NEW CAPABILITIES AND MODIFICATIONS FOR NASTRAN LEVEL 17.5 AT DTNSRDC

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SUMMARY

Since 1970 DTNSRDC has been modifying NASTRAN to suit various Navy requirements. These modifications have included major new capabilities as well as user conveniences and error corrections. This paper describes the new features added to NASTRAN Level 17.5 at DTNSRDC. The subject areas of the additions include magnetostatics, piezoelectricity, fluid-structure interactions, isoparametric finite elements, and shock design for shipboard equipment.

INTRODUCTION

The David W. Taylor Naval Ship Research and Development Center (DTNSRDC) has been involved with NASTRAN since 1968. In the ensuing 3-4 years, prior to the first public release of the program in 1972, engineers at DTNSRDC gained valuable experience with NASTRAN, often interacting with the program developers on various theoretical, programming, and user aspects. The result of that early effort was a detailed NASTRAN evaluation report, which included a brief description of our first modification to NASTRAN--the addition of a heat transfer finite element to the NASTRAN element library (ref. 1).

In subsequent years, the DTNSRDC modifications to NASTRAN were many and varied, ranging from error correction and user conveniences to new finite elements and new functional modules and rigid formats.

Since Level 17.5 was released in the Spring of 1979, our NASTRAN modification effort has remained vigorous. The subject areas of new capabilities and uses include magnetostatics, piezoelectricity, fluid-structure interactions, isoparametric finite elements, and shock design of shipboard equipment. This paper describes these subject areas as we have implemented them into NASTRAN, sample applications of some of these areas, and the correction of an important program error. All of this work will be transferred to the DTNSRDC version of Level 17.6 after the standard version is released.

MAGNETOSTATICS

The prediction of static magnetic fields around ships and submarines is of concern to the Navy because of the need for these craft to remain undetected. A numerical procedure which can predict these fields can also be used to evaluate systems which might reduce the fields, e.g. degaussing coils. Such a procedure, making use of a scalar potential rather than the less efficient vector potential, was described in reference 2. Reference 3 describes a capability for computing the magnetostatic fields about axisymmetric structures that was added to NASTRAN. However, that work was limited to the TRAPRG and TRIARG finite elements and to axisymmetric current coils. In Level 17.5, the analysis has been extended to general built-up and continuum structures with general current coil configurations. The finite elements allowed are those available for NASTRAN heat transfer analysis (ref. 4), for reasons which may be seen from the brief description of the applicable theory which follows.

The applicable Maxwell equations governing the magnetostatic case are

$$\nabla \times H = J \tag{1}$$

$$\nabla \cdot B = 0 \tag{2}$$

where

- H = magnetic field strength or intensity
- B = magnetic induction or flux density
- J = current density

The constitutive relation

$$B = \mu H \tag{3}$$

where μ is the magnetic permeability is also required. If H is separated into two parts

$$H = H_c + H_m \tag{4}$$

where H_c, the field in a homogeneous region due to current density J (as might occur in a current coil), may be computed using the Biot-Savart law, (ref. 5), then H_m becomes the only unknown. By equations (1) and (4),

$$\nabla \times H_m = 0 \tag{5}$$

so that

$$H_m = \nabla \phi \tag{6}$$

where ϕ is a scalar potential. By equations (2), (3), (4), and (6),

$$\nabla \cdot \mu \nabla \phi + \nabla \cdot \mu H_c = 0 \tag{7}$$

which can be put into the standard form

$$K\phi = F \tag{8}$$

where

$$k_{ij} = \int_V (\nabla N_i)^T \mu (\nabla N_j) dV \tag{9}$$

$$f_i = -\int_V (\nabla N_i)^T \mu H_c dV \tag{10}$$

N_i being the displacement function for a finite element at the i^{th} grid point. Equation (9) is of the same form as that required to compute the conductivity matrix in heat transfer, with μ representing magnetic permeability rather than thermal conductivity. Equation (10), which is dependent on the finite element type, is not in a standard heat transfer form and was added to NASTRAN along with the new bulk data cards needed to specify H_c. Current coils may be defined, from which NASTRAN computes H_c using the Biot-Savart law, or H_c may be specified as coming from an ambient field, or a combination of both sources of H_c may be given.

Equation (6) gives the unknown H_m, which, in standard NASTRAN terminology, is the thermal gradient, and equations (4) and (3) yield the final result.

