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A THREE-DIMENSIONAL FIELD PROGRAM*

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Summary

The high-energy microtrons studied at Argonne National Laboratory (ANL) require complicated magnetic field shapes. A three-dimensional infinite-permeability magnetic-field program was written to show that poles and coils can be devised to produce these fields. The program is in Hewlett-Packard 9845B BASIC, which limits the active mesh to about 30 000 points. In some problems the number of useful points can be greatly increased by placing virtual points one plane beyond the active mesh.

The regular cubic mesh is described by three arrays. One is a scalar potential array, H , which is derived from ampere-turns by using current cuts. Another is an information array, I , and the third is a list, L , containing other data. This data structure is similar to the Carnegie Magnet Program.¹ An element from I usually contains a bit string with directions for calculating the corresponding H . However, if more data are required, then the word from I is interpreted as the address in L where the required data are stored. Parts of L can be reused when two or more points require the same data. The organization of the data is shown in Fig. 1. This organization minimizes memory requirements and makes the calculation fast for most points.

The program has four parts: (1) prepare the problem description file, (2) load the starting mesh, (3) relax the mesh, and (4) output results.

Preliminary results indicate that the magnet edge can be quite "hard" and suggest that the required field shapes can be produced.

Problem Description File

The problem description file consists of a sequence of 160-character records. The first is the name of the problem; the second contains the dimensions of the mesh and default boundary conditions on

the mesh surface. A record that references a function of distance must be preceded by a record that defines the function. A function of distance is input as a series of breakpoints and remains in force until it is overwritten. The sequence also may be important because, when the mesh is generated, later records may cause previously stored data to be overwritten. This can produce unexpected results or can leave unused data in L .

The structures defined are contained in boxes that are four-sided right cylinders with the generatrix parallel to the Z -axis. The box is completed by a bottom Z -plane and a top Z -plane. If a box extends outside the mesh, there is a provision for describing constant-potential virtual points one step beyond the mesh.

The program can generate records that describe five structures. The last four structures require a predefined function of distance:

(1) All mesh points or virtual points within the box will be assigned the same constant potential; that is, a potential does not vary during relaxation.

(2) Each mesh point or virtual point within the box will be assigned a constant potential that depends on the perpendicular distance from the point to a given reference surface. This surface may be any one of the six surfaces of the box.

(3) Each mesh point or virtual point within the box will be assigned a constant potential that depends on the radial distance from the point to a given reference (X,Y) corner of the box.

(4) A current cut will be associated with each mesh point within the box. The value of the current cut will depend on the distance from the mesh point to the given reference surface of the box.

(5) A current cut will be associated with each mesh point within the box. The value of a current cut will depend on the radial distance from a mesh point to the given (X,Y) corner of the box.

Index, Type	H	INFORMATION, I	LIST, L
0, -	H_0	I_0	
1, -	H_1	I_1	
2, -	H_2	I_2	
:	:	:	:
1, Interior point	H_1	$I_1=000 \dots 000$	
:	:	:	
k, Constant H	H_k	$I_k=111 \dots 111$	
:	:	:	
s, Simple boundary	H_s	I_s = Bit string	
:	:	:	
c, Complex point	H_c	I_c = List index	
:	:	:	
d, Same data	H_d	I_d = Same index	
:	:	:	
x, Current cut	H_x	I_x = List index	
:	:	:	

Fig. 1. Mesh data organization.

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Figure 2 shows the appearance of the display during an input operation. At the top of the screen are the numbers 0 through 15. These correspond to the computer's special function keys. Under the numbers are brief indications of the operations. There are several pages of functions. This page is for INPUT. If Key 6 is selected, a row of asterisks will be printed under 6, and directions for the input will be presented below. The first field, code, in the bottom line is supplied by the program. The remaining fields must be filled in to produce the desired structure.

The operation CHECK is on another page. This will produce, for one or more records, a readable list and a three-dimensional plot of the structures in the problem description file. Figure 3 shows an enhanced plot of all of the structures used to describe a corner in the microtron magnet. The pole is top right and has a notch under the corner for the coil. A guard, bottom left, wraps around the coil. The coil runs up and to the left. It is represented, in part, by a keystone-shaped sheet of current cuts that sticks out the top of the mesh and extends to the right, into the pole. The coil description is completed by constant potentials in the pole (that overwrite some current cuts). The net current cut, used in this program, does not contain enough information to calculate fields inside of the coil.

Starting Mesh

The starting mesh consists of three arrays: H, I, and L. The H and L arrays are stored with SHORT precision to save memory. SHORT precision in the HP9845 is a floating point number with six decimal digits. In the range -1.000000 and +1.000000 inclusive, SHORT precision can express numbers with a maximum least count of one part in 2 000 000. Because this precision cannot be improved, H is scaled to lie in this range. SHORT precision numbers also can express strings with 20 bits. The array, I, has INTEGER precision. Its elements have 16 bits and can express integers from -32768 through 32767.

