, called "WAVYCYL", can optimize isotropic or laminated composite ring stiffened cylindrical shells with "wavy" walls.

Another class, explored in the appendix of [26] as a demonstration, can optimize simple isotropic monocoque cylindrical shells. Enough details are given, especially in the simple example given in the appendix of [26], so that the reader can, by analogy, use GENOPT and BOSOR4 to set up a user-friendly system of programs to optimize any shell of revolution that can be handled by BOSOR4.

The capability of BOSOR4 was increased to handle much larger problems than was previously possible in order to permit the analysis of long cylindrical tubes with many, many axial halfwaves along their lengths. Also, the accuracy of BOSOR4 predictions for buckling of bellows-type shells was significantly improved by incorporation of the equations of Marlowe [16].

In this paper a global optimum design is obtained for an isotropic ring-stiffened cylindrical shell with a "wavy" wall. In [26] global optimum designs are also obtained for an isotropic "wavy-walled" cylindrical shell without rings and a laminated composite "wavy-walled" cylindrical shell without rings. Decision variables include the thickness of the "wavy" cylindrical shell wall (or ply thicknesses if the wall is laminated), amplitude and axial halfwavelength of the waviness, and thicknesses and widths of the segments of the ring stiffeners. Design constraints include maximum stress, maximum lateral displacement, local buckling, general buckling, modal vibration frequency, and response to random base excitation. The loading is uniform axial compression, uniform external pressure, lateral acceleration, and axial acceleration.

Results from convergence studies on the number of axial halfwaves included explicitly in the BOSOR4 models and on the number of nodal points in each of the shell segments that form an axial halfwave of the waviness are presented, as well as results from design sensitivity analyses carried out for the optimized designs.

ACKNOWLEDGMENTS

The author is grateful to Frank Weiler, who modified the "GASP" routines used in BOSOR4 [2] and STAGS [24] to work properly in an automated optimization context. The author's son, Bill Bushnell, helped solve many desktop publishing mysteries.

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Table 4.1 A log of activities and computer runs to determine the optimum design of a "wavy" cylindrical tube stiffened by external rings.

PART 1: Activity by the GENOPT user leading to creation of a capability to optimize a fairly broad class of shells of revolution: ring stiffened cylindrical shells with straight or "wavy" walls made of isotropic or laminated composite material.

ACTIVITY	NATURE AND PURPOSE OF ACTIVITY
1 Formulate problem.	This must be done before ANY computer runs.
2. Choose and classify constants, variables. Choose names and definitions. These will appear in output.	This must be done before ANY computer runs. Properties, indices, dimensions, loadings, responses (e.g. stress, buckling, vibration, displacement), allowables, factors of safety, objective, must all be identified.
3. Run "GENTEXT". Provide names, definitions, "help" paragraphs, etc. that will later play various roles in the optimization problem to be solved.	The items decided on in Item 2 are provided interactively, leading to the *.INP file and GENOPT-written computer code some of which will be modified by the GENOPT user. The "*" in *.INP is the GENOPT-user-selected name for the class of problems to be solved later. In this particular case, this "generic" name, "*", equals "wavycyl".
4. Any quantities left out? Add them now.	Run the GENOPT processor "INSERT" as needed.
5. Provide whatever FORTRAN code is needed to compute buckling, stress, vibration, displacement, etc. for a design with given properties, dimensions.	This is the hardest part of the job. The FORTRAN subroutine skeletons, STRUCT.NEW and BEHAVIOR.NEW, generated during the "GENTEXT" interactive session (Item 3), must be "fleshed out" by the GENOPT user so that the various "behaviors" can be computed. In this case most of the code consists of BOSOR4 software, modified as described in Section 3.
6. Run "GENPROGRAMS".	This compiles the software generated automatically by GENOPT and modified as in Item 5 by the GENOPT user. When this step has been successfully completed, there exists a reasonably user-friendly system of programs, BEGIN, DECIDE, MAINSETUP, OPTIMIZE, SUPEROPT, CHOOSEPLOT, etc. for optimizing a user-provided member of the class, "wavycyl". In this case the class, "wavycyl", includes ring-stiffened cylindrical shells with straight or "wavy" walls, made of isotropic or laminated composite material. The "waviness" can be of very large amplitude, such as is so with bellows.

PART 2: Activity of the WAVYCYL user leading to the optimum designs of specific members of the class, "wavycyl".

ACTIVITY	NATURE AND PURPOSE OF ACTIVITY
7. Run PANDA2 [7,19-22] to determine ring cross section and approximate spacing, as well as the effect of ini-	PANDA2 runs much faster than "wavycyl" because it is based of the use of models with many fewer degrees of freedom (d.o.f.). See Refs. [7,19-22] for details about PANDA2. PANDA2 can handle ring-stiffened cylindrical shells with straight

	tial imperfections[19].	walls.
8.	Run the BEGIN, DECIDE, MAINSETUP, SUPEROPT, CHOOSEPLOT processors.	Optimize a member of the class, "wavycyl": an externally ring-stiffened cylindrical shell with a "wavy" wall. Fig. 1a shows a typical starting design.
9.	Investigate convergence with respect to number of d.o.f. in the BOSOR4 model.	Check the accuracy of the model.
10	Perform sensitivity analyses, especially with respect to the axial halfwavelength of the "waviness".	Experience shows that it is difficult to obtain a "global" minimum weight design. This is because there is extreme sensitivity of general buckling load factor to small changes in the axial half-wavelength of the "waviness" in the cyl. wall.

```
Table 4.2 Example of input data for the "GENTEXT" interactive session.
This table is a list of the first part of the "wavycyl.INP" file, created
as the GENOPT user executes the GENOPT process called "GENTEXT".
===========================================================================
       5  $ starting prompt index in the file wavycyl.PRO
       5  $ increment for prompt index
       0  $ Type of prompt: 0="help" paragraph, 1=one-line prompt
 This is wavycyl
 n        $ Are there more lines in the "help" paragraph?
       1  $ Type of prompt: 0="help" paragraph, 1=one-line prompt

 AXIAL    $ Name of a variable in the users program (defined below)
       2  $ Role of the variable in the users program
       2  $ type of variable:  1 =integer,  2 =floating point
 n        $ Is the variable  AXIAL  an array?
 length of cylindrical shell
 y        $ Do you want to include a "help" paragraph?
 Give nominal length in units of your case.
 n        $ Any more lines in the "help" paragraph?
 y        $ Any more variables for role types  1  or  2   ?    $10
       1  $ Type of prompt: 0="help" paragraph, 1=one-line prompt
 RADIUS   $ Name of a variable in the users program (defined below)
       2  $ Role of the variable in the users program
       2  $ type of variable:  1 =integer,  2 =floating point
 n        $ Is the variable  RADIUS  an array?
 Average nominal radius of cylindrical shell
 y        $ Do you want to include a "help" paragraph?
 The waviness oscillates about RADIUS
 n        $ Any more lines in the "help" paragraph?
 y        $ Any more variables for role types  1  or  2   ?    $15
       1  $ Type of prompt: 0="help" paragraph, 1=one-line prompt
 THICK    $ Name of a variable in the users program (defined below)
       1  $ Role of the variable in the users program
 n        $ Is the variable  THICK  an array?
 Total wall thickness
 y        $ Do you want to include a "help" paragraph?
 This is a decision variable only for an isotropic wall.
 n        $ Any more lines in the "help" paragraph?
 y        $ Any more variables for role types  1  or  2   ?    $20
       1  $ Type of prompt: 0="help" paragraph, 1=one-line prompt
 IRING    $ Name of a variable in the users program (defined below)
       2  $ Role of the variable in the users program
       1  $ type of variable:  1 =integer,  2 =floating point
 n        $ Is the variable  IRING  an array?
 Location of T-ring: -1=internal, 0=none, 1=external
 y        $ Do you want to include a "help" paragraph?
 Use IRING=-1 for internal rings; 1 for external rings; 0 for no rings.
 n        $ Any more lines in the "help" paragraph?
 y        $ Any more variables for role types  1  or  2   ?    $25
===========================================================================
```

```
Table 4.3 The portion of the "wavycyl.PRO" file corresponding to the
input data listed in the previous table "wavycyl.INP". This file contains
the prompts and "help" paragraphs that will be seen by the WAVYCYL user.
The "wavycyl.PRO" file is created by the GENOPT system. The GENOPT user
creates the prompting phrases and "help" phrases and variable names during
the "GENTEXT" interactive session.
===========================================================================
    5.0
        This is wavycyl

   10.1 length of cylindrical shell: AXIAL
   10.2
        Give nominal length in units of your case.

   15.1 Average nominal radius of cylindrical shell: RADIUS
   15.2
        The waviness oscillates about RADIUS

   20.1 Total wall thickness: THICK
   20.2
        This is a decision variable only for an isotropic wall.

   25.1 Location of T-ring: -1=internal, 0=none, 1=external: IRING
   25.2
        Use IRING=-1 for internal rings; 1 for external rings; 0 for no rings.
===========================================================================
```

Table 4.4 Glossary of variables used in "wavycyl". This table is created by the GENOPT system and is located in the "wavycyl.DEF" file.

ARRAY ?	NUMBER OF (ROWS,COLS)	ROLE	PROMPT NUMBER (wavycyl.PRO)	VARIABLE NAME	DEFINITION OF VARIABLE	BEHAV. BEHXi i
n	(0, 0)	2	10	AXIAL	= length of cylindrical shell	
n	(0, 0)	2	15	RADIUS	= Average nominal radius of cylindri	
n	(0, 0)	1	20	THICK	= Total wall thickness	
n	(0, 0)	2	25	IRING	= Location of T-ring: -1=internal, 0	
n	(0, 0)	1	30	BRINGS	= ring spacing (use zero if no rings	
n	(0, 0)	1	35	TWEB	= thickness of web of T-ring	
n	(0, 0)	1	40	HWEB	= height of web of T-ring	
n	(0, 0)	1	45	TFLANG	= thickness of outstanding flange of	
n	(0, 0)	1	50	HFLANG	= width of outstanding flange of T-r	
n	(0, 0)	2	55	ERING	= Average modulus of ring material	
n	(0, 0)	2	60	FNURNG	= Average Poisson ratio of ring mate	
n	(0, 0)	2	65	DENRNG	= Average mass density of ring mater	
n	(0, 0)	2	70	NMESHR	= Number of nodal points in each rin	
n	(0, 0)	2	75	GRAVTY	= Acceleration of gravity (e.g. 386.	
n	(0, 0)	2	80	LGAXL	= Length of tube unrestrained by axi	
n	(0, 0)	2	85	NWAVES	= Number (EVEN) of axial halfwaves i	
n	(0, 0)	1	90	WAVLEN	= Axial halfwavelength of the wavine	
n	(0, 0)	1	95	AMPLIT	= Amplitude of waviness	
n	(0, 0)	2	105	IWAVE	= Type of waviness (IWAVE=2 or 3)	
n	(0, 0)	1	115	RADSML	= Local meridional radius of curvatu	
n	(0, 0)	2	125	NMESHS	= Number of nodal points in STRAIGHT	
n	(0, 0)	2	130	NMESHC	= Number of nodal pts. in each curve	
n	(0, 0)	2	135	NMESH1	= Number of nodal pts. in "smeared"	
n	(0, 0)	2	140	MAXDOF	= Maximum number of d.o.f. of buckli	
n	(0, 0)	2	145	IBOUND	= Boundary condition index: 1 = s.s.	
n	(0, 0)	2	150	IWALL	= Type of shell wall (1=isotropic, 2	
n	(0, 0)	2	155	ESTIFF	= Youngs modulus	
n	(0, 0)	2	160	FNU	= Poisson ratio	
n	(0, 0)	2	165	DENS	= Material mass density (e.g. alum.=	
n	(0, 0)	2	175	NLAYER	= Number of layers in the wall	
n	(0, 0)	2	180	ILTYPE	= ILTYPE=layer type in LTYPE(ILTYPE)	
y	(90, 0)	2	185	LTYPE	= Layer index	
y	(90, 0)	2	190	NEWLAY	= NEWLAY: 0=not new layer type; 1=ne	
n	(0, 0)	2	195	ITLAYE	= position in TLAYER array in TLAYER	
y	(20, 0)	1	200	TLAYER	= thickness of layer type	
y	(20, 0)	1	205	ANGLE	= layup angle (deg.) for layer type	
y	(20, 0)	2	210	MTYPE	= Material index (1,2...) for layer	
y	(20, 0)	2	215	NEWMAT	= NEWMAT: 0=not new matl; 1=new matl	
y	(20, 0)	2	225	E1	= modulus in the fiber direction	
y	(20, 0)	2	230	E2	= modulus transverse to fibers	
y	(20, 0)	2	235	G	= in-plane shear modulus	
y	(20, 0)	2	240	NU	= small Poisson ratio	
y	(20, 0)	2	245	A1	= coeff. thermal expansion along fib	
y	(20, 0)	2	250	A2	= coeff. thermal expansion transvers	
y	(20, 0)	2	255	CURETP	= residual stress temperature	
y	(20, 0)	2	260	RHO	= mass density (e.g. alum.=.00025 lb	
y	(20, 0)	2	270	S1TEN	= maximum tensile stress long fibers	
y	(20, 0)	2	275	S1COMP	= max compressive stress along fiber	
y	(20, 0)	2	280	S2TEN	= max tensile stress normal to fiber	
y	(20, 0)	2	285	S2COMP	= max compressive stress normal to f	
y	(20, 0)	2	290	TAU12	= max shear stress	
n	(0, 0)	2	295	NRS	= control (0 or 1) for smeared stiff	
n	(0, 0)	2	300	NDAMP	= number of entries in table of damp	
n	(0, 0)	2	305	IBDAMP	= position in BDAMP array in BDAMP(I	
y	(20, 0)	2	310	BDAMP	= damping factor	

```
y   ( 20, 0)   2   315   BFREQ    = frequency (hertz) corresponding to
n   (  0, 0)   2   320   NSPECT   = number of entries in table of spec
n   (  0, 0)   2   325   ISPTDE   = position in BDAMP array in SPTDEN(
y   ( 20, 0)   2   330   SPTDEN   = spectral density
y   ( 20, 0)   2   335   SFREQ    = frequency (hertz) corresponding to
n   (  0, 0)   2   340   N0B      = starting number of circumferential
n   (  0, 0)   2   345   NMAXB    = ending number of circumferential w
n   (  0, 0)   2   350   INCRB    = Increment in number of circumferen
n   (  0, 0)   2   355   N0V      = starting no. of circ. waves for vi
n   (  0, 0)   2   360   NMAXV    = ending no. of circ. waves for vibr
n   (  0, 0)   2   365   INCRV    = increment in no. circ. waves for v
n   (  0, 0)   2   370   NVE      = Number of eigenvalues for each cir
n   (  0, 0)   2   375   NCASES   = Number of load cases (number of en
y   ( 20, 0)   3   380   FNX      = Axial resultant (neg. for compress
y   ( 20, 0)   3   385   FNXB     = Axial resultant (neg. for compress
y   ( 20, 0)   3   390   GAXIAL   = number of g's acceleration along c
y   ( 20, 0)   3   395   GLATRL   = Number of g's perpendicular to axi
y   ( 20, 0)   3   400   PRESS    = pressure (negative for external),
y   ( 20, 0)   3   405   PRESSB   = pressure (negative for external),
y   ( 20, 0)   4   410   STRMAX   = maximum stress in wall from nonlin   1
y   ( 20, 0)   5   415   STRALW   = maximum allowable vonMises stress,
y   ( 20, 0)   6   420   STRFS    = factor of safety for vonMises stre
y   ( 20, 0)   4   425   BUCFAC   = buckling load factor from nonlinea   2
y   ( 20, 0)   5   430   BUCALW   = allowable for buckling factor (use
y   ( 20, 0)   6   435   BUCFS    = factor of safety for buckling, non
y   ( 20, 0)   4   440   BUCHIW   = hi-wave buckling load factor, nonl   3
y   ( 20, 0)   5   445   BUCHIA   = allowable for hi-wave buckling fac
y   ( 20, 0)   6   450   BUCHIF   = factor of safety for hi-wave buckl
y   ( 20, 0)   4   455   STR0     = max. vonMises stress at 0 deg., li   4
y   ( 20, 0)   5   460   STR0A    = max. allowable vonMises stress, li
y   ( 20, 0)   6   465   STR0F    = factor of safety for vonMises stre
y   ( 20, 0)   4   470   STR180   = max. vonMises stress at 180 deg.,    5
y   ( 20, 0)   5   475   ST180A   = max. allowable vonMises stress, li
y   ( 20, 0)   6   480   ST180F   = factor of safety for vonMises stre
y   ( 20, 0)   4   485   BUC0     = buckling load factor at 0 deg., li   6
y   ( 20, 0)   5   490   BUC0A    = allowable for buckling factor (use
y   ( 20, 0)   6   495   BUC0F    = factor of safety for buckling fact
y   ( 20, 0)   4   500   B0ANTI   = load factor for antisymmetric buck   7
y   ( 20, 0)   5   505   B0ANTA   = allowable (use 1) for antisymmetri
y   ( 20, 0)   6   510   B0ANTF   = factor of safety for antisymmetric
y   ( 20, 0)   4   515   BUC0MD   = load factor for mid-wave-range buc   8
y   ( 20, 0)   5   520   BUC0MA   = allowable (use 1) for mid-wave-ran
y   ( 20, 0)   6   525   BUC0MF   = factor of safety for mid-wave-rang
y   ( 20, 0)   4   530   BUC0HI   = hi-wave buckling load factor at 0    9
y   ( 20, 0)   5   535   BUC0HA   = allowable for hi-wave buckling (us
y   ( 20, 0)   6   540   BUC0HF   = factor of safety for hi-wave buckl
y   ( 20, 0)   4   545   BUC180   = buckling load factor at 180 deg, l  10
y   ( 20, 0)   5   550   BU180A   = allowable buckling factor at 180 d
y   ( 20, 0)   6   555   BU180F   = factor of safety for buckling at 1
y   ( 20, 0)   4   560   B180HI   = hi-wave buckling load factor 180 d  11
y   ( 20, 0)   5   565   B180HA   = allowable (use 1) hi-wave buckling
y   ( 20, 0)   6   570   B180HF   = factor of safety for hi-wave buckl
y   ( 20, 0)   4   575   WWW0     = maximum normal displacement at 0 d  12
y   ( 20, 0)   5   580   WWW0A    = maximum allowable normal displacem
y   ( 20, 0)   6   585   WWW0F    = factor of safety for max. normal d
y   ( 20, 0)   4   590   WWW180   = maximum normal displacement at 180  13
y   ( 20, 0)   5   595   WW180A   = max. allowable normal displacment,
y   ( 20, 0)   6   600   WW180F   = factor of safety for normal displa
y   ( 20, 0)   4   605   FREQ     = modal frequency (hertz)             14
y   ( 20, 0)   5   610   VIBALW   = minimum allowable modal frequency
y   ( 20, 0)   6   615   VIBFS    = factor of safety for modal frequen
y   ( 20, 0)   4   620   STRRAN   = max. effective stress from random   15
```

