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SOLVING MAGNETOSTATIC FIELD PROBLEMS WITH NASTRAN

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SUMMARY

Determining the three-dimensional magnetostatic field in current-induced situations has usually involved vector potentials, which can lead to excessive computational times. A recent paper shows how such magnetic fields may be determined using scalar potentials. The present paper shows how the heat transfer capability of NASTRAN Level 17 has been modified to take advantage of the new method.

INTRODUCTION

All classical electromagnetic phenomena are governed by the four Maxwell equations:

$$\nabla \times H = J + \frac{\partial D}{\partial t} \tag{1}$$

$$\nabla \times E + \frac{\partial B}{\partial t} = 0 \tag{2}$$

$$\nabla \cdot D = \rho \tag{3}$$

$$\nabla \cdot B = 0 \tag{4}$$

where the vector quantities are defined as follows:

- H Magnetic field strength or intensity
- B Magnetic induction or flux density
- J Current density
- E Electric field strength
- D Electric displacement

and the scalar quantities are defined as follows:

- ρ Charge density
- t Time

There is also a constitutive relation between B and H, given by

$$B = \mu H \tag{5}$$

where μ is the magnetic permeability.

Electromagnetic problems are often solved by introducing and solving for the magnetic vector potential A, where

$$B = \nabla \times A \tag{6}$$

Spreeuw and Reefman (ref. 1) used this method with NASTRAN in solving for harmonically oscillating electromagnetic fields in the presence of conductors carrying alternating currents. However, in order to use the existing structural and heat transfer capabilities in NASTRAN, simplifying assumptions had to be made. In particular, the magnetic vector potential A and the source current densities J were allowed to have components in only one direction, and those components were invariant in that direction. These assumptions effectively reduce the problem to one of solving for a scalar potential, which can be handled by NASTRAN's heat transfer analyses.

In the same paper, Spreeuw and Reefman also considered a problem in which A was not unidirectional and were able to use NASTRAN's structural analysis capability only because the governing equations uncoupled for the components of A.

Another problem with this formulation is the requirement that

$$\nabla \cdot A = -\varepsilon\mu\frac{\partial\phi}{\partial t} \tag{7}$$

where ε is the electric permittivity.
Spreeuw and Reefman used a separate post-processor to handle this condition. Frye and Kasper (ref. 2), in solving magnetostatic problems using the vector potential, use a Lagrange multiplier method (similar to multi-point constraints) to satisfy constraint (7). They also point out that special boundary conditions are required at boundaries where the permeability μ changes.

In reference 3, Zienkiewicz, Lyness, and Owen have developed a method for solving general, three-dimensional magnetostatic problems using scalar potentials, so that standard heat transfer analyses may be used and constraint equation (7) is not required. They also indicate that special boundary conditions, such as those mentioned in reference 2, are not needed.

The present paper shows how this new method has been implemented in NASTRAN Level 17.

BASIC EQUATIONS AND ASSUMPTIONS

The problem to be solved is the determination of the magnetostatic field due to a body placed in an existing magnetic field produced, for example, by direct current-carrying loops. The materials are assumed to be linear, but may be anisotropic. The governing equations are:

$$\nabla \times H = J \tag{8}$$

$$B = \mu H \tag{9}$$

$$\nabla \cdot B = 0 \tag{10}$$

Zienkiewicz separates H into two parts,

$$H = H_c + H_m \tag{11}$$

H_c is the field in a homogeneous region due to current J, satisfies

$$\nabla \times H_c = J \tag{12}$$

and is computed using the Biot-Savart law. H_m is the unknown magnetic field strength and satisfies

$$\nabla \times H_m = 0 \tag{13}$$

so that

$$H_m = \nabla\phi \tag{14}$$

and

$$\nabla \cdot \mu \nabla\phi + \nabla \cdot \mu H_c = 0 \tag{14a}$$

where ϕ is the scalar potential. Zienkiewicz then uses standard variational principles, with equations (9) and (10), to arrive at the standard finite element form

$$K\phi = F \tag{15}$$

where K is the "stiffness" matrix,

F is the "load" vector, and

$$k_{ij} = \int_V (\nabla N_i)^T \mu \, \nabla N_j dV \tag{16}$$

$$f_i = \int_V (\nabla N_i)^T \mu \, H_c dV \tag{17}$$

where

N_i is the finite element shape function for the i^{th} grid point, and

V is the volume of the finite element.

The formulation (16) for k_{ij} is exactly that of the standard heat transfer conductivity matrix with magnetic permeability μ playing the role of thermal conductivity. The formulation (17) for f_i, however, is not a standard heat transfer quantity and must be computed either in a separate program and input to NASTRAN or in a new NASTRAN capability. Also, note that f_i is element-dependent, as evidenced by the shape function gradient in equation (17).

