A Transient Response of an Electromechanical Device Using Time Varying Magnetic Forces and a Review of the Differences in Approach Required in Magnetic Finite Element Analysis

Presented by G. E. Barron*

CAD COMP Inc., subsidiary of The MacNeal-Schwendler Corporation
9076 N. Deerbrook Trail, Milwaukee, WI 53223

INTRODUCTION

Mechanical motion is produced by magnetic fields in devices such as solenoids and electric motors. Prediction of the motion involves first calculating the magnetic forces and then calculating the resulting mechanical response. In this paper the method of calculating both the magnetic forces and the resulting displacements is the finite element analysis method (FEA).

First presented in this paper are finite element techniques for computation of the magnetic field, B, using Maxwell's equations which describe such phenomena. In three-dimensional magnetic field problems the magnetic vector potential FEA method is used in CAD COMP Inc.'s AOS/MAGNUM^{tm}.

* This work and paper are a collaboration of many people in the CAD COMP Inc. Consulting Services group. This includes Dr. John Brauer, Dr. Larry Larkin, and Jerry Zimmerlee. Thanks are due, as always, to Dr. Vern Overbye.

The next section of this paper describes how magnetic pressures and forces are calculated from the magnetic fields. Also discussed is how the pressures are input to a structural finite element model to determine the resulting displacements. Then data are presented for the magnetic fields using AOS/MAGNUM and resulting vibratory forces and displacements of an automotive alternator using The MacNeal-Schwendler Corporation's MSC/NASTRAN.

Finally a review is made of some of the differences required in a magnetic FEA problem versus the more familiar structural FEA project.

MAGNETIC FIELD CALCULATION

In certain devices, magnetic fields, denoted by B, exist or flow in two dimensional planes. If the plane of flow is Cartesian (x,y) then planar finite elements are used where the grid point variable is the z component of the magnetic vector potential A that is normal to the plane of flow. If the plane of flow is about an axis of symmetry z then the flux lies in the cylindrical (r,z) plane and only the normal (Θ) component of the magnetic vector potential need be computed at the grid points [1].

For planar and axisymmetric magnetic field problems the magnetic vector potential method has been formulated in the AOS/MAGNETIC^{tm}[2] FEA program for engineering workstations and in the AOS/MAGGIE^{tm}[2] FEA program for personal computers. Both programs solve for linear or saturable (nonlinear) magnetostatic fields, as well as for magnetodynamic fields with eddy currents in the frequency or time domain. Both programs also solve for electrostatic fields, electrodynamic fields, and coupled electromagnetic fields over a wide range of frequencies. The finite elements used are triangles and quadrilaterals.

In many cases magnetic fields are neither axisymmetric nor planar. In such three dimensional cases the magnetic vector potential A generally has all three vector components. The three dimensional magnetic vector potential finite element method has been formulated in the AOS/MAGNUM^{tm}[2] analysis program. The program solves for linear or saturable (nonlinear material) static magnetic fields, as well as for magnetodynamic fields with eddy currents in the frequency or time domain. The program also solves for electrostatic fields, electrodynamic fields, and coupled electromagnetic fields of a wide range of frequencies. The finite elements used are isoparametric hexahedrons, pentahedrons, and tetrahedrons.

MAGNETIC FORCE CALCULATION

If total magnetic force on an object is to be calculated, the method of virtual work can be used to obtain accurate force from a magnetic finite element model. The difference in magnetic coenergies of two computer runs with a small displacement of the movable object yields the total force [1].

If the distribution of the magnetic force needs to be calculated, then another force calculation technique must be used. The magnetic pressure or magnetic stress distribution can be obtained using Maxwell's Stress Tensor [1].

In general for saturable magnetic objects Maxwell's Stress Tensor involves the B-H curves of the materials. However, if the permeability of the materials is large, then the magnetic pressure is essentially normal to the surfaces of those materials and is given by [1]:

$$F/\text{area} = B^2/(2u_o) \qquad (1)$$

where u_o is the permeability of free space and B is the total magnetic field acting on the surface area. All units in this paper are MKS.