y	(20, 0)	5	625	STRRNA	= max. allowable stress from random	
y	(20, 0)	6	630	STRRNF	= factor of safety for stress from r	
y	(20, 0)	4	635	BUCRAN	= buckling load factor from random e	16
y	(20, 0)	5	640	BUCRNA	= allowable buckling load factor (us	
y	(20, 0)	6	645	BUCRNF	= factor of safety for buckling from	
y	(20, 0)	4	650	BRANHI	= hi-wave buckling factor from rando	17
y	(20, 0)	5	655	BRANHA	= allowable (use 1) for buckling fac	
y	(20, 0)	6	660	BRANHF	= factor of safety for hi-wave buckl	
y	(20, 0)	4	665	WWWRAN	= max. normal displacement from rand	18
y	(20, 0)	5	670	WWWRNA	= max. allowable normal displ. from	
y	(20, 0)	6	675	WWWRNF	= factor of safety for max. normal d	
n	(0, 0)	7	680	WEIGHT	= weight of the cylindrical shell	

Table 4.5 The 18 "behaviors" (responses) that are possibly evaluated for each "current" design and design perturbation by the WAVYCYL computer program

PARAMETERS WHICH DESCRIBE BEHAVIOR (e.g. stress, buckling load, frequency)

BEH. NO.	CURRENT VALUE	DEFINITION
1	2.085E+04	maximum stress in wall from nonlinear theory: STRMAX(1)
2	1.000E+10	buckling load factor from nonlinear theory: BUCFAC(1)
3	1.000E+10	hi-wave buckling load factor, nonlinear theory: BUCHIW(1)
4	3.178E+04	max. stress at 0 deg., linear theory: STR0(1)
5	2.825E+04	max. stress at 180 deg., linear theory: STR180(1)
6	1.285E+00	buckling load factor at 0 deg., linear theory: BUC0(1)
7	1.267E+00	load factor for antisymmetric buckling at 0 deg: B0ANTI(1)
8	1.946E+00	load factor for mid-wave-range buckling at 0 deg: BUC0MD(1)
9	8.876E+00	hi-wave buckling load factor, 0 deg,linear theory:BUC0HI(1)
10	1.332E+00	buckling load factor at 180 deg, linear theory: BUC180(1)
11	1.031E+01	hi-wave buckling load factor 180 deg, lin.theory: B180HI(1)
12	3.007E-01	maximum normal displacement, 0 deg., linear theory: WWW0(1)
13	2.949E-01	maximum normal displacement, 180 deg., lin.theory:WWW180(1)
14	1.001E+01	modal frequency (hertz): FREQ(1)
15	1.000E-10	maximum stress from random excitation: STRRAN(1)
16	1.000E+10	buckling load factor from random excitation: BUCRAN(1)
17	1.000E+10	hi-wave buckling factor from random excitation: BRANHI(1)
18	1.000E-10	max. normal displacement from random excitation: WWWRAN(1)

Table 4.6 Margins corresponding to the "behaviors" listed in the previous table. NOTE: The "MARGIN NOs" do NOT correspond to the "Behavior" numbers in the previous table.

MARGINS CORRESPONDING TO CURRENT DESIGN (F.S.= FACTOR OF SAFETY)

MARGIN NO.	CURRENT VALUE	DEFINITION
1	5.831E-01	1-(STRMAX(1)/STRALW(1)) X STRFS(1); F.S.= 1.00
2	3.644E-01	1-(STR0(1)/STR0A(1)) X STR0F(1); F.S.= 1.00
3	4.351E-01	1-(STR180(1)/ST180A(1)) X ST180F(1); F.S.= 1.00
4	2.830E-02	(BUC0(1)/BUC0A(1)) / BUC0F(1)-1; F.S.= 1.25
5	1.366E-02	(B0ANTI(1)/B0ANTA(1)) / B0ANTF(1)-1; F.S.= 1.25
6	5.568E-01	(BUC0MD(1)/BUC0MA(1)) / BUC0MF(1)-1; F.S.= 1.25
7	6.101E+00	(BUC0HI(1)/BUC0HA(1)) / BUC0HF(1)-1; F.S.= 1.25
8	6.556E-02	(BUC180(1)/BU180A(1)) / BU180F(1)-1; F.S.= 1.25
9	7.249E+00	(B180HI(1)/B180HA(1)) / B180HF(1)-1; F.S.= 1.25
10	6.241E-01	1-(WWW0(1)/WWW0A(1)) X WWW0F(1); F.S.= 1.00
11	6.314E-01	1-(WWW180(1)/WW180A(1)) X WW180F(1); F.S.= 1.00
12	1.208E-03	(FREQ(1)/VIBALW(1)) / VIBFS(1)-1; F.S.= 1.00
13	1.000E+00	1-(STRRAN(1)/STRRNA(1)) X STRRNF(1); F.S.= 1.00
14	1.000E+00	1-(WWWRAN(1)/WWWRNA(1)) X WWWRNF(1); F.S.= 1.00

Table 4.7 Aluminum ring-stiffened cylindrical shell with "wavy" wall:
Dimensions, properties, boundary conditions, loading, etc. (units = lb, in.)

WAVYCYL NAME	Decision Variable	Lower bound	Starting value	Optimum value	Upper bound	Definition of variable
AXIAL	no		180.0			length of cyl. shell
RADIUS	no		9.0			nominal radius of cyl.
THICK	yes	0.03	0.1	0.0306	0.5	wall thickness
IRING	no		external			location of T-ring
BRINGS	yes	10.0	20.0	10.0	110.0	ring spacing
TWEB	yes	0.05	0.1	0.0674	0.1	ring web thickness
HWEB	yes	0.2	2.0	0.674	4.0	ring web height
TFLANG	yes	0.05	0.1	0.0	0.1	ring flange thickness
HFLANG	yes	0.2	2.0	0.0	4.0	ring flange width
WAVLEN	yes	0.5	3.0	0.5555	3.0	axial halfwavelength
AMPLIT	yes	0.01	0.5	0.0665	0.8	amplitude of waviness
ERING	no		10^7			ring material modulus
FNURNG	no		0.3			ring Poisson ratio
DENRNG	no		0.00025			ring mass density
NMESHR	no		5			nodal pts.each ring seg.
GRAVTY	no		386.4			acceleration of gravity
LGAXL	no		800.0			tube length betw. z-stops
IWAVE	no		2			type of waviness
NMESHC	no		21			nodal pts.each curved seg.
NMESH1	no		97			nodal pts."smeared" seg.
MAXDOF	no		15000			max. allowable d.o.f.
IBOUND	no		1			b.c.: 1=s.s.; 2=clamped
IWALL	no		1			wall: 1=isotropic; 2=plies
ESTIFF	no		10^7			tube wall modulus
FNU	no		0.3			tube wall Poisson ratio
DENS	no		0.00025			tube wall mass density
N0B	no		0			starting c.waves, buckling
NMAXB	no		10			ending c.waves, buckling
N0V	no		0			starting circ.waves, vib.
NMAXV	no		3			ending circ.waves, vib.
NCASES	no		1			number of load cases
FNX	no		-53.0			axial load, Load Set A
FNXB	no		0.0			axial load, Load Set B
GAXIAL	no		1.5			axial acceleration (g's)
GLATRL	no		3.0			lateral acceleration
PRESS	no		-11.8			pressure, Load Set A
PRESSB	no		0.0			pressure, Load Set B
STRALW	no		50000.0			stress allowable (psi)
STRFS	no		1.0			stress factor of safety
BUCALW	no		1.0			buckling allowable
BUCFS	no		1.25			buckling factor of safety
WWW0A	no		0.8			latrl displace.allowable
WWW0F	no		1.0			latrl disp. factor safety
VIBALW	no		10.0			modal frequency allowable
VIBFS	no		1.0			frequency factor safety

```
Table 5.1 Optimum design found from PANDA2 for IMPERFECT non-wavy
cylindrical shell with external blade rings. Ampltude of general buckling
modal initial imperfection = 0.045 in; No lateral or axial g-loading.
==========================================================================
 ANALYSIS: ITYPE=2;  IQUICK=1;  LOAD SET 1;  SUBCASE 1:
 LOADING: Nx, Ny, Nxy, Mx, My =  -5.70E+01 -1.06E+02  6.03E-01
                                  0.00E+00  0.00E+00
          Nxo, Nyo, pressure  =   0.00E+00  0.00E+00 -1.18E+01

          SUMMARY OF INFORMATION FROM OPTIMIZATION ANALYSIS
VAR.DEC.ESCAPE LOWER    CURRENT    UPPER       DEFINITION
NO. VAR. VAR.  BOUND     VALUE     BOUND
 1    Y     Y  3.00E-02 4.7032E-02  2.00E-01 T(1)(SKN):thickness of cyl. skin
 2    Y     N  1.00E+01 1.0000E+01  1.00E+02    B(RNG):ring spacing, b
 3    N     N  0.00E+00 0.0000E+00  0.00E+00   B2(RNG):width of ring base, b2
 4    Y     N  1.00E-01 6.7398E-01  5.00E+00    H(RNG):height of ring
 5    Y     Y  1.00E-02 6.7398E-02  2.00E-01 T(2)(RNG):thickness of ring

   CURRENT VALUE OF THE OBJECTIVE FUNCTION:
 VAR. STR/ SEG. LAYER   CURRENT
 NO.  RNG  NO.   NO.     VALUE            DEFINITION
            0     0   2.625E+01   WEIGHT OF THE ENTIRE PANEL

 MARGINS FOR CURRENT DESIGN: LOAD CASE 1, SUBCASE 1 (Midway between rings)
 MAR. MARGIN
 NO.  VALUE              DEFINITION
 1  1.52E-01 Inter-ring bucklng, discrete model, n=9   circ.halfwaves;FS=1.25
 2  3.64E+00 eff.stress:matl=1,RNG,Iseg=3,at:TIP,layer=1,z=0.;-MID.;FS=1.
 3  1.13E-02 buck.(SAND);simp-support general buck;M=1;N=2;slope=0.;FS=1.25
 4  1.87E+04 (Max.allowable ave.axial strain)/(ave.axial strain) -1; FS=1.
 5  0.00E+00 1-[1.-V(5)^1+0.1V(4)^1]

 ****************************************
 ITERATION NO., LOAD SET NO., SUBCASE NO. =   0   1   2     AT RINGS
 ****************************************
 MARGINS FOR CURRENT DESIGN: LOAD CASE  1, SUBCASE  2   (At rings)
 MAR. MARGIN
 NO.  VALUE              DEFINITION
 1 -9.52E-03 Inter-ring bucklng, discrete model, n=9   circ.halfwaves;FS=1.25
 2  3.64E+00 eff.stress:matl=1,RNG,Iseg=3,at:TIP,layer=1,z=0.;-RNGS;FS=1.
 3  4.12E+00 buckling margin   ring   Iseg.3 . Local halfwaves=9  .RNGS;FS=1.
 4  6.87E-03 buck.(SAND);rolling with local buck.; M=1;N=9;slope=0.;FS=1.25
 5  8.52E+00 buck.(SAND);rolling only of   rings;  M=0;N=26;slope=0.;FS=1.6
 6  1.75E+04 (Max.allowable ave.axial strain)/(ave.axial strain) -1; FS=1.

 ***********  ALL 1 LOAD SETS PROCESSED  ***********
==============================================================================
```

