Team Problem 20

3-D Static Force Problem

1. General description

The model is shown in Fig.1. The center pole and yoke are made of steel. The coil is excited by a dc current. The ampere-turns are 1000, 3000, 4500 and 5000 which is sufficient to saturate the steel.

The problem is to calculate the magnetic field and electromagnetic force.

2. Analyzed Region and Boundary Conditions

If a symmetrical boundary condition can be used, the 1/4 region shown in Fig. 2 is sufficient for analysis.

3. Mesh description

The mesh is not specified.

4. Nonlinearity

The B-H curve of the steel shown in Fig. 3 is to be used. The typical values of B(T) and H(A/m) are also shown in Table 1. The curve at high *flux* densities (B>2.3T) cannot be measured and is approximated by the following equation:

$$B = \mu_0 H + Ms \qquad (1)$$

where μ_0 is the magnetic constant and Ms is the saturation magnetization (2.16T).

5. Ouantities to be Calculated

To compare results, please complete Tables 2, 3, 4 and 5. Fig. 4 shows the positions at which the flux density should be calculated.

6. Description of Computer Program

To compare formulations, variables, etc., please complete Table 6. The used memory in item No.16 in Table 6 is defined as the sum of dimensions declared in the program.

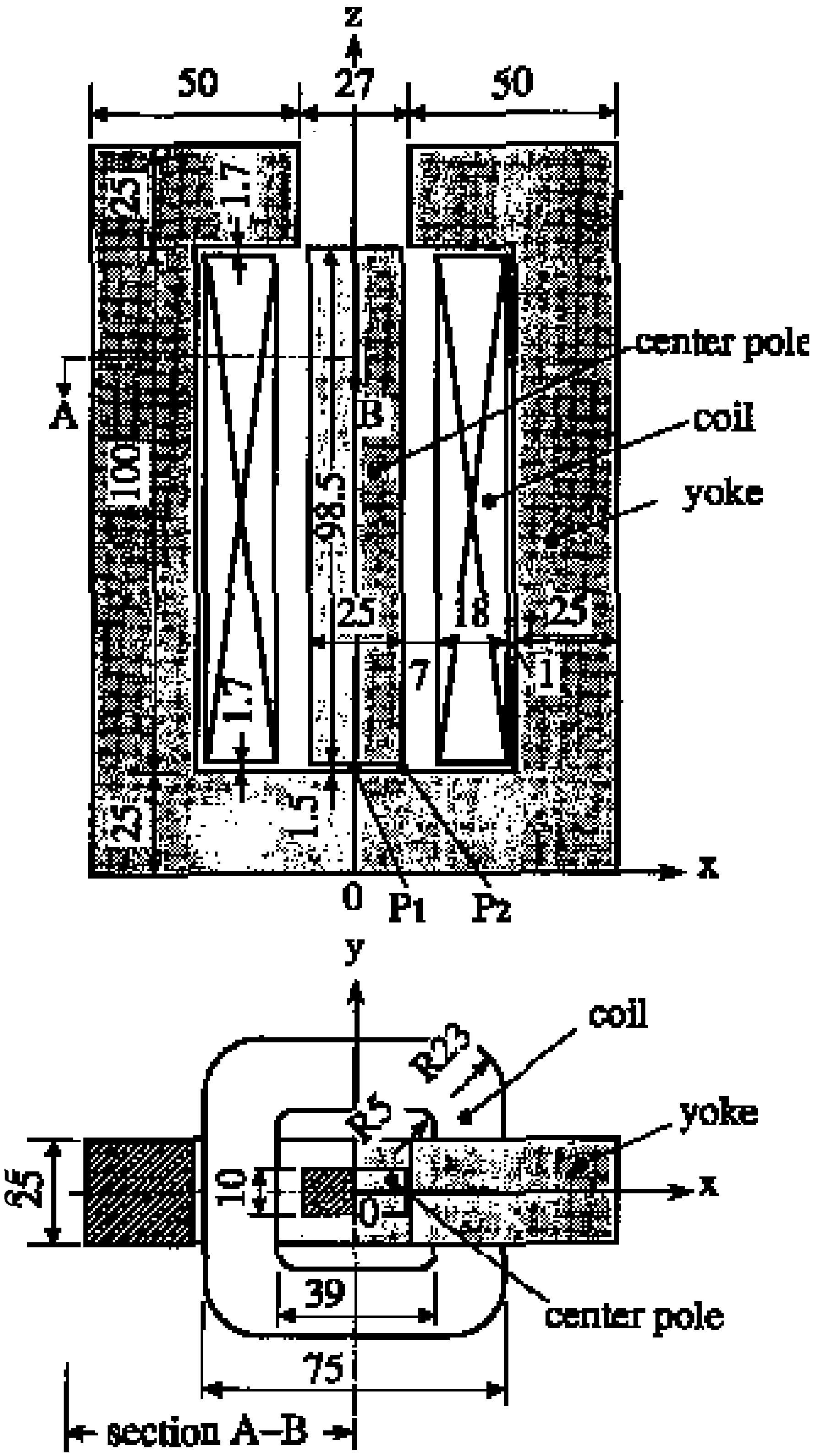
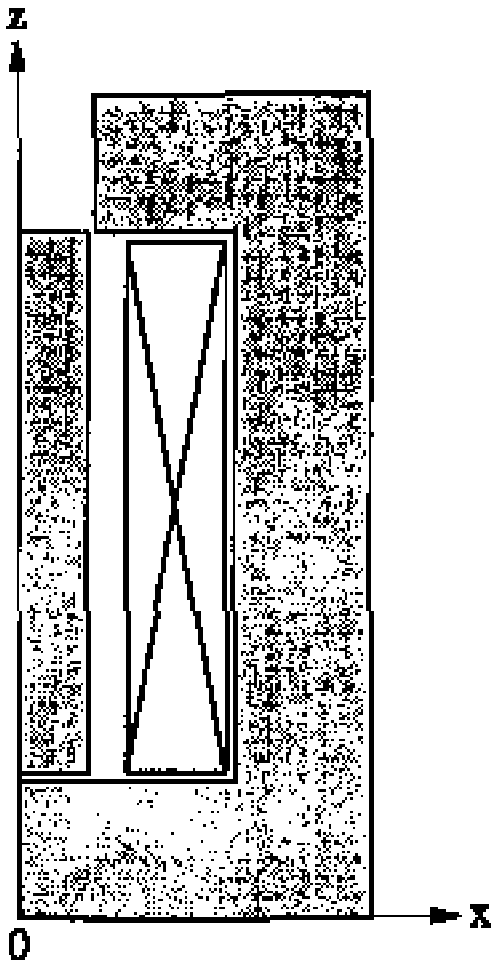
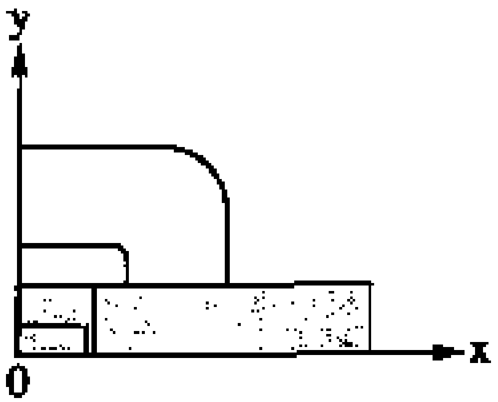