STRUCTURAL MOTION CALCULATION

There are two general types of structural motion caused by magnetic fields that can be calculated by finite element analysis. They are rigid body motion and deformable body motion.

Rigid body motion applies often to objects such as actuators and solenoids. A moveable part of the object, often called the armature, is considered as a rigid body of mass m. It is constrained to move in one direction only, say the x direction. It may also be constrained by a spring of spring constant k and be subject to damping with damping constant c. The equation of motion of the armature is then

$$F = m(d^2x/dt^2) + c(dx/dt) + k\,x \qquad (2)$$

where F is the magnetic force on the armature from Equation (1).

Deformable motion requires a multi degree-of-freedom matrix form for Equation (2). The magnetic forces of Equation (1) must be applied as loads to a structural finite element model, thereby allowing the magnetic object to deform. The deformation usually varies with time, producing vibration and related acoustic noise. The structural finite element solution outputs the vibratory displacements.

THREE-DIMENSIONAL EXAMPLE

Figure 1 shows a section of an automotive alternator. The magnetic flux path is highly three dimensional, so three dimensional electromagnetic finite element analysis is performed [3].

Figure 2 shows some of the three dimensional finite elements (excluding the air elements) used to model one pole pitch, or 30 degrees, of a typical 12 pole alternator. Periodic boundary conditions [4] are used at the pole boundaries to allow solution for any speed and electrical load. Typically approximately 2000 grid points and 2500 hexahedral, pentahedral, and tetrahedral finite elements are required, made of steel, air, or copper.

Figures 3a, 3b, 3c display three dimensional saturable B fields computed by AOS/MAGNUM at a typical speed and load. Usually the highest B occurs in the rotor at no stator load. Typically the ratio of flux linking the stator to that in the rotor core is 65 percent or less. Good agreement has been obtained between calculated and measured electrical output [4].

Vibration and related acoustic noise of an alternator is produced by the magnetic fields and forces. To calculate the vibration, structural finite element analysis is performed.

The structural loads act on all the inner surfaces of the stator and on all the outer surfaces of the rotor. They are given by Maxwell's Stress Tensor as in Equation (1). These loads are input to the dynamic response solution option of MSC/NASTRAN^{tm}[5].

Figure 4 shows one structural analysis application of a sixty degree segment of an alternator model with a simplified housing along with the rotor and stator mesh used in AOS/MAGNUM analysis. The shaft is made from CBAR elements. In this case rotated image superelements were used with grid point displacements in a cylindrical coordinate system. No advantage was made of dihedral symmetry in the sixty degree segment in order to avoid use of left-hand and right-hand mirror image coordinate systems. Also, the residual structure was considerably reduced by using a larger primary superelement.

Rear housing needle bearing and front housing thrust bearing modeling made use of MSC/NASTRAN rigid body elements to connect the shaft to the front housing in radial and axial translation as well as bending, while the rear-housing was joined only in radial translation. A rigid element was also used to model engine support in the primary and 120 degree displaced image superelement. Plate element thickness was adjusted to force front housing axial stiffness to that of a full model front housing. The rear housing primarily adds mass to the model.

Other alternator models have been made using a full front and rear housing and full rotor and stator. Generally the superelement approach results in reduced computing requirements. Polar mass moments of inertia for slip rings, external fans, and pulleys are modeled using CMASS2 elements, while CONM2 elements model the translational mass.

Component Mode Synthesis (SOL 63) is used to obtain structure natural frequencies and eigenvectors. Plots of the mode shapes are examined in detail to identify front housing axial modes, rotor shaft beaming, and antiphase oscillation between the pulley (and external fan if used) and the rotor mass. Generalized Dynamic Reduction or the newer Lanczos eigenvalue extraction methods have both been used with success.