Table 5.2 Sample output (some editing) corresponding to optimized externally stiffened wavy cylindrical shell. This file is called testnew6.OPM. These results were arrived at via the runstream listed in Section 5.3.

```
===========================================================================
      N         $ Do you want a tutorial session and tutorial output?
         2      $ Choose an analysis you DON'T want (1, 2,..), IBEHAV
      Y         $ Any more analysis types NOT wanted (Y or N) ?
         3      $ Choose an analysis you DON'T want (1, 2,..), IBEHAV
      Y         $ Any more analysis types NOT wanted (Y or N) ?
        15      $ Choose an analysis you DON'T want (1, 2,..), IBEHAV
      Y         $ Any more analysis types NOT wanted (Y or N) ?
        16      $ Choose an analysis you DON'T want (1, 2,..), IBEHAV
      Y         $ Any more analysis types NOT wanted (Y or N) ?
        17      $ Choose an analysis you DON'T want (1, 2,..), IBEHAV
      Y         $ Any more analysis types NOT wanted (Y or N) ?
        18      $ Choose an analysis you DON'T want (1, 2,..), IBEHAV
      N         $ Any more analysis types NOT wanted (Y or N) ?
         0      $ NPRINT= output index (0=GOOD, 1=ok, 2=debug, 3=too much)
         2      $ Choose type of analysis (1=opt., 2=fixed, 3=sensit.) ITYPE
         5      $ How many design iterations in this run (3 to 25)?
         1      $ Choose (1="conservative"), (2="liberal") move limits, IMOVE
      Y         $ Do you want default (RATIO=10) for initial move limit jump?
      Y         $ Do you want the default perturbation (dx/x = 0.05)?
      N         $ Do you want to reset total iterations to zero (Type H)?

 ************ END OF THE  testnew6.OPT  FILE ***********
 ************ OCTOBER, 1999 VERSION OF GENOPT ****************
 ******** BEGINNING OF THE  testnew6.OPM  FILE *********

 *********************** MAIN PROCESSOR *********************
 The purpose of the mainprocessor, OPTIMIZE, is to perform,
 in a batch mode, the work specified by MAINSETUP for the case
 called testnew6.  Results are stored in the file  testnew6.OPM.
 Please inspect testnew6.OPM before doing more design iterations.
 ************************************************************

 STRUCTURAL ANALYSIS FOR DESIGN ITERATION NO.   0: (fixed design analysis)
 This is the final optimum design arrived at via the runstream listed in
 Section 5.3.
  STRUCTURAL ANALYSIS WITH UNPERTURBED DECISION VARIABLES
 VAR. DEC. ESCAPE LINK. LINKED  LINKING    LOWER     CURRENT     UPPER
  NO. VAR.  VAR.  VAR.    TO   CONSTANT    BOUND      VALUE      BOUND
  Total wall thickness: THICK
   1   Y     Y     N      0    0.00E+00  3.00E-02 3.0605E-02  5.00E-01
  ring spacing (use zero if no rings): BRINGS
   2   N     N     N      0    0.00E+00  0.00E+00 1.0000E+01  0.00E+00
  thickness of web of T-ring: TWEB
   3   N     N     N      0    0.00E+00  0.00E+00 6.7398E-02  0.00E+00
  height of web of T-ring: HWEB
   4   N     N     N      0    0.00E+00  0.00E+00 6.7398E-01  0.00E+00
  thickness of outstanding flange of T-ring: TFLANG
   5   N     N     N      0    0.00E+00  0.00E+00 0.0000E+00  0.00E+00
  width of outstanding flange of T-ring: HFLANG
   6   N     N     N      0    0.00E+00  0.00E+00 0.0000E+00  0.00E+00
  Axial halfwavelength of the waviness: WAVLEN
   7   N     N     N      0    0.00E+00  0.00E+00 5.5555E-01  0.00E+00
  Amplitude of waviness: AMPLIT
   8   Y     N     N      0    0.00E+00  1.00E-02 6.6471E-02  8.00E-01
  Local meridional radius of curvature: RADSML
   9   N     N     N      0    0.00E+00  0.00E+00 0.0000E+00  0.00E+00

 *************** UNPERTURBED DESIGN: IMODX = 0 ***************
```

```
 BEGIN COMPUTATIONS FOR THE UNPERTURBED (CURRENT) DESIGN
  LOAD SET NO.  1

*** SYMMETRIC BUCKLING LOAD FACTORS AND MODE SHAPES ***
LINEAR BUCKLING LOAD FACTOR, 0 DEGREES, MODEL 2 (CIRC. WAVES)
The entire length (  9.0000E+01) of the cyl. has smeared       (See Item 12,
waviness and smeared rings. The purpose of this analysis is     Section 5.3
to obtain a general buckling eigenvalue to be used in the       of [26])
formula for FN2ADD(1) = added hoop compression from the
growth of the initial general buckling modal imperfection
during loading. FN2ADD(1) is used for inter-ring buckling.
   eigenvalue(circ. waves)
       1.9767E+01(   0)          (See Items 12a and 12b in Section 5.3
       2.0167E+01(   1)           of [26] for a discussion.)
       2.5841E+00(   2)  <--- critical value; compare with 1.3333 from the
       6.6902E+00(   3)                        model with discrete rings.
       1.1560E+01(   4)
       1.4550E+01(   5)
===== BUCKLING MODAL SYMMETRY AT SYMMETRY PLANE =====
Crit. buckling factor, BUCSMR(smeared waviness, SMEARED rings)=  2.5841E+00
Critical number of circumferential waves, NWVCRT=    2

*** SYMMETRIC BUCKLING LOAD FACTORS AND MODE SHAPES ***        (See Items
LINEAR BUCKLING LOAD FACTOR, 0 DEGREES, MODEL 2 (CIRC. WAVES)   12a,b in
The entire length (  9.0000E+01) of the cyl. has smeared        Section 5.3
waviness and DISCRETE rings. The purpose of this analysis is    of [26])
to obtain a general buckling eigenvalue to be used in the
formula for FN2ADD(2) = added hoop compression from the
growth of the initial general buckling modal imperfection
during loading. FN2ADD(2) is used in the stress analysis.
   eigenvalue(circ. waves)
       1.3333E+00(   2)    <--- compare with 2.5841 from smeared ring model.
===== BUCKLING MODAL SYMMETRY AT SYMMETRY PLANE =====
Crit. buckling factor, BUCDIS(smeared waviness, discrete rings)=  1.3333E+00
Critical number of circumferential waves, NWVCRT=    2

*** ANTISYMMETRIC BUCKLING LOAD FACTORS AND MODE SHAPES ***
BUCKLING LOAD FACTOR FROM INDIC=1, MODEL 2 (CIRC. WAVES).       (See Item 13,
The inter-ring length (  1.0000E+01) of the cyl. has smeared     Section 5.3
waviness and discrete end rings. The purpose of this analysis    of [26])
is to obtain inter-ring buckling eigenvalues to be used to
determine the minimum circ. wavnumber, NWAVLC, that corres-
ponds to inter-ring buckling in the larger models used later.
   eigenvalue(circ. waves)
       1.7298E+01(   2)
       7.7756E+00(   3)
       2.5047E+00(   4)
       2.0709E+00(   5) <--- critical value for local (inter-ring) buckling
       2.6127E+00(   6)      from simple model. See Item 13 in Section 5.3 of
       3.5024E+00(   7)      [26]. The critical circumferential wavenumber,
       4.4283E+00(   8)      NWVCRT = 5
       5.4695E+00(   9)
       6.4417E+00(  10)
       7.4923E+00(  11)      (From these calculations and from Eq. 5.26,
       8.6456E+00(  12)       the WAVYCYL system sets the minimum circ.
       9.9042E+00(  13)       wavenumber corresponding to inter-ring
       1.1252E+01(  14)       buckling, NWAVLC = 0.7*HWVCRT +0.5 = 4 .
       1.2761E+01(  15)       NWAVLC is used later in SUBROUTINE STABIL to
       1.4410E+01(  16)       see if Ny(add) (see Eq. 5.22), that is,
       1.6214E+01(  17)       FN2ADD(1), should be added to the prebuckling
       1.8179E+01(  18)       hoop stress resultant for the perfect shell.)
       2.0304E+01(  19)
```

```
        2.2599E+01(  20)
  ===== BUCKLING MODAL ANTISYMMETRY AT SYMMETRY PLANE =====
  Crit. buckling factor, BUCLOC(smeared waviness, DISCRETE end rings)=2.0709E+00
  Critical number of circumferential waves, NWVCRT=     5
                                                                  Item, Eq.,
  Output from STRUCT (See Section 5.3 of [26]):                  Table Nos.
                                                                 Item Eq. Tab
  Maximum stress from nonlinear theory (no rings),STRMXX=  2.0847E+04  7  -    -
  End shortening under unit axial compression,     ENDUV=  8.0057E-04  8  -    -
  Modal frequency correspnding to 2 circ. waves,   FREQ2=  4.7935E+01  9  -    -
  Ratio of wavy arclength to straight length,     ARCRAT=  1.0377E+00 10  -   5.1
  Reduction factor for axial stiffness,           C11RAT=  3.8546E-02 10  -   5.1
  Hoop bending stiffness ratio,C55RAT=C55(eff)/C55(wall)=  2.5002E+01 10  -   5.1
  2nd ratio of wavy arclength to straight length, ARCRT2=  1.0377E+00  -  -    -
  Weight of the entire Model No. 2,               WEIGHT=  1.7817E+01 14  -    -
  Nx from axial g-loading and unsupported tube,   FNXADD= -2.1005E+00 15 5.27 -
  Effective mass density of shell wall material,  DENSHL=  2.5000E-04  -  -    -
  Mass density of ring material,                  DENRNG=  2.5000E-04  -  -    -
  Effective density of shell with smeared rings,  RHOEFF=  2.8711E-04  -  -   5.1
  Amplitude of initial general buckling imperfection, W0=  4.5000E-02 12b 5.25 -
 (C22-C12**2/C11)*(C25/C22)*(n/R)**2*W0/(EIG1-1)=FN2ADD(1)=-1.9077E+01 12 5.22 -
 (C22-C12**2/C11)*(C25/C22)*(n/R)**2*W0/(EIG2-1)=FN2ADD(2)=-3.4059E+02 12 5.22 -
 in which
 EIG1 = buckling load factor, smeared waviness and SMEARED  rings=2.5841E+00
 and
 EIG2 = buckling load factor, smeared waviness and DISCRETE rings=1.3333E+00
 Smallest buckling circumferential wavenumber for which FN2ADD(1)= -1.9077E+01
 is added to the hoop load from pressure in buckling analyses NWAVLC=4 (Item 13)

  Output from STRUCT for linear nonsymmetric stress analysis:         location
                                                                      seg node
  Max. critical stress,  theta=0, load set A,   STRNON(1)=  3.1778E+04, 156 023
  Max. critical stress,  theta=0, load set B,   STRNON(2)=  0.0000E+00,      0
  Max. normal displace., theta=0, load set A,   WWWNON(1)= -3.0072E-01, 157 007
  Max. normal displace., theta=0, load set B,   WWWNON(2)=  0.0000E+00,      0
  Max. critical stress,  theta=180,load set A,  STRNON(1)=  2.8246E+04,  23 011
  Max. critical stress,  theta=180,load set B,  STRNON(2)=  0.0000E+00,      0
  Max. normal displace., theta=180,load set A,  WWWNON(1)=  2.9489E-01, 157 007
  Max. normal displace., theta=180,load set B,  WWWNON(2)=  0.0000E+00,      0

  The 18 behaviors listed in Table 6.1, minus the behaviors, 2, 3, and 15-18,
  indicated in the testnew6.OPT file listed at the beginning of this table,
  are evaluated next. See Section 6.2 of [26] for discussions.

  ============================================================
  BEGIN COMPUTATIONS IN SUBROUTINE BEHX1 (NONLINEAR STRESS).    (Behavior No. 1)
  IMODX= 0; LOAD SET NO.  1
  Maximum nonlinear effective stress, STRMAX=  2.0847E+04

  ============================================================
  BEGIN SUBROUTINE BEHX4 (LINEAR NONAXISYMMETRIC STRESS, 0deg).(Behavior No. 4)
  IMODX= 0; LOAD SET NO.  1
  Maximum stress from linear theory at 0 deg, STR0(ILOADX)=    3.1778E+04

  ============================================================
  BEGIN SUBROUTINE BEHX5 (LINEAR NONAXISYMMETRIC STRESS, 180d).(Behavior No. 5)
  IMODX= 0; LOAD SET NO.  1
  Maximum stress, linear theory at 180 deg, STR180(ILOADX)=    2.8246E+04

  ============================================================
  BEGIN SUBROUTINE BEHX6 (LINEAR BUCKLING AT 0 DEGREES).        (Behavior No. 6)
  LOW-WAVE-RANGE, IMODX= 0; LOAD SET NO.  1
```

```
SYMMETRIC BUCKLING ABOUT MIDLENGTH SYMMETRY PLANE
***** SYMMETRIC BUCKLING LOAD FACTORS AND MODE SHAPES *****
LINEAR BUCKLING LOAD FACTOR, 0 DEGREES, MODEL 2 (CIRC. WAVES)
   eigenvalue(circ. waves)
       9.6037E+00(   0)                           (NOTE: the three ranges of
       9.2534E+00(   1)                            circ. wavenumber: low-n,
       1.2854E+00(   2)  <--- general buckling     mid-n, and high-n, were set
       2.4793E+00(   3)                            up to capture general bucklng,
       1.3122E+00(   4)  <--- local (inter-ring)  local buckling, and even more
       1.3657E+00(   5)       buckling             local buckling. In this case
===== BUCKLING MODAL SYMMETRY AT SYMMETRY PLANE    it turns out that both general
Critical buckling load factor, BUC0=  1.2854E+00  and local buckling are cap-
Critical number of circ. waves,NWVCRT=2            tured by the low-n range.
                                                   That's okay.)

*** SYMMETRIC BUCKLING LOAD FACTORS AND MODE SHAPES ***
LINEAR BUCKLING LOAD FACTOR, 0 DEGREES, MODEL 2 (CIRC. WAVES)
THE ENTIRE LENGTH (  9.0000E+01) OF THE CYL. HAS "SMEARED" WAVINESS.
   eigenvalue(circ. waves)
       1.7813E+01(   0)                          (The purpose of this "smeared"
       1.8377E+01(   1)                           model is to see how accurate
       1.3327E+00(   2)  <--- general buckling    smearing the waviness is.
       2.7517E+00(   3)                           The "smeared waviness" results
       2.1689E+00(   4)                           are not used for optimization.)
       1.7910E+00(   5)  <--- local (inter-ring) buckling
===== BUCKLING MODAL SYMMETRY AT SYMMETRY PLANE =====
Crit. buckling factor,  BUC0("smeared waviness")=  1.3327E+00
Critical number of circumferential waves, NWVCRT=    2

=============================================================
BEGIN SUBROUTINE BEHX7 (LINEAR BUCKLING AT 0 DEGREES).       (Behavior No. 7)
LOW-WAVE-RANGE, IMODX= 0; LOAD SET NO.  1
ANTI-SYMMETRIC BUCKLING ABOUT MIDLENGTH SYMMETRY PLANE
*** ANTISYMMETRIC BUCKLING LOAD FACTORS AND MODE SHAPES ***
LINEAR BUCKLING LOAD FACTOR, 0 DEGREES, MODEL 2 (CIRC. WAVES)
   eigenvalue(circ. waves)
       9.6037E+00(   0)
       9.2535E+00(   1)
       1.3204E+00(   2)  <--- general buckling
       2.4896E+00(   3)
       1.2671E+00(   4)  <--- local (inter-ring) buckling
       1.3505E+00(   5)
===== BUCKLING MODAL ANTISYMMETRY AT SYMMETRY PLANE =====
Critical buckling load factor, BUC0=  1.2671E+00
Critical number of circumferential waves, NWVCRT=    4

*** ANTISYMMETRIC BUCKLING LOAD FACTORS AND MODE SHAPES ***
LINEAR BUCKLING LOAD FACTOR, 0 DEGREES, MODEL 2 (CIRC. WAVES)
THE ENTIRE LENGTH (  9.0000E+01) OF THE CYL. HAS "SMEARED" WAVINESS.
   eigenvalue(circ. waves)
       1.7813E+01(   0)                         (See the note above in the
       1.8377E+01(   1)                          section for symmetric buckling
       1.3591E+00(   2)  <--- general            with "smeared waviness" along
       2.8315E+00(   3)       buckling           the entire length of the cyl.)
       2.0897E+00(   4)
       1.7626E+00(   5)  <--- local (inter-ring) buckling
===== BUCKLING MODAL ANTISYMMETRY AT SYMMETRY PLANE =====
Crit. buckling factor,  BUC0("smeared waviness")=  1.3591E+00
Critical number of circumferential waves, NWVCRT=    2

=============================================================
BEGIN SUBROUTINE BEHX8 (LINEAR BUCKLING AT 0 DEGREES).       (Behavior No. 8)
```

```
MID-WAVE-RANGE, IMODX= 0; LOAD SET NO.  1
***** SYMMETRIC BUCKLING LOAD FACTORS AND MODE SHAPES *****
LINEAR BUCKLING LOAD FACTOR, 0 DEGREES, MODEL 2 (CIRC. WAVES)
   eigenvalue(circ. waves)
       1.9602E+00(   6)
       2.3984E+00(   7)                        (Note: there is no further
       2.7866E+00(   8)                         minimum eigenvalue(n) in
       3.1569E+00(   9)                         this range of circ. waves.)
       3.9330E+00(  10)
===== BUCKLING MODAL SYMMETRY AT SYMMETRY PLANE =====
Critical buckling load factor, BUC0=  1.9602E+00
Critical number of circumferential waves, NWVCRT=    6

*** ANTISYMMETRIC BUCKLING LOAD FACTORS AND MODE SHAPES ***
LINEAR BUCKLING LOAD FACTOR, 0 DEGREES, MODEL 2 (CIRC. WAVES)
   eigenvalue(circ. waves)
       1.9460E+00(   6)
       2.3940E+00(   7)                        (Note: there is no further
       2.7795E+00(   8)                         minimum eigenvalue(n) in
       3.1568E+00(   9)                         this range of circ. waves.)
       3.9328E+00(  10)
===== BUCKLING MODAL ANTISYMMETRY AT SYMMETRY PLANE =====
Critical buckling load factor, BUC0=  1.9460E+00
Critical number of circumferential waves, NWVCRT=    6

============================================================
BEGIN SUBROUTINE BEHX9(HI-WAVE LINEAR BUCKLING AT 0 DEGREES). (Behavior No. 9)