Equation (15) is solved for ϕ subject to standard natural or forced boundary conditions. H_m can then be computed from equation (14), and the final results can be obtained using equations (11) and (9).

NASTRAN IMPLEMENTATION

To solve magnetostatic problems with NASTRAN Level 17 using the methods of the previous section, we select rigid format 1, HEAT approach. However, we have modified the program to

1) compute the H_c field due to circular, direct current-carrying loops;
2) accept a specified H_c field;
3) compute f_i (equation (17)) for the axisymmetric solid ring elements TRAPRG and TRIARG;
4) perform the addition specified in equation (11), where H_m is a transformation of the "temperature" gradients; and
5) output B (equation (9)) for subsequent NASTRAN plotting.

The implementation thus far has been limited to solid axisymmetric problems using TRAPRG and TRIARG finite elements and is running on the DTNSRDC CDC 6000 computers.

NEW BULK DATA CARDS

Two new bulk data cards have been introduced into the program for computing H_c fields. They are CEMLOOP, for computing the H_c fields due to circular current loops, and SPCFLD, for specifying H_c at selected grid points. (See figures 1 and 2 for detailed descriptions of these cards.)

MODIFIED NASTRAN ROUTINES

Nineteen existing NASTRAN routines have been modified to accommodate the new capability. The routines and the nature of the modifications are as follows:

Routine	Reason for Change
IFP,IFS4P,IFX1BD-IFX7BD	Recognize and check new bulk data cards CEMLOOP and SPCFLD.
LD21	Restart with CEMLOOP and SPCFLD in Static Heat Transfer Analysis.
GP3A,GP3BD	Recognize CEMLOOP and SPCFLD as "heat transfer" load specifications and place on HSLT (Heat Static Load Table).

Routine	Reason for Change
SSGSLT	Retrieve CEMLOOP and SPCFLD specifications from HSLT. CEMLOOP cards are copied directly to data block NEWSLT for later processing. All SPCFLD specifications are combined into one vector giving total H_c at all grid points. This vector is placed on NEWSLT.
EXTERN	Call new routine EANDM, which retrieves CEMLOOP and SPCFLD specifications from NEWSLT and computes f as given in equation (17).
XBSBD, XMPLBD	Specify table updates so that NASTRAN will recognize new functional module EMFLD.
XSEM14	Call new functional module EMFLD.
OFP1A	Specify new headings to output new data block HOEH1 giving magnetic field strength and induction.
OFPZZZZ	Call for new headings from OFP1A when HOEH1 is recognized.

NEW ROUTINES

Three new routines have been developed. Subroutine EANDM reads into open core CEMLOOP and SPCFLD data from data block NEWSLT, reads information for an element from the Element Summary Table (EST), and calls an element-dependent routine to compute the load as given in equation (17).

Subroutine EMRING is called by EANDM and computes the load due to CEMLOOP and SPCFLD specifications for solid axisymmetric trapezoidal (TRAPRG) and triangular (TRIARG) rings. We assume that H_c is constant over an element. Therefore, for TRIARG elements, H_c is computed at the centroid due to all CEMLOOP's using an elliptic integral formulation. If SPCFLD's are given, H_c is computed to be the average of the H_c's at the three vertices. Each TRAPRG element is divided into four overlapping triangles, and each triangle is treated as a TRIARG element. Once H_c has been computed for a triangle, equation (17) is used to compute the load at each grid point forming the triangle. Subroutine EMRING also outputs to Fortran file 11 certain element information, including H_c, for later processing by functional module EMFLD. This is a temporary method for passing information from EMRING to EMFLD. The normal method, of course, is to use data blocks. However, subroutine EMRING resides in functional module SSG1, and adding a new output data block to that existing module would require a change to every rigid format in the program. These changes will be made at a later time.

Subroutine EMFLD, which is also a new functional module, computes the magnetic field strength and induction, according to equations (11) and (9), for each finite element in the model. EMFLD retrieves from data block HOEF1 the "temperature" gradient for an element. Since the gradient H_m was computed in an element coordinate system, EMFLD transforms it into basic coordinates. Then Fortran file 11 is searched to match the element identification number, and, on a match, H_c for the element is retrieved, added to the transformed H_m, and put out to data block HOEH1. Also computed and output to HOEH1 is the magnetic induction B. HOEH1 is later output using normal Output File Processor (OFP) execution. EMFLD also computes and outputs other information for plotting purposes, as explained in the next section.