One unanticipated addition to NASTRAN was required when it was discovered that the program did not compute thermal gradients for the isoparametric solids IHEX1, IHEX2, and IHEX3, as needed by equation (6). An example of this capability is shown in figure 1. The finite element model depicts a solid sphere (shaded part) which has been placed into a uniform, ambient, axial magnetic field. TRIARG elements were used and only the upper half was modeled due to symmetry. The NASTRAN results are compared with theoretical results in Table 1.

PIEZOELECTRICITY

The analysis of sonar transducers requires accounting for the effects of their piezoelectric materials. The theory for these materials couples the structural displacements to electric potentials (ref. 6). This theory was incorporated into NASTRAN only for the TRIAAX and TRAPAX finite elements (ref. 7). These elements, trapezoidal and triangular in cross-section respectively, are solid, axisymmetric rings whose degrees-of-freedom are expanded into Fourier series, thus allowing nonaxisymmetric loads.

The piezoelectric constitutive relations may be written as

$$\begin{Bmatrix} \{\sigma\} \\ \{D\} \end{Bmatrix} = \begin{bmatrix} [c^E] & [e] \\ [e]^T & -[\varepsilon^S] \end{bmatrix} \begin{Bmatrix} \{\varepsilon\} \\ \{E\} \end{Bmatrix} \tag{11}$$

where $\{\sigma\}$ = stress components = $\lfloor \sigma_{rr}, \sigma_{zz}, \sigma_{\theta\theta}, \sigma_{rz}, \sigma_{r\theta}, \sigma_{z\theta} \rfloor^T$

$\{D\}$ = components of electric flux density = $\lfloor D_{rr}, D_{zz}, D_{\theta\theta} \rfloor^T$

$\{\varepsilon\}$ = mechanical strain components

$\{E\}$ = electric field components

$[c^E]$ = elastic stiffness tensor evaluated at constant electric field

$[e]$ = piezoelectric tensor

$[\varepsilon^S]$ = dielectric tensor evaluated at constant mechanical strain

The displacement vector of a point within an element is taken to be

$$\{\bar{u}\} = \begin{Bmatrix} u \\ v \\ w \\ \phi \end{Bmatrix} \tag{12}$$

where u, v, and w are the ring displacements in the radial, tangential, and axial directions, respectively, and ϕ is the electric potential. The latter degree-of-freedom is taken to be the fourth degree-of-freedom at each ring. Each of these quantities is expanded into a Fourier series with respect to the azimuth position θ. The Fourier series for the electric potential ϕ has the same form as the Fourier series for radial displacement u, as given in the NASTRAN Theoretical Manual (ref. 4).

The "stiffness" matrix for the N^{th} harmonic is

$$[K^{(N)}] = \pi \int_r \int_z [B^{(N)}]^T \begin{bmatrix} [c^E] & [e] \\ [e]^T & -[\varepsilon^S] \end{bmatrix} [B^{(N)}] \, r dr dz \tag{13}$$

where $[B^{(N)}]$ is the matrix of "strain-displacement" coefficients for the N^{th} harmonic.

Equations (12) and (13) indicate that the matrix equation to be solved for static analysis may be partitioned as follows:

$$\begin{bmatrix} [K_{\delta\delta}] & [K_{\delta\phi}] \\ [K_{\phi\delta}] & [K_{\phi\phi}] \end{bmatrix} \begin{Bmatrix} \{\delta\} \\ \{\phi\} \end{Bmatrix} = \begin{Bmatrix} \{F_\delta\} \\ \{F_\phi\} \end{Bmatrix} \tag{14}$$

where $\{\delta\} = \lfloor u_1, v_1, w_1, \ldots, u_n, v_n, w_n \rfloor^T$

$\{\phi\} = \lfloor \phi_1, \ldots, \phi_n \rfloor^T$

$\{F_\delta\}$ = vector of structural forces

and $\{F_\phi\}$ = vector of electrical charges

In addition to the new data cards describing the piezoelectric materials, many modifications and corrections to NASTRAN were made, including the computation of complex stresses and forces for the TRAPAX and TRIAAX elements.

An example of a piezoelectric problem is shown in figure 2. This is an axially polarized PZT-4 piezoelectric disk, whose natural frequencies are to be determined. Table 2 compares the NASTRAN results with experimental and MARTSAM results (ref. 8). MARTSAM uses finite elements similar to NASTRAN's TRIAAX and TRAPAX elements, but with quadratic displacement functions rather than the linear displacement functions in NASTRAN. The MARTSAM results were obtained with a much coarser mesh.

FLUID-STRUCTURE INTERACTION

Investigation of the coupling of fluid and structural effects has been an important part of the DTNSRDC program during the past few years. Applications include vibrations of submerged structures (refs. 9 and 10), shock response of submerged structures (refs. 11 and 12), and the response of fluid-filled pipes.