IMODX= 0; LOAD SET NO.  1                                      turned off for
*** ANTISYMMETRIC BUCKLING LOAD FACTORS AND MODE SHAPES ***    optimization
LINEAR HI-WAVE BUCKLING LOAD FACTOR, 0 DEGREES (CIRC. WAVES)   in this case.)
   eigenvalue(circ. waves)
       1.0608E+01(  16)
       1.3804E+01(  22)
       1.4299E+01(  28)
       1.5267E+01(  34)                        (Note: there is no further
       1.6641E+01(  40)                         minimum eigenvalue(n) in
       1.8286E+01(  46)                         this range of circ. waves.
       1.9902E+01(  52)                         Only buckling antisymmetric
       2.1461E+01(  58)                         with respect to the mid-
       2.3044E+01(  64)                         length symmetry plane is
       2.4655E+01(  70)                         explored for the high-n
       2.6279E+01(  76)                         range. This is because for
       2.7875E+01(  82)                         high-n buckling the ring
       2.9325E+01(  88)                         at the midlength symmetry
       3.0360E+01(  94)                         plane will surely prevent
       3.0955E+01( 100)                         radial displacement there)
===== BUCKLING MODAL ANTISYMMETRY AT SYMMETRY PLANE =====
Critical buckling load factor, BUC0HI=  1.0608E+01
Critical number of circumferential waves, NWVCRT=   16

============================================================
BEGIN SUBROUTINE BEHX10 (LINEAR BUCKLING AT 180 DEGREES).   (Behavior No. 10
IMODX= 0; LOAD SET NO.  1                                    was turned off
***** SYMMETRIC BUCKLING LOAD FACTORS AND MODE SHAPES *****  during optimiza-
LINEAR BUCKLING LOAD FACTOR, 180 DEG., MODEL 2 (CIRC. WAVES) tion in this case)
   eigenvalue(circ. waves)
       1.1756E+01(   0)                       (NOTE: In WAVYCYL the buckling
       1.1769E+01(   1)                        load factors for the 180-deg
       1.3189E+00(   2)  <--- general buckling meridian are computed over
       2.6115E+00(   3)                        both the low-n and mid-n
       1.4124E+00(   4)  <--- local (inter-ring) ranges in one "behavior"
       1.4360E+00(   5)       buckling         subroutine, BEHX10. The n-
```

```
        2.1050E+00(   6)                         range is not divided up into
        2.5998E+00(   7)                         two sub-ranges. Also, the
        3.1652E+00(   8)                         "symmetric" and "antisymme-
        3.7065E+00(   9)                         tric buckling evaluations are
        4.6040E+00(  10)                         conducted in the same routine)
 ===== BUCKLING MODAL SYMMETRY AT SYMMETRY PLANE =====
 Critical buckling load factor, BUC180=  1.3189E+00
 Critical number of circumferential waves, NWVCRT=    2

 *** ANTISYMMETRIC BUCKLING LOAD FACTORS AND MODE SHAPES ***
 LINEAR BUCKLING LOAD FACTOR, 180 DEG., MODEL 2 (CIRC. WAVES)
    eigenvalue(circ. waves)
        1.1756E+01(   0)
        1.1769E+01(   1)                         (NOTE; We are still in
        1.3573E+00(   2)  <--- general buckling    SUBROUTINE BEHX10)
        2.6118E+00(   3)
        1.3854E+00(   4)  <--- local (inter-ring) buckling
        1.4317E+00(   5)
        2.1050E+00(   6)
        2.5998E+00(   7)
        3.1651E+00(   8)
        3.7065E+00(   9)
        4.6040E+00(  10)
 ===== BUCKLING MODAL ANTISYMMETRY AT SYMMETRY PLANE =====
 Critical buckling load factor, BUC180=  1.3573E+00
 Critical number of circumferential waves, NWVCRT=    2

 =============================================================
 BEGIN SUBROUTINE BEHX11 (HI-WAVE LINEAR BUCKLNG 180 DEGREES).(Behavior No. 11
 IMODX= 0; LOAD SET NO.  1                                     turned off for
 *** ANTISYMMETRIC BUCKLING LOAD FACTORS AND MODE SHAPES ***   optimization)
 LINEAR HI-WAVE BUCKLING LOAD FACTOR, 180 DEG. (CIRC. WAVES)
    eigenvalue(circ. waves)
        1.1037E+01(  16)
        1.5923E+01(  22)
        1.6160E+01(  28)
        1.6962E+01(  34)                        (As with buckling along the
        1.8243E+01(  40)                         meridian at 0 degrees, only
        1.9847E+01(  46)                         antisymmetric buckling with
        2.1552E+01(  52)                         respect to the symmetry plane
        2.3258E+01(  58)                         at the midlength is explored
        2.4989E+01(  64)                         for the case of high-n
        2.6752E+01(  70)                         buckling.)
        2.8544E+01(  76)
        3.0347E+01(  82)
        3.2085E+01(  88)
        3.3340E+01(  94)
        3.3888E+01( 100)
 ===== BUCKLING MODAL ANTISYMMETRY AT SYMMETRY PLANE =====
 Critical buckling load factor, B180HI=  1.1037E+01
 Critical number of circumferential waves, NWVCRT=   16

 =============================================================
 BEGIN SUBROUTINE BEHX12 (MAX. NORMAL DISPLACEMENT, 0 DEG.).  (Behavior No. 12
 IMODX= 0; LOAD SET NO.  1                                    turned off during
                                                              optimization.)
 Max. normal displacement, linear theory, 0 deg, WWW0(ILOADX)=3.0072E-01

 =============================================================
 BEGIN SUBROUTINE BEHX13 (MAX. NORMAL DISPLACEMENT, 180 DEG.).(Behavior No. 13
 IMODX= 0; LOAD SET NO.  1                                    turned off during
                                                              optimization.)
```

```
Max. normal displac., linear theory, 180 deg, WWW180(ILOADX)=2.9489E-01

==========================================================
BEGIN SUBROUTINE BEHX14 (MODAL FREQUENCY, AXISYM. LOADING).  (Behavior No. 14)
IMODX= 0; LOAD SET NO.  1
***** FREQUENCIES AND MODE SHAPES *****
      FREQUENCY(CIRC. WAVES)
       9.2244E+01(   0)
       1.0012E+01(   1)  <--- critical value: "beam-type" vibration
       5.6759E+01(   2)       This is used during optimization cycles
       2.3223E+02(   3)
=======================================
Critical modal vibration frequency, FREQ=  1.0012E+01
Critical number of circumferential waves, NWVCRT=    1

***** FREQUENCIES AND MODE SHAPES: "SMEARED" WAVINESS *****
      FREQUENCY(CIRC. WAVES)
       1.0428E+02(   0)
       1.1439E+01(   1)  <--- critical value: "beam-type" vibration
       5.4769E+01(   2)       The "smeared waviness" model is not
       2.2424E+02(   3)       used during optimization cycles.
=======================================
Critical modal vibration frequency, FREQ=  1.1439E+01
Critical number of circumferential waves, NWVCRT=    1

Find natural frequency for axial length=  8.0000E+02   (Length between axial
                                                        motion restraints.)
***** FREQUENCY AND MODE SHAPE FOR 0 CIRC. WAVES *****
      FREQUENCY(CIRC. WAVES)
       2.2228E+01(   0)
=======================================
Critical modal vibration frequency, FREQ=  2.2228E+01
Critical number of circumferential waves, NWVCRT=    0


***** RESULTS FOR LOAD SET NO.  1  ******
PARAMETERS WHICH DESCRIBE BEHAVIOR (e.g. stress, buckling load)
BEH.   CURRENT
NO.     VALUE             DEFINITION
 1    2.085E+04    maximum stress in wall from nonlinear theory: STRMAX(1 )
 2    1.000E+10    buckling load factor from nonlinear theory: BUCFAC(1 )
 3    1.000E+10    hi-wave buckling load factor, nonlinear theory: BUCHIW(1 )
 4    3.178E+04    max. stress at 0 deg., linear theory: STR0(1 )
 5    2.825E+04    max. stress at 180 deg., linear theory: STR180(1 )
 6    1.285E+00    buckling load factor at 0 deg., linear theory: BUC0(1 )
 7    1.267E+00    load factor for antisymmetric buckling at 0 deg: B0ANTI(1)
 8    1.946E+00    load factor for mid-wave-range buckling at 0 deg: BUC0MD(1)
 9    8.876E+00    hi-wave buckling load factor, 0 deg,linear theory:BUC0HI(1)
10    1.332E+00    buckling load factor at 180 deg, linear theory: BUC180(1 )
11    1.031E+01    hi-wave buckling load factor 180 deg, lin.theory: B180HI(1)
12    3.007E-01    maximum normal displacement, 0 deg., linear theory: WWW0(1)
13    2.949E-01    maximum normal displacement, 180 deg., lin.theory:WWW180(1)
14    1.001E+01    modal frequency (hertz): FREQ(1 )
15    1.000E-10    maximum stress from random excitation: STRRAN(1 )
16    1.000E+10    buckling load factor from random excitation: BUCRAN(1 )
17    1.000E+10    hi-wave buckling factor from random excitation: BRANHI(1)
18    1.000E-10    max. normal displacement from random excitation: WWWRAN(1)

MARGINS CORRESPONDING TO CURRENT DESIGN (F.S.= FACTOR OF SAFETY)
MARGIN CURRENT                                                         BEHAVIOR
NO.     VALUE            DEFINITION                                     NUMBER
 1    5.831E-01  1-(STRMAX(1 )/STRALW(1 )) X STRFS(1 ); F.S.=  1.00       1
```

```
  2     3.644E-01  1-(STR0(1 )/STR0A(1 )) X STR0F(1 ); F.S.=  1.00          4
  3     4.351E-01  1-(STR180(1 )/ST180A(1 )) X ST180F(1 ); F.S.=  1.00      5
  4     2.830E-02  (BUC0(1 )/BUC0A(1 )) / BUC0F(1 )-1; F.S.=  1.25          6
  5     1.366E-02  (B0ANTI(1 )/B0ANTA(1 )) / B0ANTF(1 )-1; F.S.=  1.25      7
  6     5.568E-01  (BUC0MD(1 )/BUC0MA(1 )) / BUC0MF(1 )-1; F.S.=  1.25      8
  7     6.101E+00  (BUC0HI(1 )/BUC0HA(1 )) / BUC0HF(1 )-1; F.S.=  1.25      9
  8     6.556E-02  (BUC180(1 )/BU180A(1 )) / BU180F(1 )-1; F.S.=  1.25     10
  9     7.249E+00  (B180HI(1 )/B180HA(1 )) / B180HF(1 )-1; F.S.=  1.25     11
 10     6.241E-01  1-(WWW0(1 )/WWW0A(1 )) X WWW0F(1 ); F.S.=  1.00         12
 11     6.314E-01  1-(WWW180(1 )/WW180A(1 )) X WW180F(1 ); F.S.=  1.00     13
 12     1.208E-03  (FREQ(1 )/VIBALW(1 )) / VIBFS(1 )-1; F.S.=  1.00        14
 13     1.000E+00  1-(STRRAN(1 )/STRRNA(1 )) X STRRNF(1 ); F.S.=  1.00     15
 14     1.000E+00  1-(WWWRAN(1 )/WWWRNA(1 )) X WWWRNF(1 ); F.S.=  1.00     18

******************** DESIGN OBJECTIVE *******************
   CURRENT VALUE OF THE OBJECTIVE FUNCTION:
VAR.   CURRENT
NO.     VALUE             DEFINITION
 1     1.782E+01  weight of the cylindrical shell: WEIGHT  (NOTE: This is the
******************** DESIGN OBJECTIVE *******************   weight of half the
***********  ALL 1 LOAD CASES PROCESSED ***********         length of the tube)

PARAMETERS WHICH ARE ALWAYS FIXED.  NONE CAN BE DECISION VARIAB.
VAR.   CURRENT
NO.     VALUE             DEFINITION
 1     1.800E+02  length of cylindrical shell: AXIAL
 2     9.000E+00  Average nominal radius of cylindrical shell: RADIUS
 3     1.000E+07  Average modulus of ring material: ERING
 4     3.000E-01  Average Poisson ratio of ring material: FNURNG
 5     2.500E-04  Average mass density of ring material: DENRNG
 6     3.864E+02  Acceleration of gravity (e.g. 386.4 in/sec**2): GRAVTY
 7     8.000E+02  Length of tube unrestrained by axial hanger: LGAXL
 8     1.000E+07  Youngs modulus: ESTIFF
 9     3.000E-01  Poisson ratio: FNU
10     2.500E-04  Material mass density (e.g. alum.=0.00025lb-sec**2/in: DENS
11     1.000E-02  damping factor: BDAMP(1 )
12     1.000E-02  damping factor: BDAMP(2 )
13     1.000E-02  damping factor: BDAMP(3 )
14     5.000E-02  damping factor: BDAMP(4 )
15     5.000E+00  frequency (hertz) corresponding to damping factor: BFREQ(1)
16     1.000E+01  frequency (hertz) corresponding to damping factor: BFREQ(2)
17     3.000E+01  frequency (hertz) corresponding to damping factor: BFREQ(3)
18     5.000E+02  frequency (hertz) corresponding to damping factor: BFREQ(4)
19     3.000E-01  spectral density: SPTDEN(1)
20     5.000E-01  spectral density: SPTDEN(2)
21     1.000E+00  spectral density: SPTDEN(3)
22     2.000E+00  spectral density: SPTDEN(4)
23     1.000E+00  spectral density: SPTDEN(5)
24     5.000E+00  frequency (hertz) corresponding to spectral density: SFREQ(1)
25     8.000E+00  frequency (hertz) corresponding to spectral density: SFREQ(2)
26     1.200E+01  frequency (hertz) corresponding to spectral density: SFREQ(3)
27     1.000E+02  frequency (hertz) corresponding to spectral density: SFREQ(4)
28     5.000E+02  frequency (hertz) corresponding to spectral density: SFREQ(5)

PARAMETERS WHICH ARE ENVIRONMENTAL FACTORS (e.g. loads, temps.)
VAR.   CURRENT
NO.     VALUE             DEFINITION
 1    -5.300E+01  Axial resultant (neg. for compression),Load Set A: FNX(1)
 2     0.000E+00  Axial resultant (neg. for compression), Load Set B: FNXB(1)
 3     1.500E+00  number of g's acceleration along cylinder axis: GAXIAL(1)
 4     3.000E+00  Number of g's perpendicular to axis of cylinder: GLATRL(1)
 5    -1.180E+01  pressure (negative for external), Load Set A: PRESS(1)
```

```
  6     0.000E+00  pressure (negative for external), Load Set B: PRESSB(1)

 PARAMETERS WHICH ARE CLASSIFIED AS ALLOWABLES (e.g. max. stress)
 VAR.    CURRENT
 NO.      VALUE              DEFINITION
  1     5.000E+04  maximum allowable stress, nonlinear theory: STRALW(1)
  2     1.000E+00  allowable buckling factor (use 1.0), nonlin.theory: BUCALW(1)
  3     1.000E+00  allowable hi-wave bucklng factor, nonlin.theory: BUCHIA(1)
  4     5.000E+04  max. allowable stress, linear theory: STR0A(1)
  5     5.000E+04  max. allowable stress, linear theory: ST180A(1)
  6     1.000E+00  allowable buckling factor (use 1), linear theory: BUC0A(1)
  7     1.000E+00  allowable (use 1), antisymmetric buckling, 0 deg.: B0ANTA(1)
  8     1.000E+00  allowable (use 1), mid-wave-range buckling, 0 deg: BUC0MA(1)
  9     1.000E+00  allowable for hi-wave buckling (use 1) at 0 deg.: BUC0HA(1)
 10     1.000E+00  allowable buckling factor,180 deg., linear theory: BU180A(1)
 11     1.000E+00  allowable (use 1), hi-wave buckling at 180 deg: B180HA(1)
 12     8.000E-01  maximum allowable normal displacemt, linear theory: WWW0A(1)
 13     8.000E-01  max. allowable normal displacment, linear theory: WW180A(1)
 14     1.000E+01  minimum allowable modal frequency: VIBALW(1)
 15     5.000E+04  max. allowable stress from random excitation: STRRNA(1)
 16     1.000E+00  allowable buckling load factor, random excit.: BUCRNA(1)
 17     1.000E+00  allowable (use 1), buckling factor, random excit.: BRANHA(1)
 18     8.000E-01  max. allowable normal displ., random excitation: WWWRNA(1)

 PARAMETERS WHICH ARE FACTORS OF SAFETY
 VAR.    CURRENT
 NO.      VALUE              DEFINITION
  1     1.000E+00  factor of safety stress, nonlinear theory: STRFS(1)
  2     1.250E+00  factor of safety buckling, nonlinear theory: BUCFS(1)
  3     1.250E+00  factor of safety hi-wave buckling: BUCHIF(1)
  4     1.000E+00  factor of safety stress, linear theory: STR0F(1)
  5     1.000E+00  factor of safety stress, linear theory: ST180F(1)
  6     1.250E+00  factor of safety buckling factor, linear theory: BUC0F(1)
  7     1.250E+00  factor of safety antisymmetric buckling, 0 deg: B0ANTF(1)
  8     1.250E+00  factor of safety mid-wave-range buckling, 0 deg: BUC0MF(1)
  9     1.250E+00  factor of safety hi-wave buckling, linear theory: BUC0HF(1)
 10     1.250E+00  factor of safety buckling at 180 deg, lin. theory: BU180F(1)
 11     1.250E+00  factor of safety hi-wave buckling at 180 deg.: B180HF(1)
 12     1.000E+00  factor of safety max. normal displacement: WWW0F(1)
 13     1.000E+00  factor of safety normal displacment: WW180F(1)
 14     1.000E+00  factor of safety modal frequency: VIBFS(1)
 15     1.000E+00  factor of safety stress from random excitation: STRRNF(1)
 16     1.250E+00  factor of safety, buckling from random excitation: BUCRNF(1)
 17     1.250E+00  factor of safety hi-wave buckling, random excit.: BRANHF(1)
 18     1.000E+00  factor of safety max. normal displ., random excit.: WWWRNF(1)

    0 INEQUALITY CONSTRAINTS WHICH MUST BE SATISFIED

 Menu of commands: CHOOSEPLOT, OPTIMIZE, MAINSETUP, CHANGE,
                   DECIDE, SUPEROPT

 IN ORDER TO AVOID FALSE CONVERGENCE OF THE DESIGN, BE SURE TO
 RUN  "OPTIMIZE"  MANY TIMES DURING AN OPTIMIZATION.
 ******************** END OF testnew6.OPM FILE *****************
======================================================================
```