Fig. 1. 3-D model for verification of force calculation

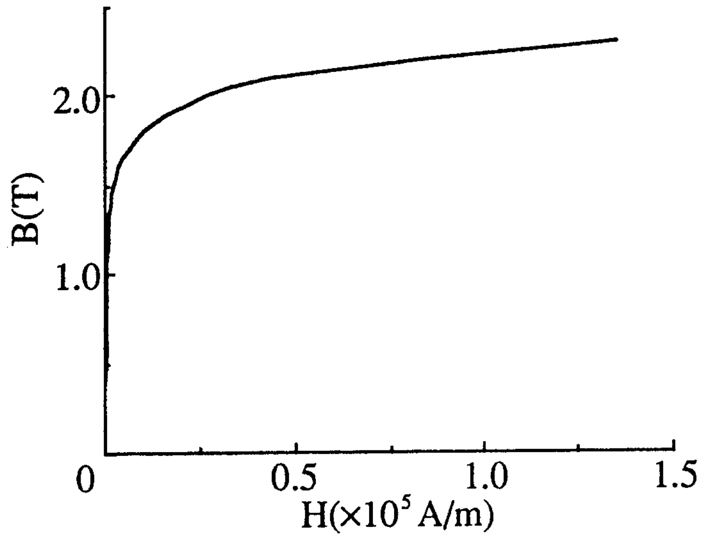


front view

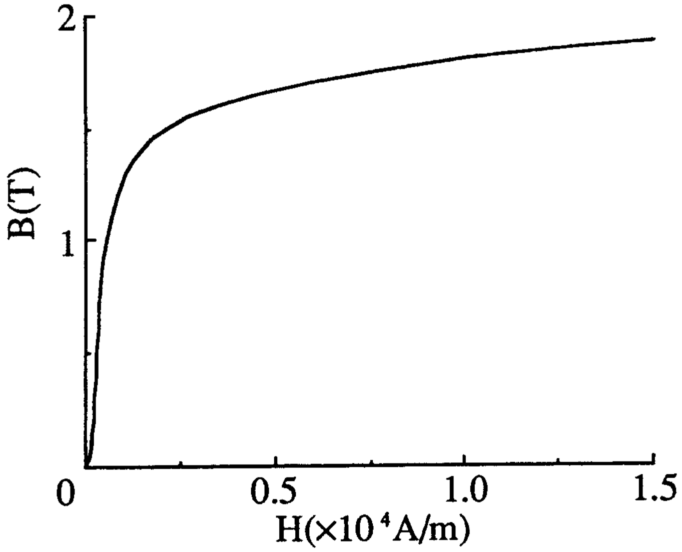


plan view

Fig. 2 Analyzed region



(a) H < 1.5×10^5



(b) H < 1.5×10^4

Fig. 3 B-H curve of steel

Table 1 Typical data of B-H curve

No.	B(T)	H(A/m~	No.	B(T)	H(A/m)
1	0.0	0	22	1.50	2130
2	0.01	27	23	1,55	2670
3	0.025	58	24	1.60	3480
4	0.05	100	25	1.65	4500
5	0.10	153	26	1.70	5950
6	0.15	185	27	1.75	7650
7	0.20	205	28	1.80	10100
8	0.30	233	29	1.85	13000
9	0.40	255	30	1.90	15900
10	0.50	285	31	1.95	21100
11	0.60	320	32	2.00	26300
12	0.70	355	33	2.05	32900
13	0.80	405	34	2.10	42700
14	0.90	470	35	2.15	61700
15	1.00	555	36	2.20	84300
16	1.10	673	37	2.25	110000
17	1.20	836	38	2.30	135000
18	1.30	1065			
19	1.35	1220			
20	1.40	1420			
21	1.45	1720			