Although these new applications did not require additions to NASTRAN, they did involve inventive use of DMAP and unusual use of existing data cards. This relatively new subject area shows the power of NASTRAN and its DMAP capability to adapt to new uses without requiring modification of the source code.

ISOPARAMETRIC FINITE ELEMENTS

A number of additions and modifications have been made to NASTRAN in the area of isoparametric finite elements.

1. A two-dimensional membrane element IS2D8, with quadratic displacement functions, was added to the finite element library. This element has complete NASTRAN capability with the exception of piecewise-linear analysis. The element has been used in a number of applications where the CQDMEM1 element would have required a much finer mesh.

2. The standard version of NASTRAN computes grid point stresses of the isoparametric solids IHEX1, IHEX2, and IHEX3 directly at the grid points. However, it has been shown that the stresses computed at the grid points are inferior to stresses extrapolated to the grid points from stresses calculated at the Gauss integration points (ref. 13). This extrapolation method has been added to the program for the IHEX1, IHEX2, IHEX3, and IS2D8 elements.

3. The isoparametric solid elements are limited to isotropic materials in the standard version of NASTRAN. We have added a capability for rectangular anisotropy for those elements.

4. As mentioned in the Magnetostatics section, a thermal gradient computation has been added for the isoparametric solids.

5. Although Level 17.5 allows for the choice of single precision or double precision arithmetic for some computations, including element matrix generation, it did not allow this choice for the isoparametric solids; only double precision was allowed. Since DTNSRDC uses CDC computers with 60-bit single precision words, a single-double choice for these elements was added. Generation time for the single precision stiffness matrix for one IHEX2 element with three Gauss integration points was reduced on the CDC 6400 computer from 12 CPU seconds to 4.

SHOCK DESIGN OF SHIPBOARD EQUIPMENT

The Dynamic Design-Analysis Method (DDAM) was developed for the shock design of shipboard equipment (ref. 14). This method is similar in many respects to the techniques used in earthquake analysis. In fact, an earthquake analysis using NASTRAN has been performed (ref. 15). However, DDAM, rather than some variation of it, is required by naval shipbuilding specifications for shipboard equipment. Therefore, we are presently developing a DMAP procedure and a functional module to perform DDAM analyses.

Briefly, the steps in the DDAM method are as follows:

1. Compute the normal modes and natural frequencies.
2. For each mode, the i^{th}, for example, compute the participation factor

$$P_i = \frac{1}{m_i} \{\phi_i\}^T [M]\{D\} \tag{15}$$

where P_i = participation factor for the i^{th} mode

m_i = modal mass term for the i^{th} mode = $\{\phi_i\}^T[M]\{\phi_i\}$

$[M]$ = mass matrix

$\{\phi_i\}$ = i^{th} mode shape

$\{D\}$ = direction cosine vector defining desired direction (DDAM analyzes one direction at a time)

3. Calculate the effective mass and effective weight in each mode.

$$M_i^{eff} = P_i\{\phi_i\}^T[M]\{D\} = m_i P_i^2 \tag{16}$$

$$W_i^{eff} = g\, M_i^{eff} \tag{17}$$

where

M_i^{eff} = effective mass in i^{th} mode

W_i^{eff} = effective weight in i^{th} mode

g = acceleration of gravity

4. Using the effective weights just computed, locate the design spectrum value V_i for each mode in the desired direction.

5. Compute the effective static force for each mode.

$$\{F_i\} = P_i V_i \omega_i [M] \{\phi_i\} \tag{18}$$

where ω_i is the i^{th} natural frequency.

6. Perform a static analysis with each load to compute stresses. (There will be one static analysis for each desired mode in each desired direction.)

7. Compute the so-called NRL sum (ref. 16) of the stresses at each desired point (element centroids) as follows:

$$S_j = \left| S_{jm} \right| + \sqrt{\sum_{b}^{b \neq m} (S_{jb})^2}$$

where S_{jm} = the maximum stress at the j^{th} point (taken over the modes under consideration)

Two NASTRAN runs will be required for a complete DDAM analysis; the first will perform steps 1-3, and the second, steps 5-7. The D and V terms will be input through DMI cards, although some default values will be available for V. A post-processor, possibly included in NASTRAN as a new functional module, will perform the NRL sums in step 7.