The second step is to model transient response (SOL 72) with the magnetic forces applied as discussed above. About 15 natural frequencies are used up to about 2000 Hz. PARAM HFREQ and LFREQ are often used to exclude the lower frequency mode of the entire alternator vibrating as a rigid body on the engine attachment mounts. A nominal 5% of critical damping was used in all transient analysis. The time step used was 1/200th of the period of the fundamental input passing frequency of a stator tooth. A total of five cycles of the force was input and analyzed. In the rotor the force pattern repeats every 60 degrees. In the stator each tooth sees the same loading but at different times.

Figure 5 shows a typical magnetic force load on a grid point as a function of time. Figure 6 shows a typical displacement vs. time calculated by MSC/NASTRAN. Videotapes of an animation of the vibratory response of an alternator calculated by MSC/NASTRAN have been made as well as changes in the B field as the rotor rotates. These videotapes will be shown at the conference.

From the vibration it may be possible to predict the acoustic noise; however, no such quantitative calculations have yet been made for this effort. However, qualitative correlation with experimental acoustic noise has occurred. For example, frequencies at which large surface vibrations are calculated have agreed with frequencies at which significant audible noise was measured.

DIFFERENCES IN APPROACH REQUIRED IN MAGNETIC FINITE ELEMENT ANALYSIS

Most attendees at The MacNeal-Schwendler Corporation's User's Conference are more familiar with the approach used in structural or mechanical FEA, so below some of the differences are summarized to provide insight into considerations which the analyst using AOS/MAGNUM must take into account.

Structures	Magnetics
Many problems can be handled with a linear static analysis. Usually it is considered undesirable if some part of the structure yields.	Many electromagnetic devices operate near or above saturation during some part of their operation. This requires a nonlinear FEA solution for a greater percentage of applications than structural.
For a structural finite element, the primary field variable is the displacement vector. For a first order element formulation, a linear distribution in the displacement would give a constant strain element and hence constant stress for a linear stress-strain material. See Figure 7 for the structural material property curve.	For magnetic solutions the primary variable is the magnetic vector potential, A. An element with a linear formulation in A within the element would be a constant flux density, B, element, and constant magnetic field intensity, H, for a linear material. Electromagnetic engineers talk of a B-H curve for their materials yet as shown in Figure 7, it must be shown as H-B to be analogous to a stress-strain curve.
The primary solution variable, displacement, can readily be measured and seen for high flexible structures and is very meaningful to the design engineer.	The magnetic vector potential, A, cannot easily be measured, and except for computer contour plots of constant A can only be seen by sprinkling iron fillings on a sheet of paper and laying the paper on top of the magnet (a high school physics experience.)

After noting the definitions in Figure 7, note that a structural material is initially stiff and then becomes flexible as it yields. Stresses reach nearly a maximum value and the element can carry no additional load (integral of stress d·A).

The magnetic material conversely starts out flexible (highly permeable, e.g., the field can "permeate" or has low reluctance) and at saturation it stiffens. At this point B is at a maximum in the element and any additional current load (integral H·dl) cannot easily permeate or flow through the material.

When stress nearly tops out on a yield curve, the strain can continue and if more load is applied, the part can and will break.

When B reaches a maximum and more current is applied, H can climb, but nothing breaks. Instead, since the flux B cannot be encouraged to increase locally, the flux pours out (as would a fluid) into adjacent elements which are not saturated. In many electromechanical devices all the flux stays in the steel parts until saturation occurs and then the flux goes out into the surrounding air.

The FEA model need only include the actual steel, aluminum, titanium or other components of the structure. Air adds no stiffness and need not be modeled.

Because of the effect discussed above, air needs to be modeled in and around the steel and copper, etc., parts. Air finite elements may seem almost imaginary but they possess a finite permeability. Air is important in a magnetic FEA solution. Air remains linear. Air elements tend to make the total model larger than one initially suspects by looking at the physical electro-mechanical device.

Actual printed output data for the solution, e.g., displacements, reaction forces and the primary element recovery for stress and strain are very useful for the structural engineer.