Table 5.3 Results from convergence study with respect to: 1. number of nodes in each little toroidal segment (NMESHC) 2. total number of degrees of freedom (d.o.f.) in BOSOR4 MODEL 2 Results for an optimized PERFECT shell with the following dimensions: wall thickness, THICK = 0.03 in.; Ring spacing, BRINGS=10 in.; ring thickness, TWEB = 0.06798 in., Ring height, HWEB=0.6815 in.; axial halfwavelength of waviness, WAVLEN=0.55556 in.; amplitude (0.5*peak-to-peak) of waviness, AMPLIT = 0.061541 in.

discretization	prebuckling state		linear buckling		vibration
(nodes,d.o.f.)	max.stress	max.displc.	sym.buckling	antisym.buck.	frequency
(NMESHC,MAXDOF)	(psi)	(in.)	eigenv.(n)	eigenv.(n)	eigenv.(n)
(31, 15000)				1.2982(2)	
(21, 15000)	23095	-0.26400	1.2588(2)	1.2986(2)	10.579(1)
(21, 15000)			1.3448(5)	1.3255(5)	
(21, 9000)	23119	-0.26312	1.2354(2)	1.2617(2)	10.620(1)
(21, 9000)			1.3631(5)	1.3271(5)	
(11, 9000)	23266	-0.26844	1.2529(2)	1.2928(2)	10.471(1)
(11, 9000)			1.3231(5)	1.3039(5)	
(5, 9000)	24214	-0.29427	1.2160(2)	1.2604(2)	9.8546(1)
(5, 9000)			1.1971(5)	1.1792(5)	
(21, 6000)	23109	-0.25934	1.2609(2)	1.2288(2)	10.928(1)
(21, 6000)			1.3905(5)	1.3361(5)	
(21, 3000)	23097	-0.25415	1.2702(2)	1.2857(2)	11.436(1)
(21, 3000)			1.5109(5)	1.3674(5)	
smeared waviness for entire model		-0.25070	1.3148(2)	1.3434(2)	12.043(1)
smeared waviness for entire model			1.8200(5)	1.7851(5)	

NOTE: for buckling, n=2 corresponds to general instability;
n=5 corresponds to inter-ring (local) buckling

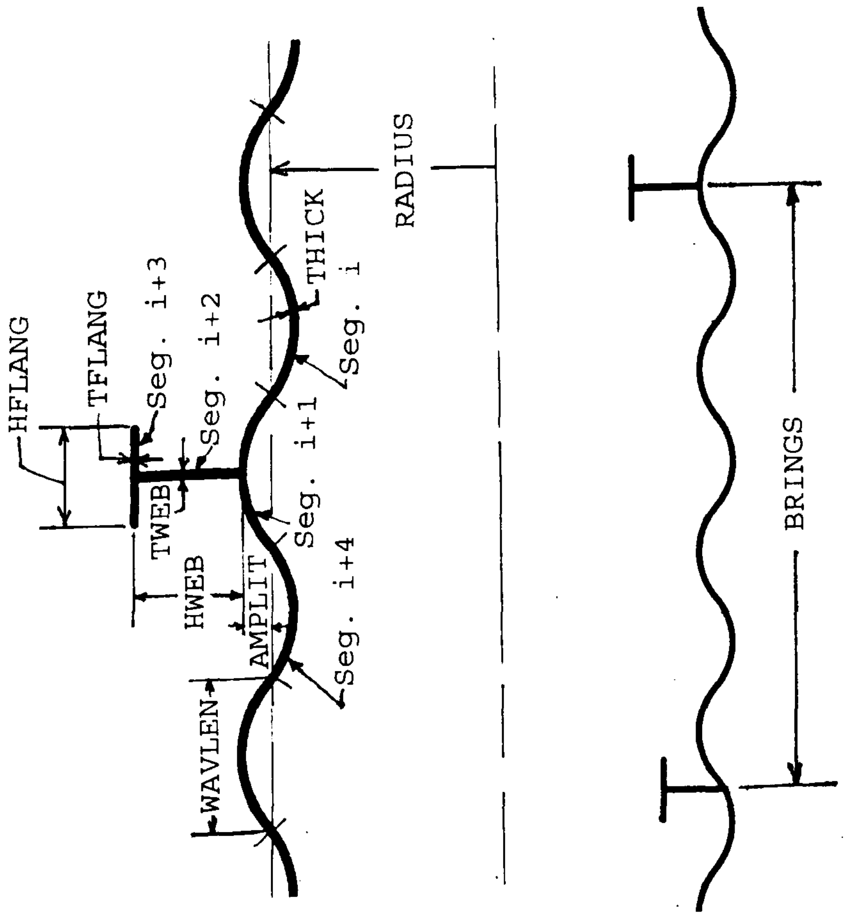

HFLANG
TFLANG
Seg. i+3
Seg. i+2
TWEB
HWEB
AMPLIT
WAVLEN
Seg. i+4
Seg. i+1
Seg. i
THICK
RADIUS
BRINGS

FIG. 2

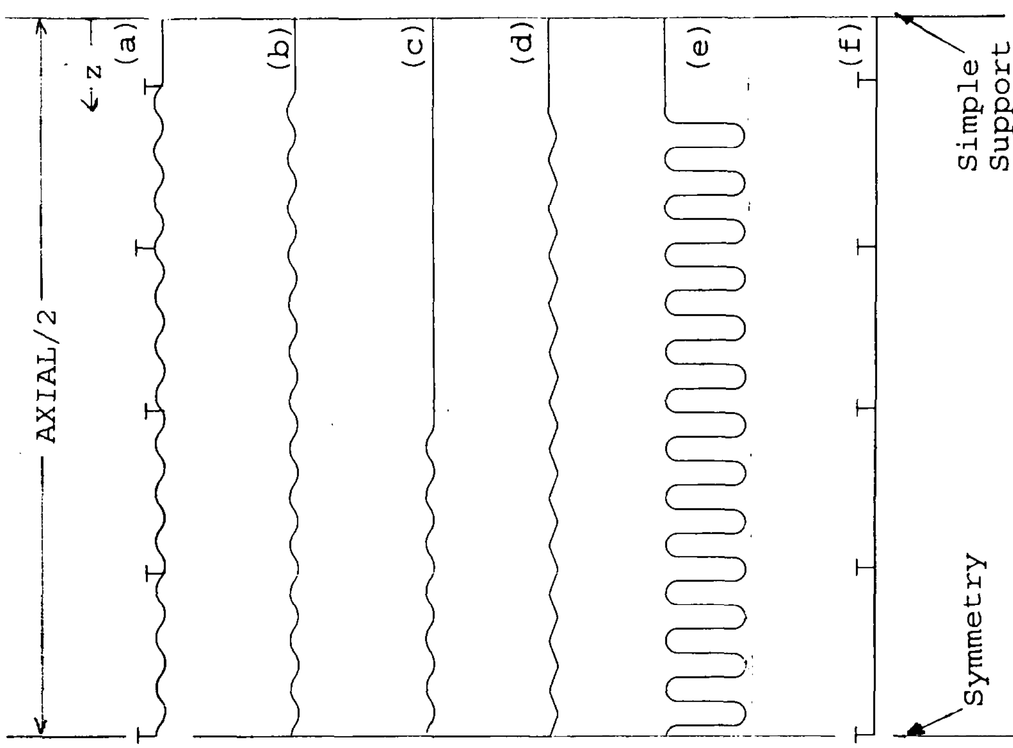

AXIAL/2
z
(a)
(b)
(c)
(d)
(e)
(f)
Simple Support
Symmetry

FIG. 1

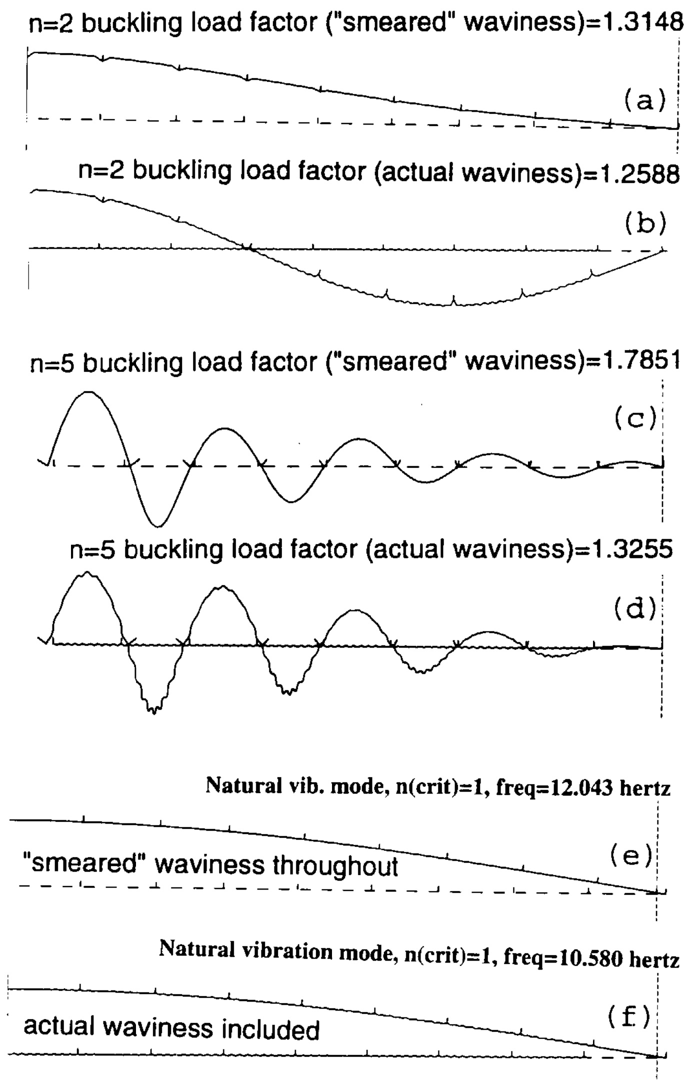

n=2 buckling load factor ("smeared" waviness)=1.3148
(a)
n=2 buckling load factor (actual waviness)=1.2588
(b)
n=5 buckling load factor ("smeared" waviness)=1.7851
(c)
n=5 buckling load factor (actual waviness)=1.3255
(d)
Natural vib. mode, n(crit)=1, freq=12.043 hertz
"smeared" waviness throughout
(e)
Natural vibration mode, n(crit)=1, freq=10.580 hertz
actual waviness included
(f)