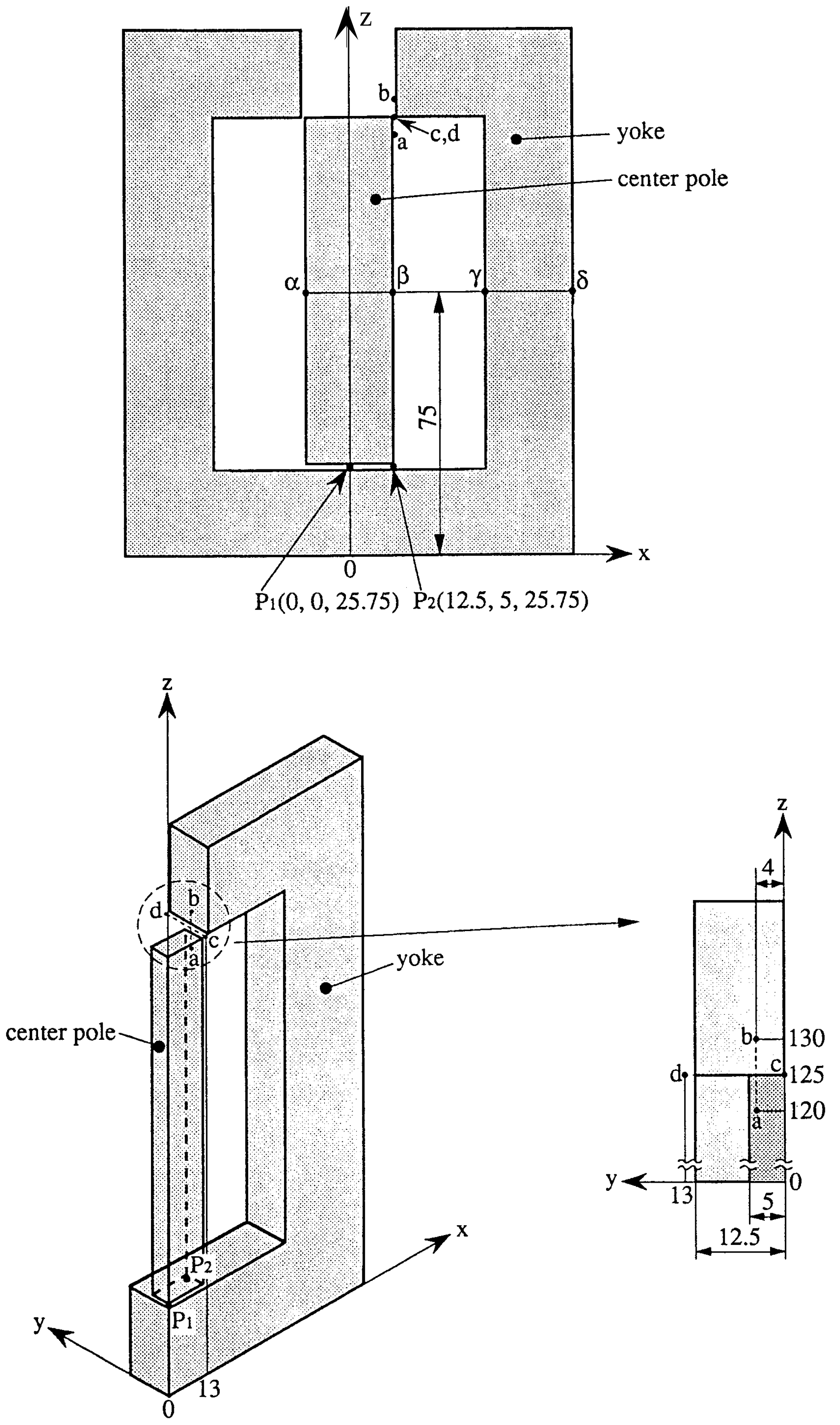


Fig. 4 Position at which the flux density should be calculated (see Tables 2, 3, and 4)

Table 2 z-directional components Bz of flux densities at points P_1 and P_2 (see Fig.4)

	coordinates (mm)			ampere-turns (AT)			
position	x	y	z	1000	300Q	4500	5000
P_1	0.0	0.0	25.75				
P_2	12.5	*5.0*	25.75				

Table 3 z-directional component in center pole (α−β) and Bz of average flux densities yoke (γ−δ) (see Fig.4)

	coordinates (mm)			ampere-turns (AT)			
position	x	y	z	1000	3000	4500	5000
α−β	$-12.5 \le x \le 12.5$	$-5.0 \le y \le 5.0$	75.0				
γ−δ	$38.5 \le x \le 63.5$	$-12.5 \le y \le 12.5$	75.0				

Table 4 x-directional components Bx of flux densities along lines a-b and c-d (see Fig.4)

	coordinates (mm)			ampere-turns (AT)			
No.	x	y	z	1000	3000	4500	5000
1(a)	13.0	4.0	120.0				
2			121.0				
3			122.0				
4			123.0				
5			124.0				
6			125.0				
7			126.0				
8			127.0				
9			128.0				
10			129.0				
911(b)			130.0				
12(c)	13	0.0	125.0				
13		1.0					
14		2.0					
15		3.0					
16		4.0					
17		*5.0*					
18		6.0					
19		7.0					
20		8.0					
21		9.0					
22		10.0					
23		11.0					
24		12.0					
25 (d)		13.0					