The A vector is not very useful directly and current reaction loads don't help as much as in structures where a reaction load might be the input to designing say a foundation footing. The primary element recovery items, B and H, are interesting to see in a color plot in order to determine where steel is saturating, but useful performance data needs additional post processing.

The above summarizes some of the important differences in magnetic FEA versus structures. Post processing of B and H into meaningful performance data is discussed in Chapter 5 of the book [1]. A summary [6] of magnetic FEA versus thermal and fluid flow FEA may be of interest for further reading.

CONCLUSIONS

Techniques have been presented for calculating magnetic forces and resulting displacements by use of finite element analysis. The magnetic vector potential finite element method has been shown to be useful for three-dimensional problems. The resulting magnetic forces have been calculated using Maxwell's Stress Tensor for use as loads in structural finite element models. Calculations for a highly three dimensional automotive alternator have illustrated how magnetic forces produce structural vibrations.

REFERENCES

[1] J. R. Brauer (ed.), What Every Engineer Should Know About Finite Element Analysis, New York: Marcel Dekker, Inc., 1988.

[2] AOS/MAGNETIC, AOS/MAGGIE, and AOS/MAGNUM are proprietary products of CAD COMP Inc., 9076 N. Deerbrook Trail, Milwaukee, WI 53223, phone 414-357-8723.

[3] F. L. Zeisler and J. R. Brauer, "Automotive Alternator Electromagnetic Calculations Using Three Dimensional Finite Elements", IEEE Trans. on Magnetics, November 1985, pp. 2453-2456.

[4] J. R. Brauer, G. A. Zimmerlee, T. A. Bush, R. J. Sandel, and R. D. Schultz, "3D Finite Element Analysis of Automotive Alternators Under Any Load", IEEE Trans. on Magnetics, Vol. 24, No. 1, January 1988.

[5] MSC/NASTRAN is a proprietary product of the MacNeal-Schwendler Corp., 815 Colorado Blvd., Los Angeles, CA 90041.

[6] Jeffrey M. Steele, Solving Magnetic Problems, CAE Magazine, July 1986.