FIG. 3

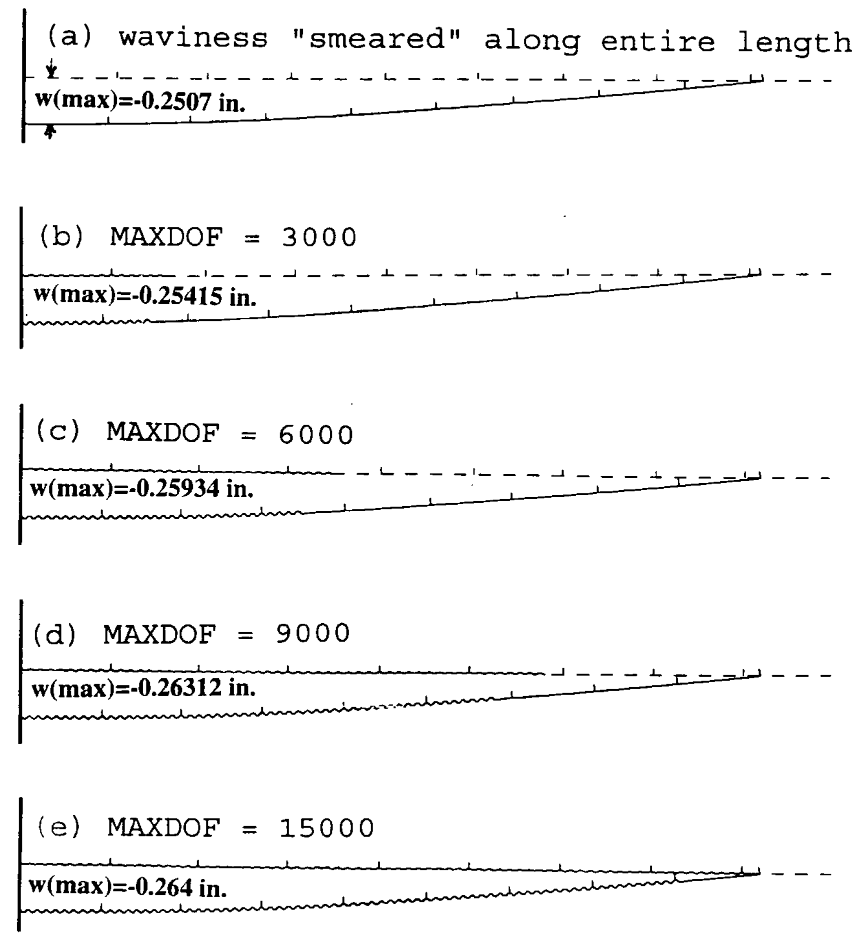

(a) waviness "smeared" along entire length
w(max)=-0.2507 in.
(b) MAXDOF = 3000
w(max)=-0.25415 in.
(c) MAXDOF = 6000
w(max)=-0.25934 in.
(d) MAXDOF = 9000
w(max)=-0.26312 in.
(e) MAXDOF = 15000
w(max)=-0.264 in.

FIG. 4

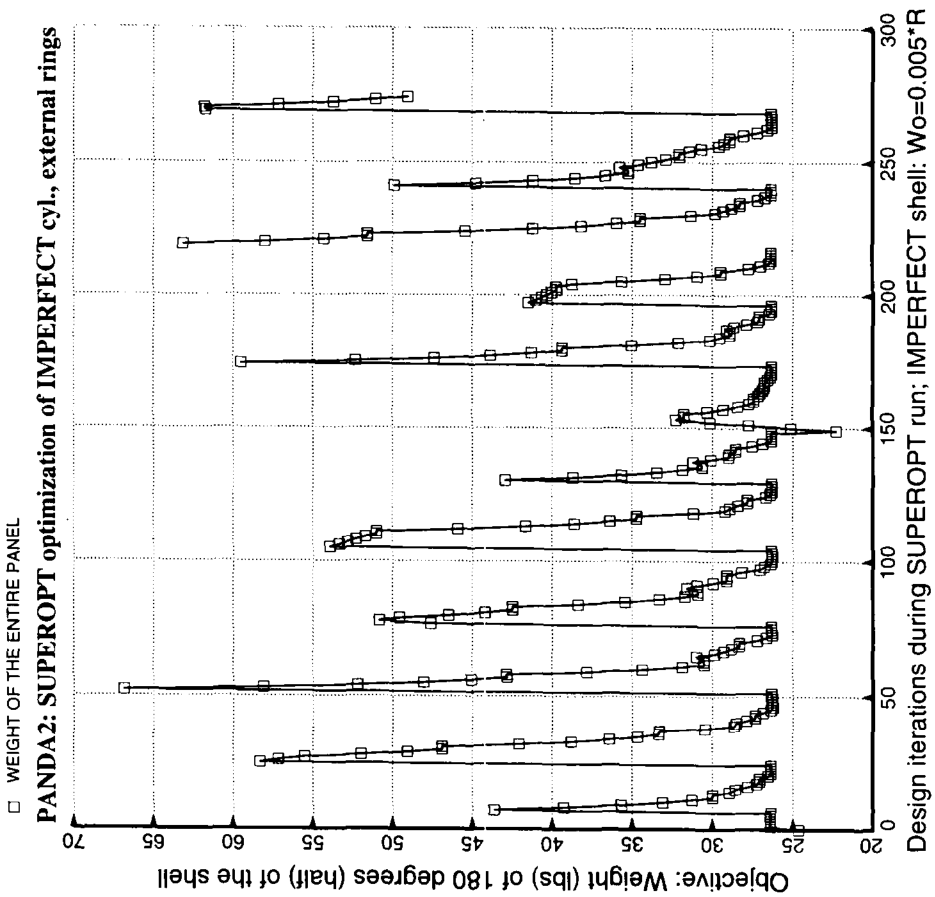

WEIGHT OF THE ENTIRE PANEL
PANDA2: SUPEROPT optimization of IMPERFECT cyl., external rings
Objective: Weight (lbs) of 180 degrees (half) of the shell
Design iterations during SUPEROPT run; IMPERFECT shell: Wo=0.005*R

FIG. 5

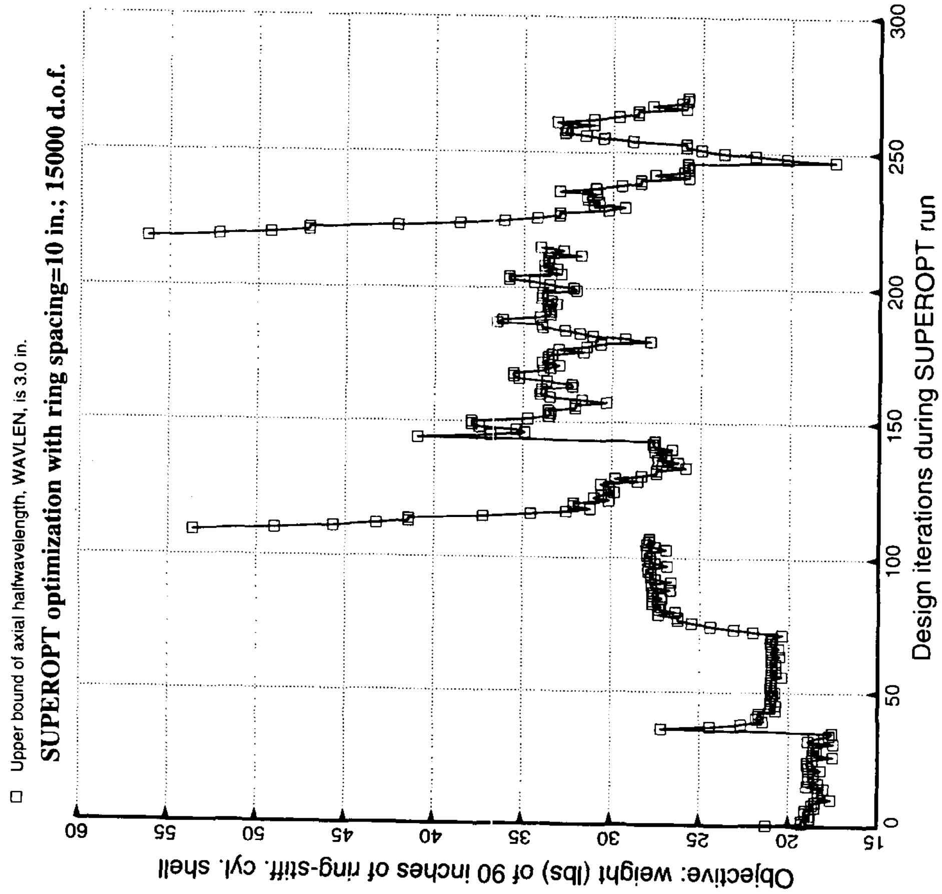

Upper bound of axial halfwavelength, WAVLEN, is 3.0 in.
SUPEROPT optimization with ring spacing=10 in.; 15000 d.o.f.
Objective: weight (lbs) of 90 inches of ring-stiff. cyl. shell
Design iterations during SUPEROPT run

FIG. 6

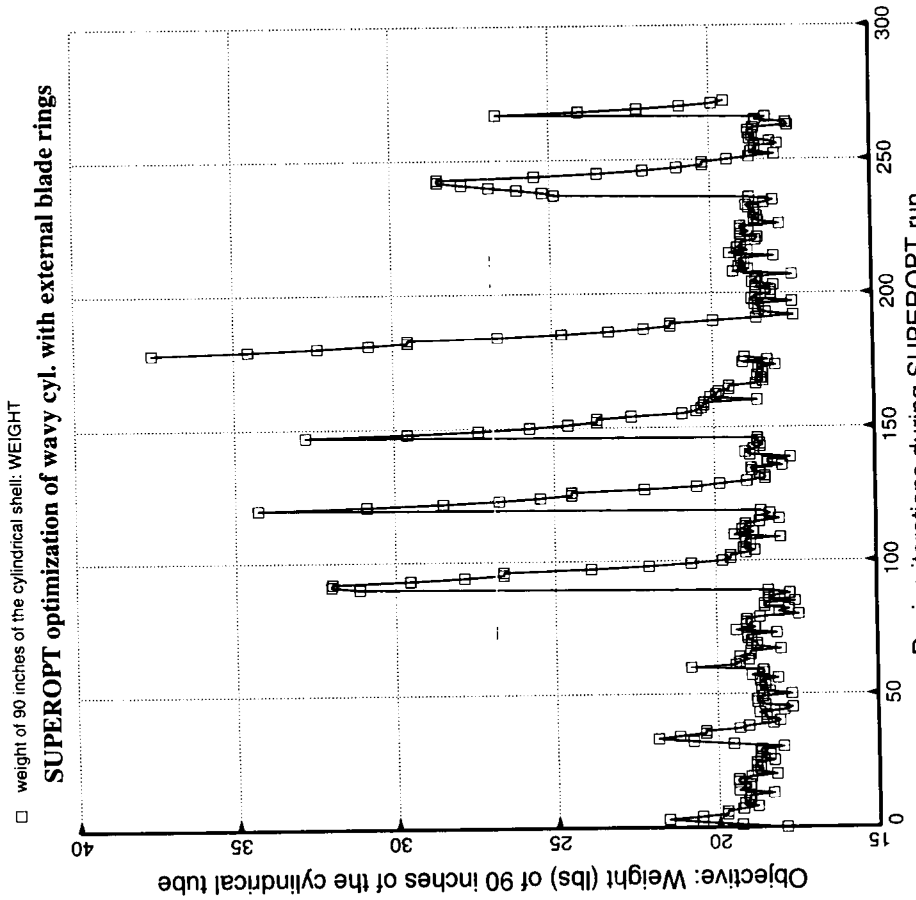

□ weight of 90 inches of the cylindrical shell: WEIGHT
SUPEROPT optimization of wavy cyl. with external blade rings
Objective: Weight (lbs) of 90 inches of the cylindrical tube
15
20
25
30
35
40
0
50
100
150
200
250
300
Design iterations during SUPEROPT run

FIG. 7

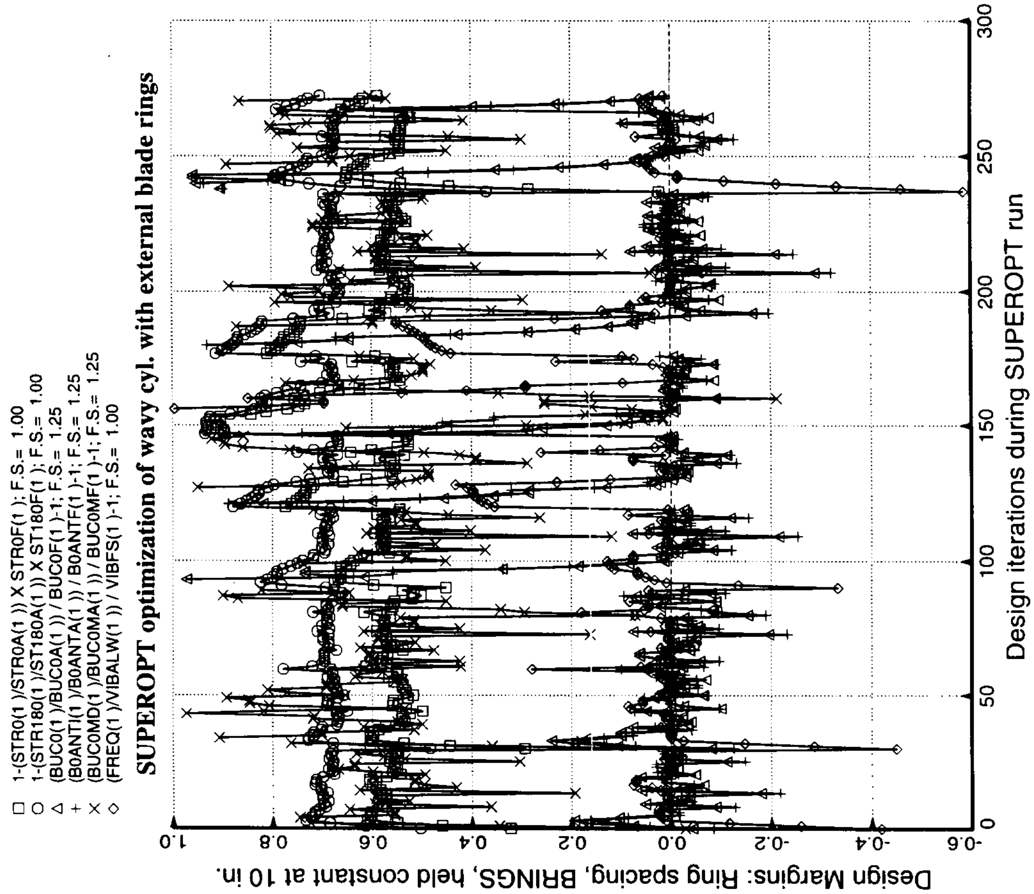

□ 1-(STR0(1)/STR0A(1)) X STR0F(1); F.S.= 1.00
○ 1-(STR180(1)/ST180A(1)) X ST180F(1); F.S.= 1.00
△ (BUC0(1)/BUC0A(1)) / BUC0F(1)-1; F.S.= 1.25
+ (B0ANTI(1)/B0ANTA(1)) / B0ANTF(1)-1; F.S.= 1.25
× (BUC0MD(1)/BUC0MA(1)) / BUC0MF(1)-1; F.S.= 1.25
◇ (FREQ(1)/VIBALW(1)) / VIBFS(1)-1; F.S.= 1.00
SUPEROPT optimization of wavy cyl. with external blade rings
Design Margins: Ring spacing, BRINGS, held constant at 10 in.
-0.6
-0.4
-0.2
0.0
0.2
0.4
0.6
0.8
1.0
0
50
100
150
200
250
300
Design iterations during SUPEROPT run