ERROR CORRECTIONS

Numerous error corrections have been made to Level 17.5 by DTNSRDC and reported to COSMIC, but perhaps the most important involved the stiffness matrix computation for the six elements QDMEM1, QDMEM2, SHEAR, TWIST, TRAPAX, and TRIAAX. The method of matrix computation for these elements was changed from SMA-type in Level 17.0 to EMG-type in Level 17.5. The change introduced an error which occurred only for certain combinations of grid point numberings for these elements.

All the error corrections reported to COSMIC are expected to appear in the forthcoming Level 17.6.

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Table 1. Ferromagnetic Sphere Results

DATA POINT	ANALYTIC SOLUTION		NASTRAN SOLUTION		DEVIATION	
1	0.396 TESLA	56.3°	0.396 TESLA	59.0°	0.0%	2.7°
2	0.843	52.7	0.840	53.5	0.3	0.8
3	1.488	0.0	1.537	0.0	3.3	0.0
4	0.523	86.9	0.527	87.1	0.7	0.2
5	0.941	76.5	0.921	76.3	2.1	0.2
6	0.417	79.2	0.409	80.6	1.9	1.4
7	0.571	74.6	0.579	74.5	1.5	0.1
8	0.705	83.7	0.697	83.6	1.1	0.1
9	0.479	86.7	0.483	86.8	.7	0.1
10	0.526	85.3	0.532	85.4	1.1	0.1
11	0.566	88.3	0.562	88.5	0.7	0.2
12	0.492	89.3	0.499	89.3	1.5	0.1
13	0.499	88.6	0.505	88.6	1.3	0.0
14	0.516	89.1	0.523	89.0	1.6	0.1

Table 2. Natural Frequencies of Piezoelectric Disk

Mode	Natural Frequencies (cps)		
	Experimental	MARTSAM Mesh	NASTRAN Mesh
1	22042	23298	24323
2	-----	59805	61114
3	-----	103048	104689