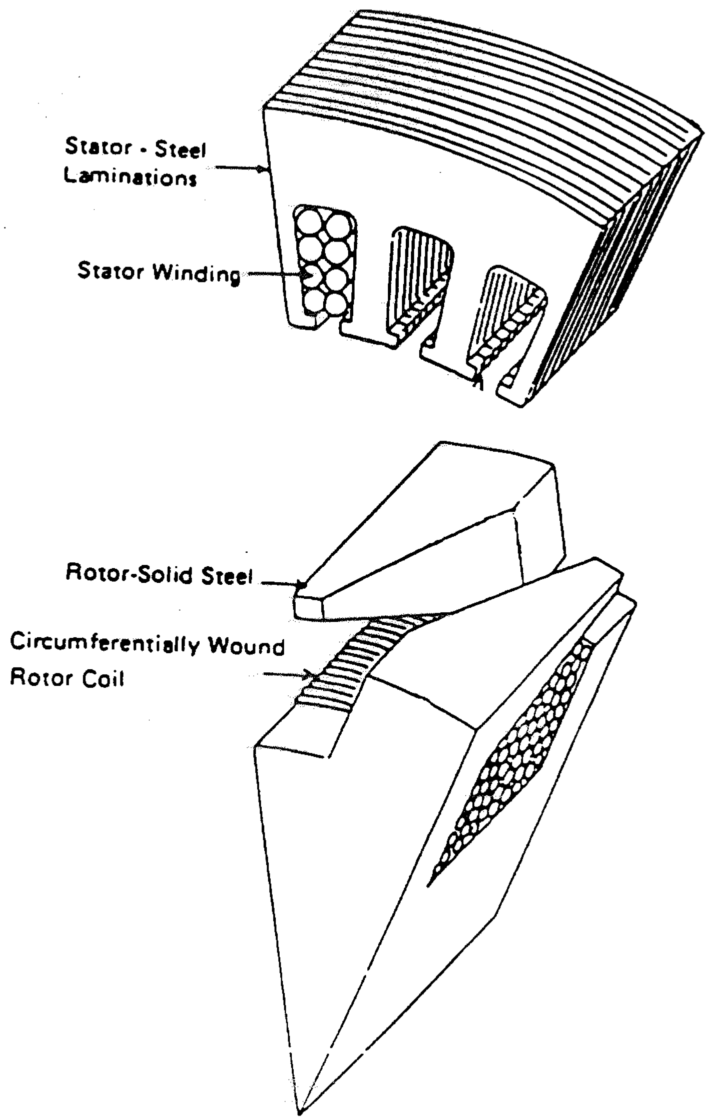


Figure 1. Sketch of one pole pitch of a 12-pole automotive alternator [1].

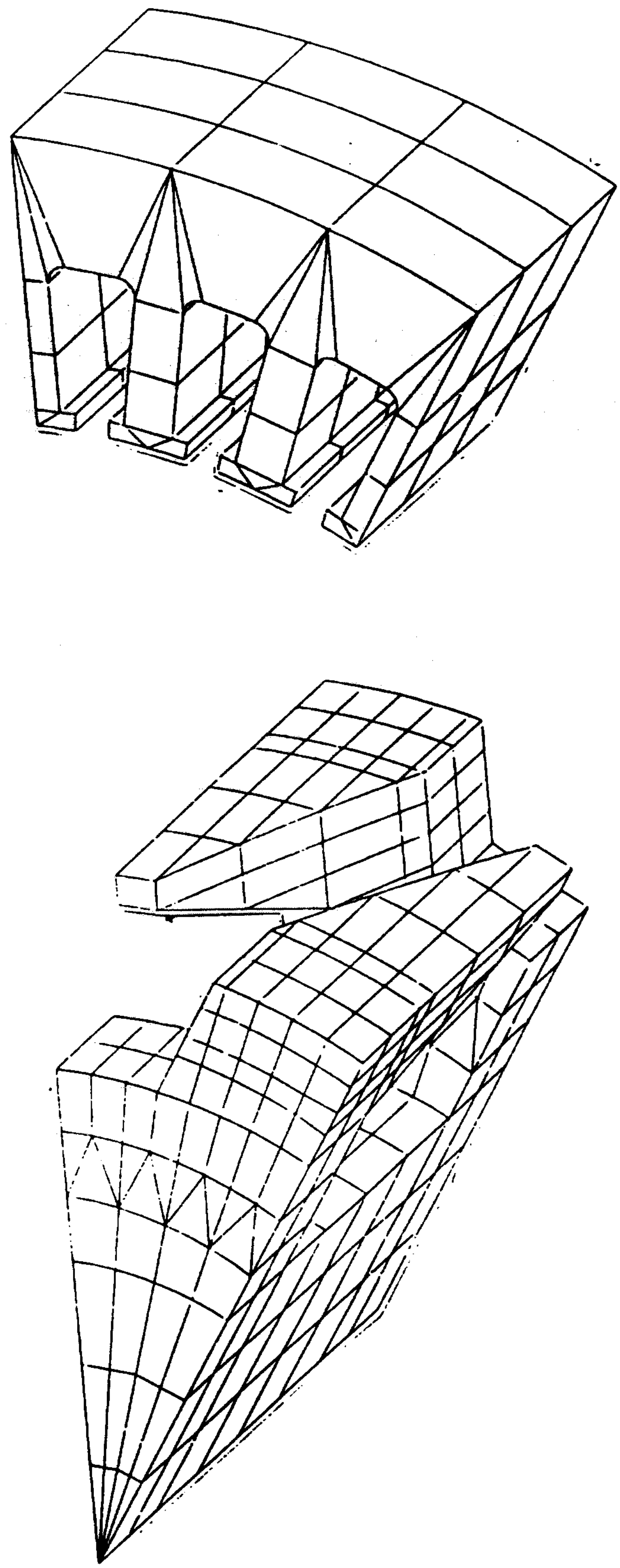


Figure 2. Steel finite elements for model of Figure 1.