Table 5 z-directional components Fz of force

ampere-turns (AT)	electromagnetic force (Nm)
1000	
3000	
4500	
5000	

Table 6 Description of computer program

No.	Item	Specification
1	Code name	
2	Formulation	☐ 1. FEM (Finite Element Method) ☐ 2. BEM (Boundary Element Method) ☐ 3. IEM (Integral Equation Method) ☐ 4. FDM (Finite Difference Method) ☐ 5. combination (+) ☐ 6. others ((Please write references in item No.17)
3	Governing equations	
4	Solution variables	
5	Gauge condition	☐ 1. not imposed 2. imposed ☐ (a) impose the condition on governing equations directly ☐ (b) penalty function method ☐ (c) Lagrange multiplier method ☐ (d) others (+) (Please write references in item No.17)
6	Technique for non-linear problem[2]	☐ 1 Newton-Raphson method [2] ☐ 2. Modified Newton-Raphson-method ☐ 3. Incremental method ☐ 4. SOR[3] ☐ 5. others ( ) (Please write references in item No.17)
	Convergence criterion for non-linear iteration	

Table 6 Description of computer program (continued)

No.	Item	Specification
7	Approximation method of B-H curve	☐ 1. spline ☐ 2. Akima[4] ☐ 3. straight lines ☐ 4. others( ) (please write references in item No.17)
8	Technique for open boundary problem [5]	☐ 1. truncation ☐ 2. mapping ☐ 3. ballooning ☐ 4. Zienkiewicz's infinite element[1] ☐ 5. Tong’s infinite element[6] ☐ 6. BEM or IEM ☐ 7. others ( ) (please write references in item No.17)
9	Calculation method of magnetic field produced by exciting current	☐ 1. Biot-Savart law (analytical) ☐ 2. Biot-Savart law (numerical) ☐ 3. taking into account exciting current in governing equations directly
10	Property of coefficient matrix of linear equations	1. symmetric ☐ (la) sparse ☐ (lb) full 2. asymmetric ☐ (2a) sparse ☐ (2b) full ☐ 3. combination
11	Solution method for linear equations	☐ 1. ICCG ☐ 2. ILUBCG ☐ 3. ILUCGS[7] ☐ 4. SOR ☐ 5. LDL^T ☐ 6. LU ☐ 7. Gauss elimination method ☐ 8. others ( ) (please write references in item No.17)
	Convergence criterion for iteration method	

Table 6 Description of computer program (continued)

No.	Item			Specification	
12	Element type			☐ 1. tetrahedron ☐ 2. triangular prism ☐ 3. hexahedron ☐ 4. triangle ☐ 5. rectangle ☐ 6. others ( ) (please write references in item No.17)	
				☐ 1. nodal element (nodes) ☐ 2. edge element (edges)[8]	
13	Number of elements				
14	Number of nodes				
15	Number of unknowns				
16	Computer	name			
		speed		(MIPS),	(MFLOPS).
		main memory (MB)			
		used memory (MB)			
		precision of data (bits)			
		CPU time (sec)	total		
			solving linear equations		
17	References on Nos.1 to 12, etc.				

7. References

[1] O.C.Zienkiewicz "The Finite Element Method (Third Edition)", McGraw-Hill (1977).

[2] P.P.Silvester, H.S.Cabayan & B.T.Browne "Efficient Techniques for Finite Element Analysis of Electrical Machines", IEEE Trans. PA&S, PAS-92, 6, 1274 (1973).

[3] J.H.Hwang & W.Lord: "Finite Element Analysis of the Magnetic Field Distribution inside a Rotating Ferromagnetic Bar", IEEE Trans. Magnetics, MAG-lO, 4, 1113 (1974).

[4] H.Akima : "A New Method of Interpolation and Smooth Curve Fitting Based on Local Procedures", Journal of ACM, 17, 4, *589* (1970).

[5] C.R.I.Emson "Methods for the Solution of Open-Boundary Electromagnetic-Field Problems", IEE Proc., 135, Pt.A, 3, 151(1988).

[6] P.Tong & J.N.Rossetos : "Finite-Element Method (Basic Technique and Implementation)", MIT Press (1977).

[7] P.Sonneveld: "CGS, a Fast Lanczos-Type Solver for Nonsymmetric Linear Systems", Report 84-16, Department of Mathematics and Informatics, Delft University of Technology, The Netherlands (1984).

[8] A.Bossavit & J.C.Verite "The "TRIFOU" Code : Solving the 3-D Eddy-Currents Problem by Using H as State Variable", IEEE Trans. Magnetics, MAG-19, 6, 2465 (1983).