PLOTTING MAGNETOSTATIC RESULTS

Normal NASTRAN plot processing allows for deformed plots based on grid point displacements or contour plots of stresses. In the present analysis, however, the "displacements" (the scalar potentials) are of little use by themselves. The "stresses" (H or B fields coming from EMFLD) are more useful, but what we would really like to see for "nice" plots are the lines of induction. The lines of induction indicate the direction of the magnetic induction B, and the number of lines per unit area indicates the magnitude of B. While we do not presently plot these lines of induction, we do plot the actual induction, magnitude and direction, for each element. Therefore, functional module EMFLD outputs other quantities as follows. For each element, two coincident grid points are created at the centroid of the element, and the corresponding GRID cards are punched. Also punched is a PLOTEL card connecting the two grid points. (The length of the PLOTEL element is zero.) Then a "displacement" vector is created by assigning zero values to each of the original grid points in the model and assigning the magnetic induction value for an element to each of the two coincident grid points created for the element. (The "displacement" vector uses six degrees of freedom per grid point since B is a vector, not a scalar.) This vector is packed in EMFLD and output in DMAP using module OUTPUT1. On a subsequent NASTRAN run, the new GRID and PLOTEL cards are merged with the original data, the "displacement" vector is retrieved using DMAP module INPUTT1 as data block UGV, and a deformed plot is requested with the VECTOR R option. This NASTRAN run is performed with rigid format 1, DISP approach, and ALTERs are used to execute only those modules required for deformed plots. The plots show the original structure as an underlay, and a vector is drawn at each element centroid indicating the magnitude and direction of B in that element.

SAMPLE PROBLEMS

At the time that this paper was being prepared, the only axisymmetric problems run with NASTRAN for which analytical results were readily available were problems with uniform permeability. The comparison between the NASTRAN and analytical results was very good. Although problems with nonuniform permeability have been run with NASTRAN and "reasonable-looking" results have been obtained, analytical results, required for verification, are still forthcoming.

REFERENCES

1. Spreeuw, E.; and Reefman, R.J.B.: Rigid Format Alter Packets for the Analysis of Electromagnetic Field Problems. Fourth NASTRAN Users' Colloquium, NASTRAN: Users' Experiences, NASA TM X-3278, September 1975, pp. 557-570.

2. Frye, J.W.; and Kasper, R.G.: Analysis of Magnetic Fields Using Variational Principles and CELAS2 Elements. Sixth NASTRAN Users' Colloquium, NASA Conference Publication 2018, October 1977, pp. 175-192.

3. Zienkiewicz, O.C.; Lyness, John; and Owen, D.R.J.: Three-Dimensional Magnetic Field Determination Using a Scalar Potential - A Finite Element Solution. IEEE Transactions on Magnetics, Vol. MAG-13, No. 5, September 1977, pp. 1649-1656.

Input Data Card CEMLOOP Circular Current Loop

Description: Defines a circular current loop in magnetic field problems.

Format and Example:

1	2	3	4	5	6	7	8	9	10
CEMLOOP	SID	J	AXI	X1	Y1	Z1	X2	Y2	+A
+A	Z2	XC	YC	ZC	CID				
CEMLOOP	3	2.5	1	5.2	0.	2.25			

Field	Contents
SID	Load set identification number (integer > 0).
J	Current through loop (units of positive charge/sec)(real ≥ 0).
AXI	= 0 nonaxisymmetric problem (not yet implemented) = 1 axisymmetric problem; TRAPRG and TRIARG elements are implied (integer).
X1,Y1,Z1 X2,Y2,Z2	Coordinates of two points through which the loop passes (given in coordinate system CID)(real).
XC,YC,ZC	Coordinates of center of loop (given in coordinate system CID) (real).
CID	Coordinate system identification number (integer ≥ 0).

Remarks:

1. Load sets must be selected in the Case Control Deck (LOAD=SID) to be used by NASTRAN.

2. If AXI=1, Y1 must be 0. or blank, and all data fields after Z1 must be 0. or blank. (Continuation card need not be present.)

Figure 1. Bulk Data Description of CEMLOOP

Input Data Card SPCFLD Specified Magnetic Field

Description: Specifies magnetic field at selected grid points.

Format and Example:

1	2	3	4	5	6	7	8	9	10
SPCFLD	SID	HCX	HCY	HCZ	G1	G2	G3	G4	
SPCFLD	18	12.25	0.	62.	8	17	103	1	

or

SPCFLD	SID	HCX	HCY	HCZ	GID1	THRU	GID2		
SPCFLD	18	12.25	0.	62.	9	THRU	27		

or

SPCFLD	SID	HCX	HCY	HCZ	-1				
SPCFLD	18	12.25	0.	62.	-1				

Field	Contents
SID	Load set identification number (integer > 0).
HCX,HCY,HCZ	Components of specified H_c field (real).
Gi,GIDi	Grid point identification numbers (integer > 0).
-1	Implies the H_c field applies at all grid points.

Remarks:

1. Load sets must be selected in the Case Control Deck (LOAD=SID) to be used by NASTRAN.

2. All grid points referenced by GID1 THRU GID2 must exist.

Figure 2. Bulk Data Description of SPCFLD