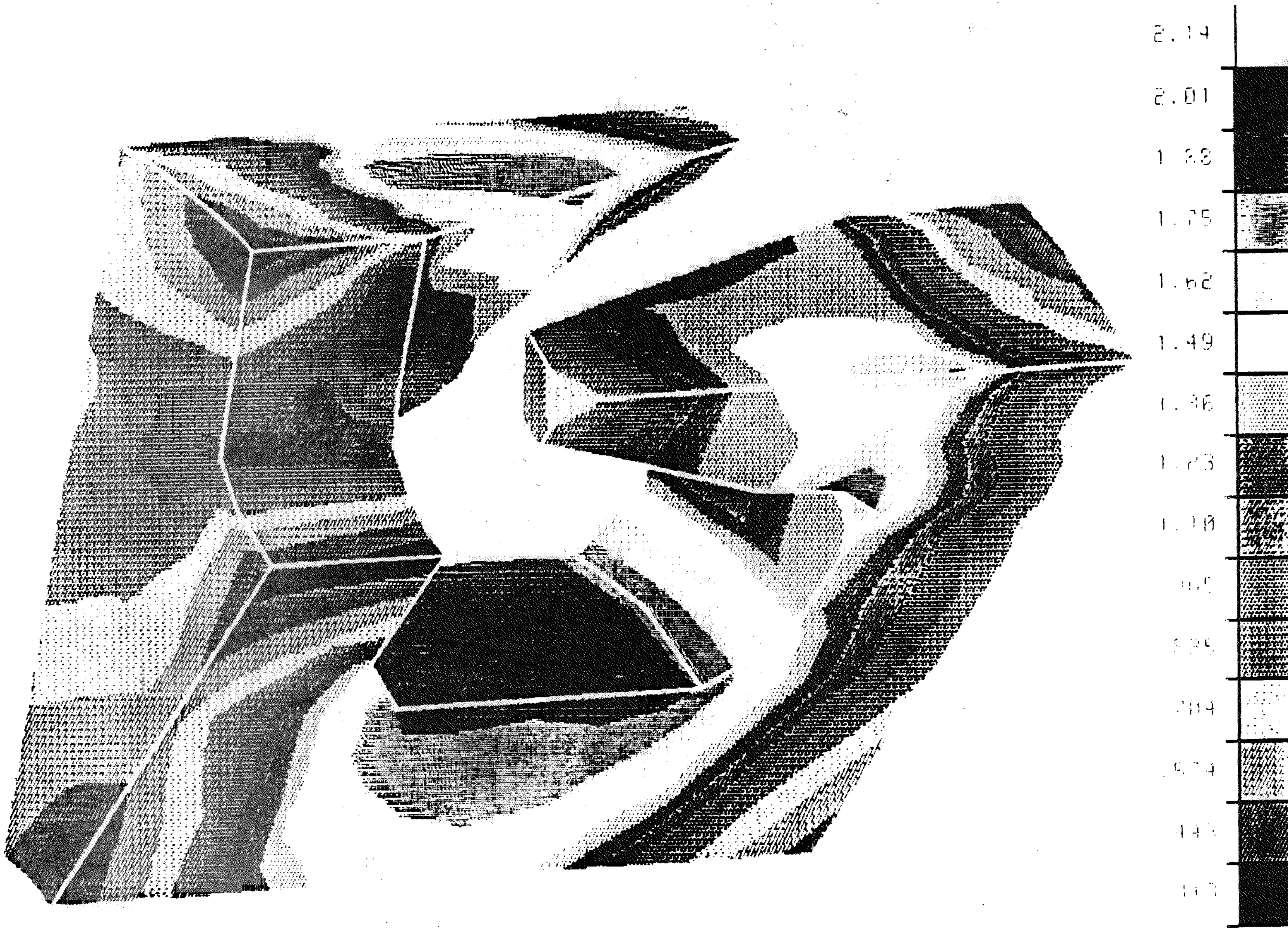


Figure 3. Color displays of B distribution in alternator, shown monochromatically
a) rotor