Relaxation calculations are directed by bit strings. The bit string is either the I associated with a point or else it is in L. If Bit 15 in I is 1, then -I is the index of the bit string in L.

(1) If the bit string is 0 0000 0000 0000, then the point is an interior point with $\mu = 1$ in all directions.

Fig. 3. CHECK output for a corner in microtron pole.

(2) In other cases, when Bit 15 is zero, the string has the structure

0 zzzz yyyy xxxxx .

If zzzz is nonzero, then a special calculation is used on the Z-axis. Similarly, if yyyy or xxxxx is nonzero, then a special calculation is used on the corresponding axis. Only a few of the possible meanings are exploited:

Bits: zzzz	Meaning of bit sequence
11zzz	Special calculation on the positive axis.
10zzz	Special calculation on the negative axis.
zz000	H in the indicated direction is -1.
zz001	H in the indicated direction is 1.
zz010	A two-dimensional boundary plane.
zz011	Reflect one-half step out of the mesh.

INPUT							
0	1	2	3	4	5	6	7
NAME	MESH	f(*)	H=const.	strt. H	circ. H	strt.CUT	circ.CUT

8	9	10	11	12	13	14	15
BOX	LIST	INSERT	DELETE	EDIT	*EDITLN*	*SET*	*FILES*

USING THE ACTIVE FUNCTION OF DISTANCE
FOR A BOX WITH STRAIGHT CURRENT CUTS TANGENT TO:

SIDE = 1: (X1,Y1)(X2,Y2)	SIDE = 2: (X2,Y2)(X3,Y3)
SIDE = 3: (X3,Y3)(X4,Y4)	SIDE = 4: (X4,Y4)(X1,Y1)
SIDE = 5: Zmin	SIDE = 6: Zmax

INPUT SIDE NUMBER

INPUT MINIMUM Z AND MAXIMUM Z, Zmax >= Zmin

INPUT COORDINATES OF CORNERS: X1, Y1, X2, Y2, X3, Y3, X4, Y4

				X2>X1	Y3>Y2	X4<X3	Y1<Y4
--	--	--	--	-------	-------	-------	-------

CODE	SIDE	Zmin	Zmax	X1...	Y1...	X2...	Y2...	X3...	Y3...	X4...	Y4...
13	4	9	9	20	0	31	0	31	42	-4	42

Fig. 2. An input operation.

These strings are used primarily to direct calculations on the surface of the mesh.

(3) If the bit string from I is 1 1111 1111 1111, then the associated potential is constant. This bit string is used for boundary points and for other points where no relaxation is required.

(4) When the bit string is in L, then Bit 15 has two different meanings:

(a) When Bit 15 is 0, then H in the positive Z direction is in L and has a value between minus one and one; xxxxx and yyyyy have the same meaning as in (2).

(b) If Bit 15 is 1, then the current cut from L is used in calculating the potential. The remaining bits have the same meaning as in (2).

Relaxing the Mesh

The equation for relaxing the mesh is

$$HO' = \left(\frac{H1 + H2 + H3 + H4 + H5 + H6 + X}{6} - HO \right) \cdot Q + HO.$$

Here HO' is the new value for the potential,

HO is the old value for the potential, and

H1, H2, H3, H4, H5, and H6 are the potentials of the nearest neighbors.

X is the net current cut.

Q is the overrelaxation constant.

The potentials, H, are relaxed according to instructions in the bit strings. Values of H beyond the boundary, if required, are implied in I or are given in L. Current cuts are in L. In the case of a two-dimensional boundary, the unused values of H are eliminated and the sum is divided by 4. In the case of a reflecting plane one-half step beyond the boundary, H in the direction of the boundary is eliminated, and the sum is divided by 5.

Relaxation of the mesh is performed in a number of steps. For each step, the number of relaxations and the relaxation constant may be specified. Whether or not the errors are to be calculated also can be specified. This process requires ~10 h.

Output

Programs have been written to print tables of H and to plot some contours. Figure 4 shows ampere-turn contours in the pole-surface plane for the example shown in Fig. 3. For a good edge, the contours in the center of the figure should be straight and horizontal. They could be improved by shims on the corners of the pole and guard. The same result is illustrated in Fig. 5, which shows contours of dB_x/dz . This quantity should be zero along the orbits in an ideal field.

Conclusions

Although this program is useful, it is clear also that it is very limited. The data structure allows additional capabilities to be added, if they are consistent with the memory size and computing speed of the HP9845.

Fig. 4. Potential contours in the pole-face plane.

Fig. 5. Contours of dB_x/dz .

Reference

1. M. H. Foss, "Carnegie Magnet Program," Proc. Second International Conference on Magnet Technology, Oxford, England, p. 102, (1967).