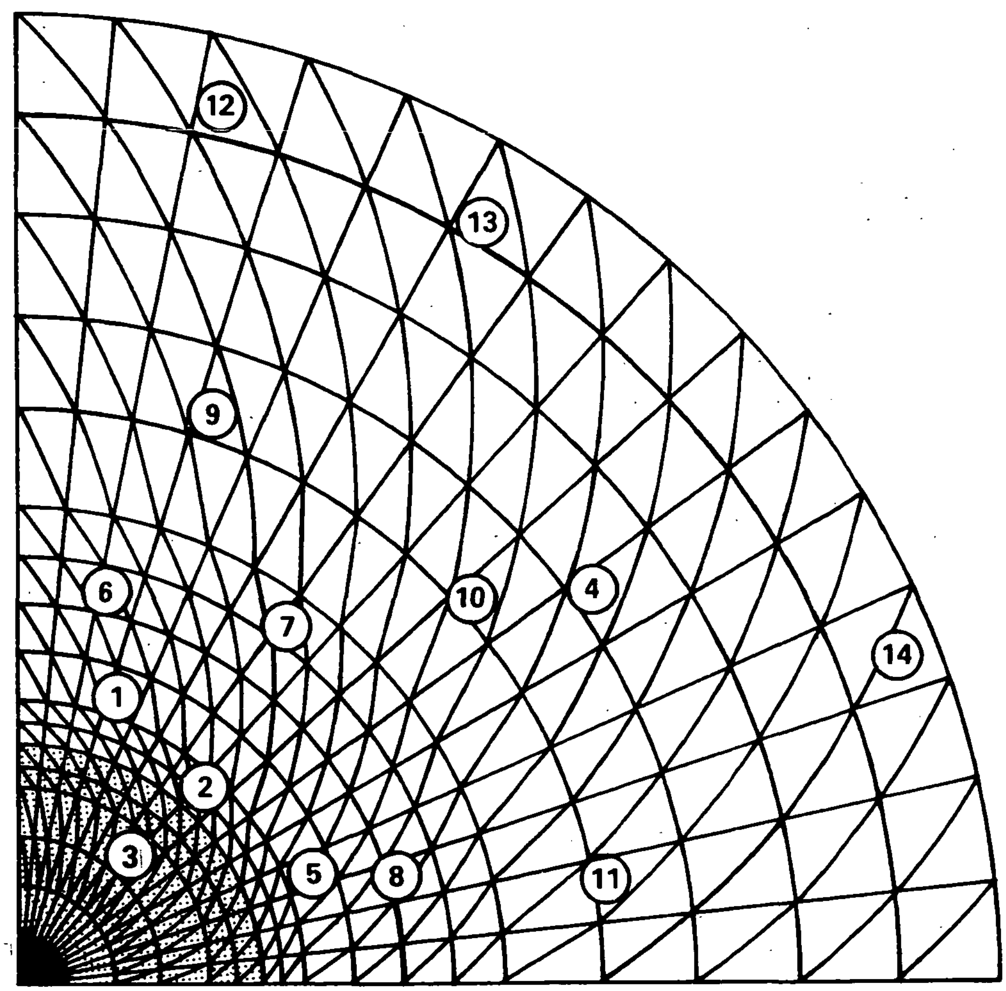

Figure 1 — Finite Element Mesh of Ferromagnetic Sphere

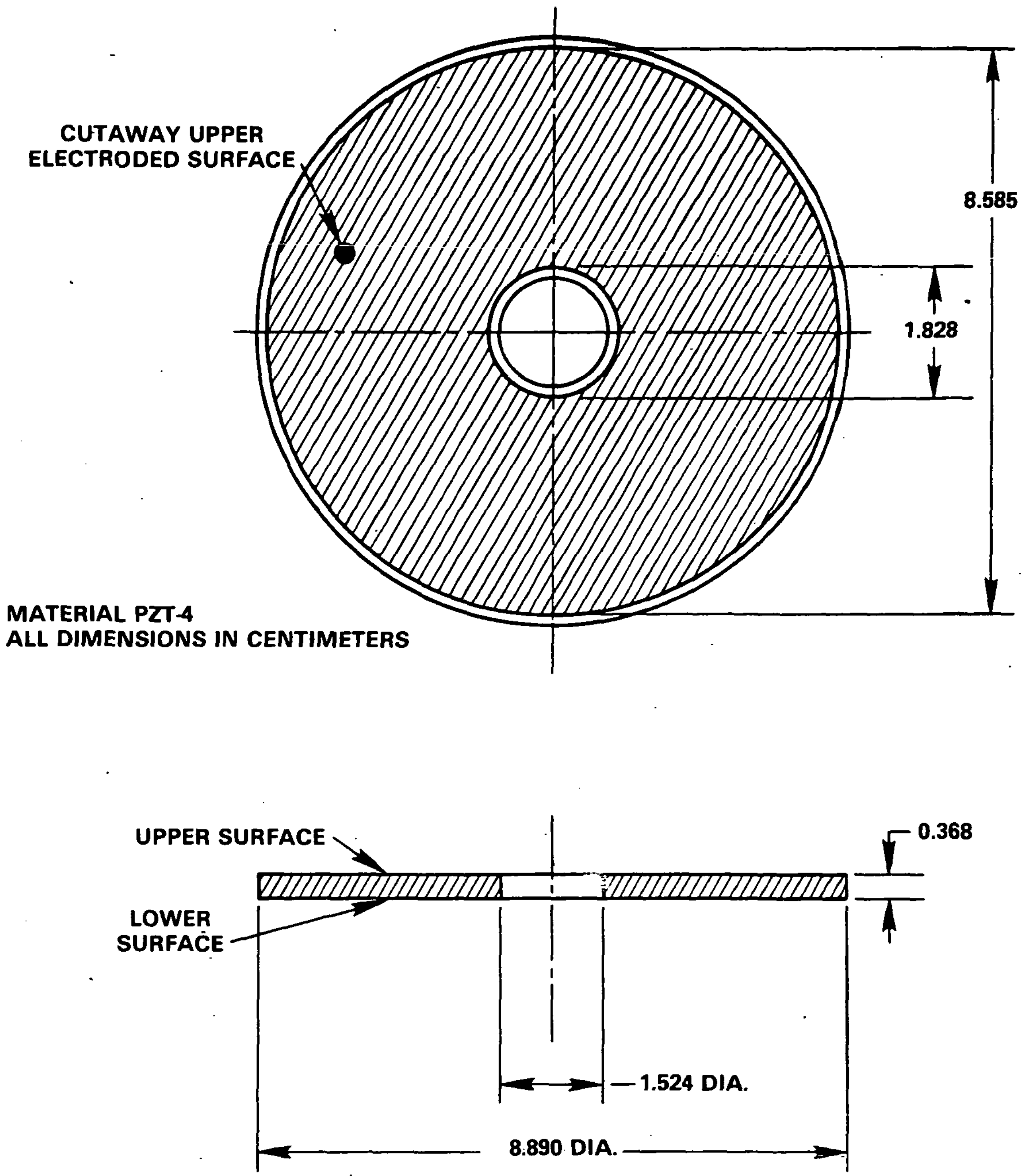

Figure 2 - Piezoelectric Disk