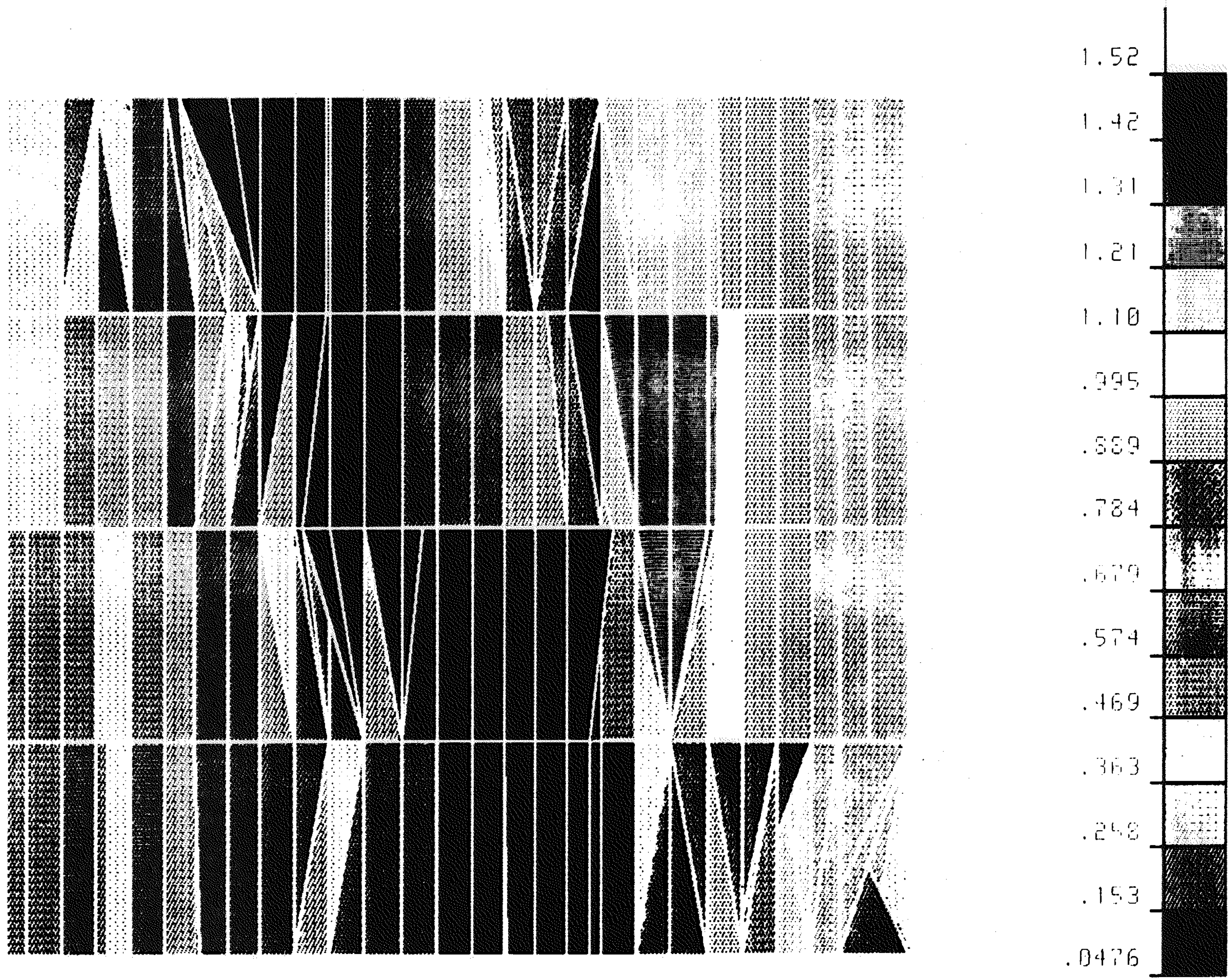


Figure 