FIG. 8

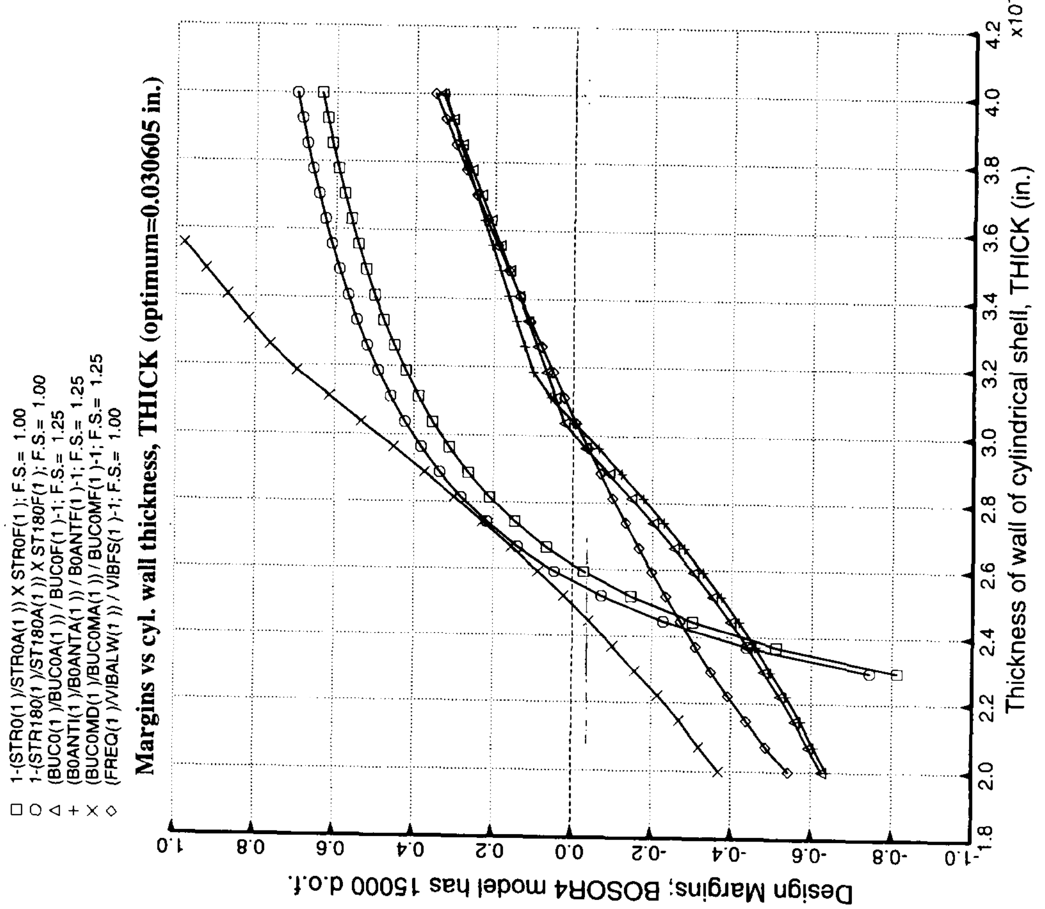

Margins vs cyl. wall thickness, THICK (optimum=0.030605 in.)
1-(STR0(1)/STR0A(1)) X STR0F(1); F.S.= 1.00
1-(STR180(1)/ST180A(1)) X ST180F(1); F.S.= 1.00
(BUC0(1)/BUC0A(1)) / BUC0F(1)-1; F.S.= 1.25
(B0ANTI(1)/B0ANTA(1)) / B0ANTF(1)-1; F.S.= 1.25
(BUC0MD(1)/BUC0MA(1)) / BUC0MF(1)-1; F.S.= 1.25
(FREQ(1)/VIBALW(1)) / VIBFS(1)-1; F.S.= 1.00
Design Margins; BOSOR4 model has 15000 d.o.f.
Thickness of wall of cylindrical shell, THICK (in.)
x10^-2

FIG. 10

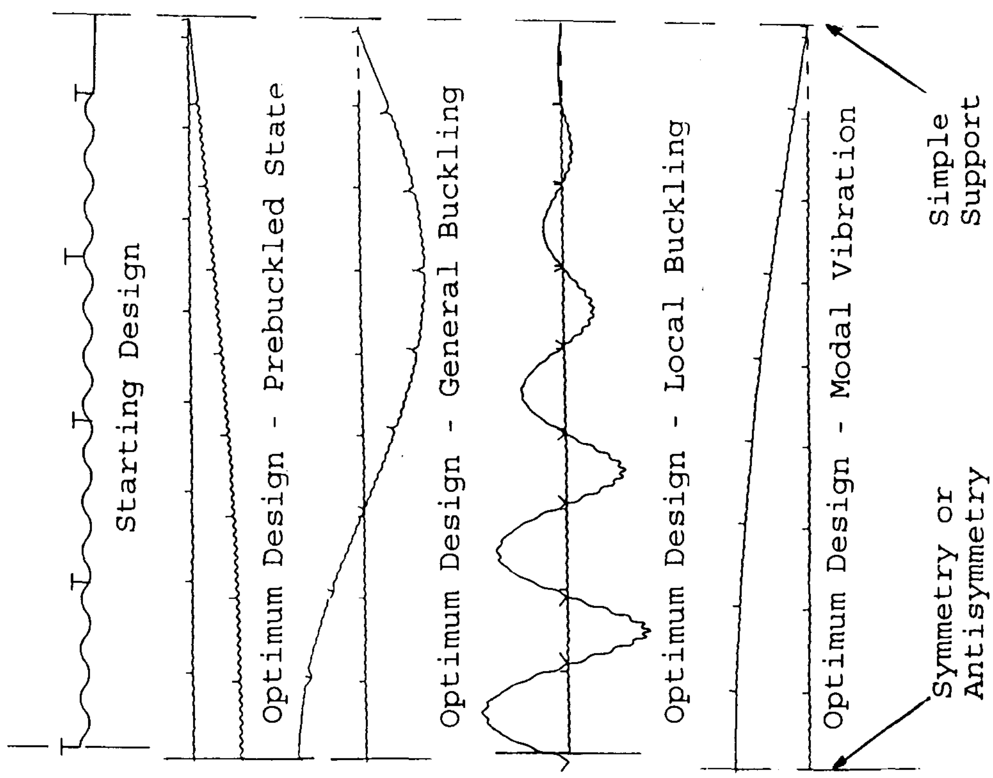

Starting Design
Optimum Design - Prebuckled State
Optimum Design - General Buckling
Optimum Design - Local Buckling
Optimum Design - Modal Vibration
Simple Support
Symmetry or Antisymmetry

FIG. 9

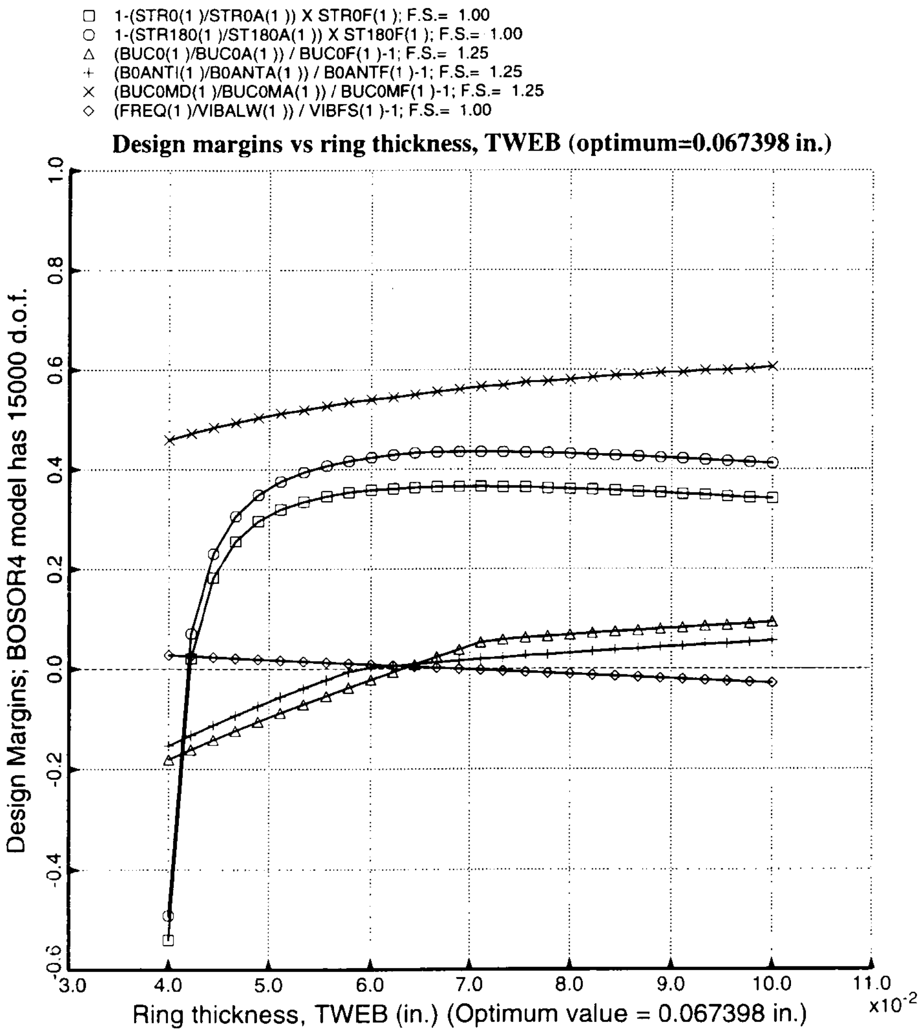

□ 1-(STR0(1)/STR0A(1)) X STR0F(1); F.S.= 1.00
○ 1-(STR180(1)/ST180A(1)) X ST180F(1); F.S.= 1.00
△ (BUC0(1)/BUC0A(1)) / BUC0F(1)-1; F.S.= 1.25
+ (B0ANTI(1)/B0ANTA(1)) / B0ANTF(1)-1; F.S.= 1.25
× (BUC0MD(1)/BUC0MA(1)) / BUC0MF(1)-1; F.S.= 1.25
◇ (FREQ(1)/VIBALW(1)) / VIBFS(1)-1; F.S.= 1.00
Design margins vs ring thickness, TWEB (optimum=0.067398 in.)
Design Margins; BOSOR4 model has 15000 d.o.f.
Ring thickness, TWEB (in.) (Optimum value = 0.067398 in.)
x10^-2

FIG. 11

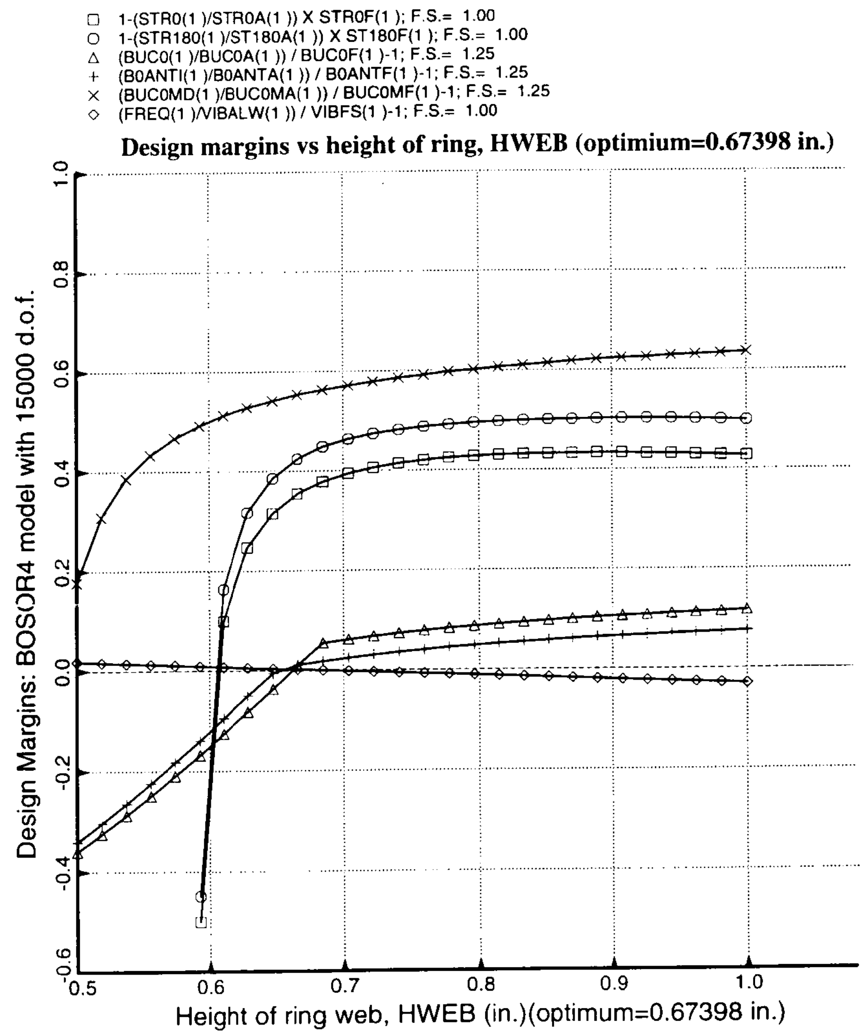

□ 1-(STR0(1)/STR0A(1)) X STR0F(1); F.S.= 1.00
○ 1-(STR180(1)/ST180A(1)) X ST180F(1); F.S.= 1.00
△ (BUC0(1)/BUC0A(1)) / BUC0F(1)-1; F.S.= 1.25
+ (B0ANTI(1)/B0ANTA(1)) / B0ANTF(1)-1; F.S.= 1.25
× (BUC0MD(1)/BUC0MA(1)) / BUC0MF(1)-1; F.S.= 1.25
◇ (FREQ(1)/VIBALW(1)) / VIBFS(1)-1; F.S.= 1.00
Design margins vs height of ring, HWEB (optimium=0.67398 in.)
Design Margins: BOSOR4 model with 15000 d.o.f.
Height of ring web, HWEB (in.)(optimum=0.67398 in.)

FIG. 12

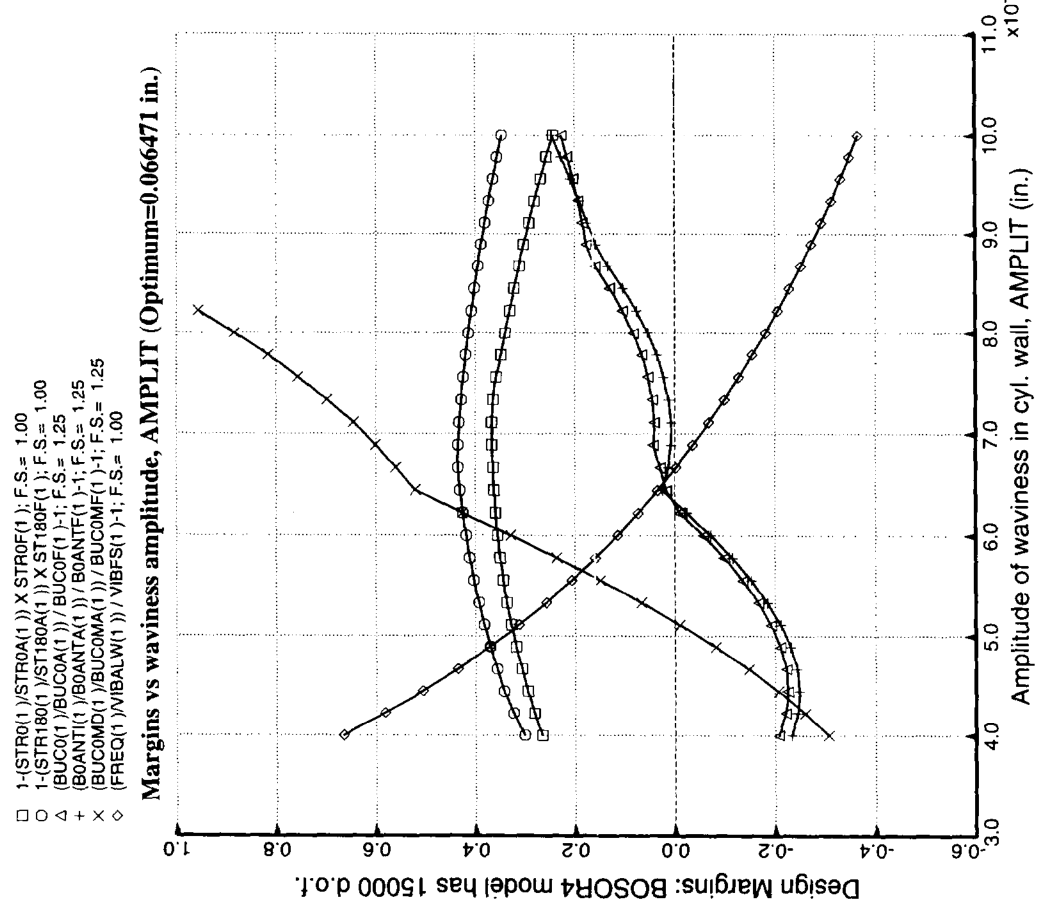

□ 1-(STR0(1)/STR0A(1)) X STR0F(1); F.S.= 1.00
○ 1-(STR180(1)/ST180A(1)) X ST180F(1); F.S.= 1.00
△ (BUC0(1)/BUC0A(1)) / BUC0F(1)-1; F.S.= 1.25
+ (B0ANTI(1)/B0ANTA(1)) / B0ANTF(1)-1; F.S.= 1.25
× (BUC0MD(1)/BUC0MA(1)) / BUC0MF(1)-1; F.S.= 1.25
◇ (FREQ(1)/VIBALW(1)) / VIBFS(1)-1; F.S.= 1.00
Margins vs waviness amplitude, AMPLIT (Optimum=0.066471 in.)
Design Margins: BOSOR4 model has 15000 d.o.f.
Amplitude of waviness in cyl. wall, AMPLIT (in.)
x10^-2

FIG. 13

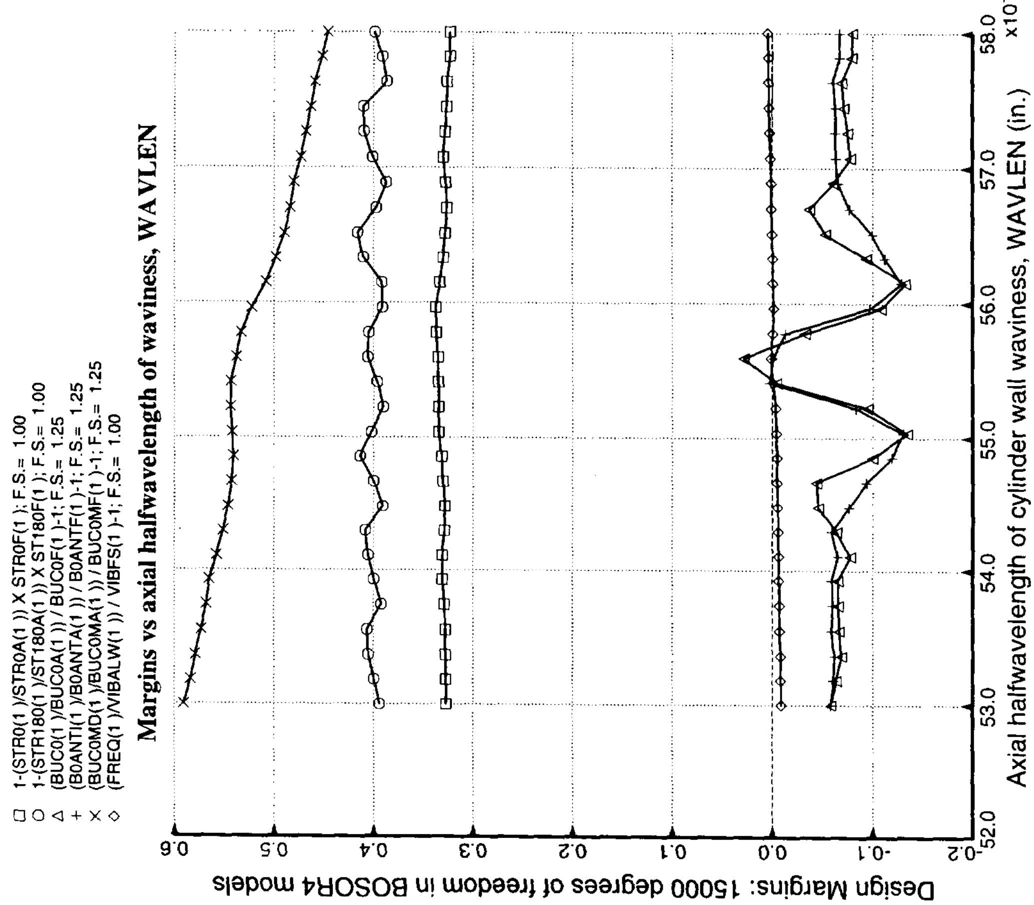
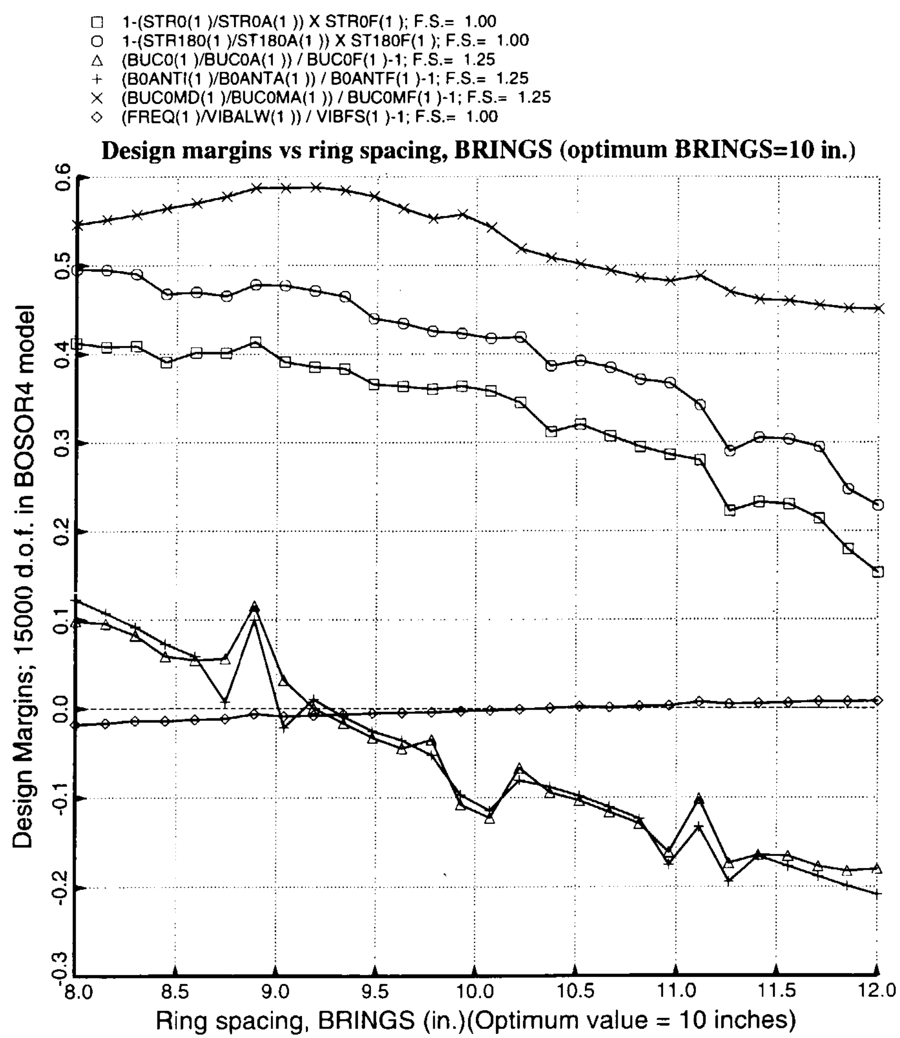
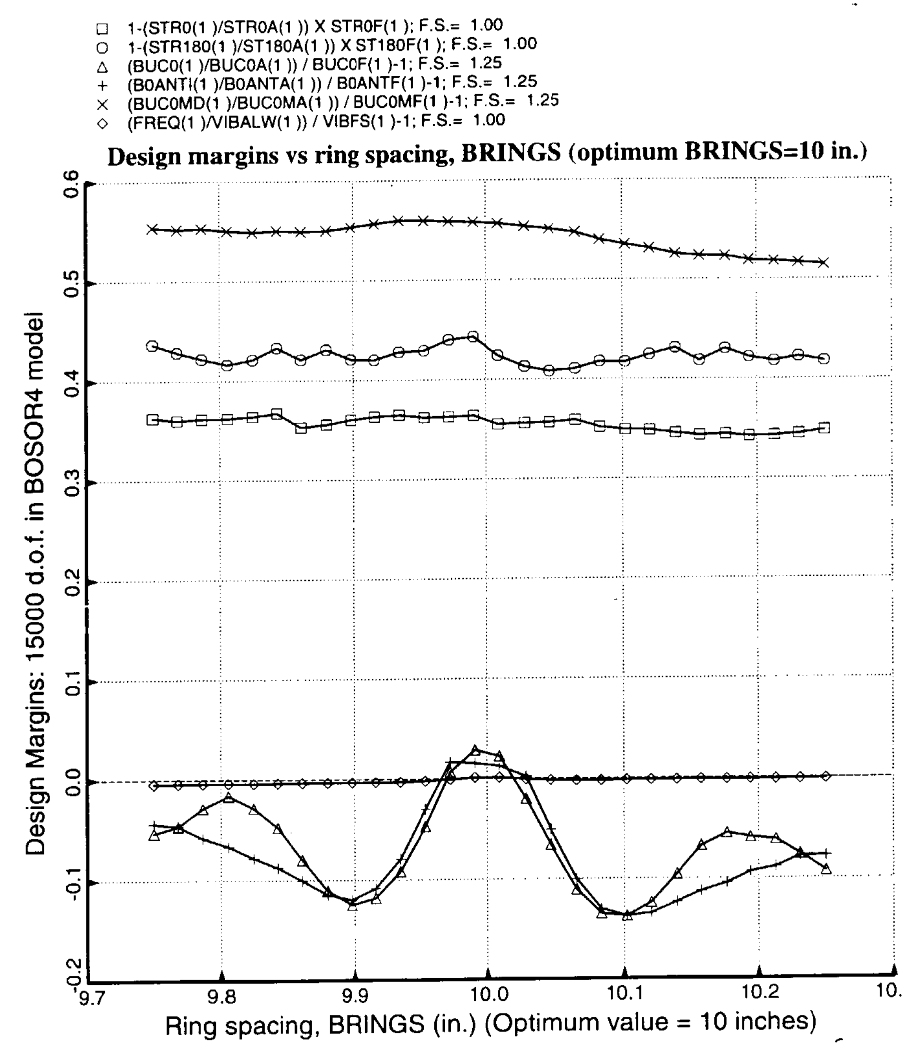

□ 1-(STR0(1)/STR0A(1)) X STR0F(1); F.S.= 1.00
○ 1-(STR180(1)/ST180A(1)) X ST180F(1); F.S.= 1.00
△ (BUC0(1)/BUC0A(1)) / BUC0F(1)-1; F.S.= 1.25
+ (B0ANTI(1)/B0ANTA(1)) / B0ANTF(1)-1; F.S.= 1.25
× (BUC0MD(1)/BUC0MA(1)) / BUC0MF(1)-1; F.S.= 1.25
◇ (FREQ(1)/VIBALW(1)) / VIBFS(1)-1; F.S.= 1.00
Margins vs axial halfwavelength of waviness, WAVLEN
Design Margins: 15000 degrees of freedom in BOSOR4 models
Axial halfwavelength of cylinder wall waviness, WAVLEN (in.)
x10^-2

FIG. 14



□ 1-(STR0(1)/STR0A(1)) X STR0F(1); F.S.= 1.00
○ 1-(STR180(1)/ST180A(1)) X ST180F(1); F.S.= 1.00
△ (BUC0(1)/BUC0A(1)) / BUC0F(1)-1; F.S.= 1.25
+ (B0ANTI(1)/B0ANTA(1)) / B0ANTF(1)-1; F.S.= 1.25
× (BUC0MD(1)/BUC0MA(1)) / BUC0MF(1)-1; F.S.= 1.25
◇ (FREQ(1)/VIBALW(1)) / VIBFS(1)-1; F.S.= 1.00
Design margins vs ring spacing, BRINGS (optimum BRINGS=10 in.)
Design Margins; 15000 d.o.f. in BOSOR4 model
Ring spacing, BRINGS (in.)(Optimum value = 10 inches)

FIG. 15



□ 1-(STR0(1)/STR0A(1)) X STR0F(1); F.S.= 1.00
○ 1-(STR180(1)/ST180A(1)) X ST180F(1); F.S.= 1.00
△ (BUC0(1)/BUC0A(1)) / BUC0F(1)-1; F.S.= 1.25
+ (B0ANTI(1)/B0ANTA(1)) / B0ANTF(1)-1; F.S.= 1.25
× (BUC0MD(1)/BUC0MA(1)) / BUC0MF(1)-1; F.S.= 1.25
◇ (FREQ(1)/VIBALW(1)) / VIBFS(1)-1; F.S.= 1.00
Design margins vs ring spacing, BRINGS (optimum BRINGS=10 in.)
Design Margins: 15000 d.o.f. in BOSOR4 model
Ring spacing, BRINGS (in.) (Optimum value = 10 inches)

FIG. 16