3b). air gap

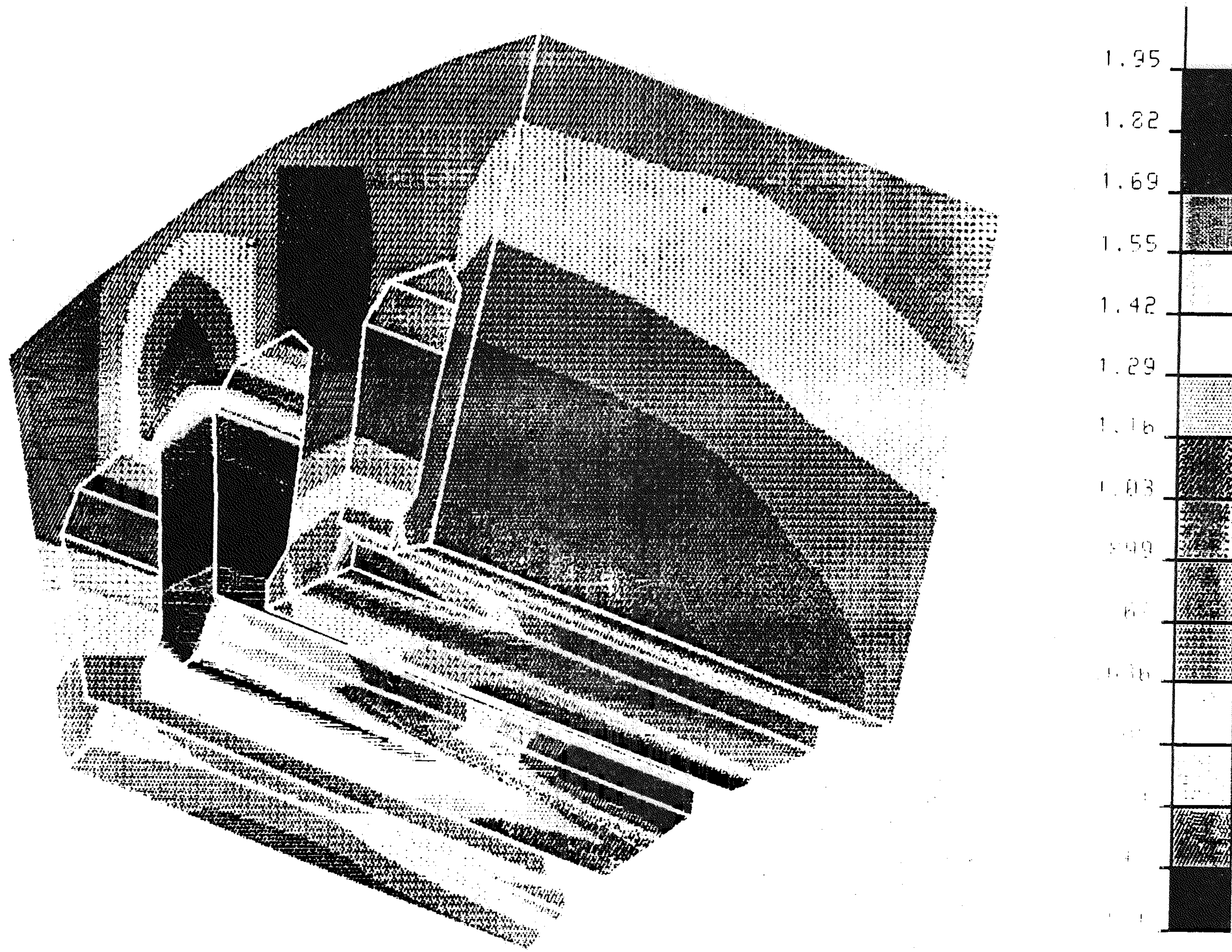
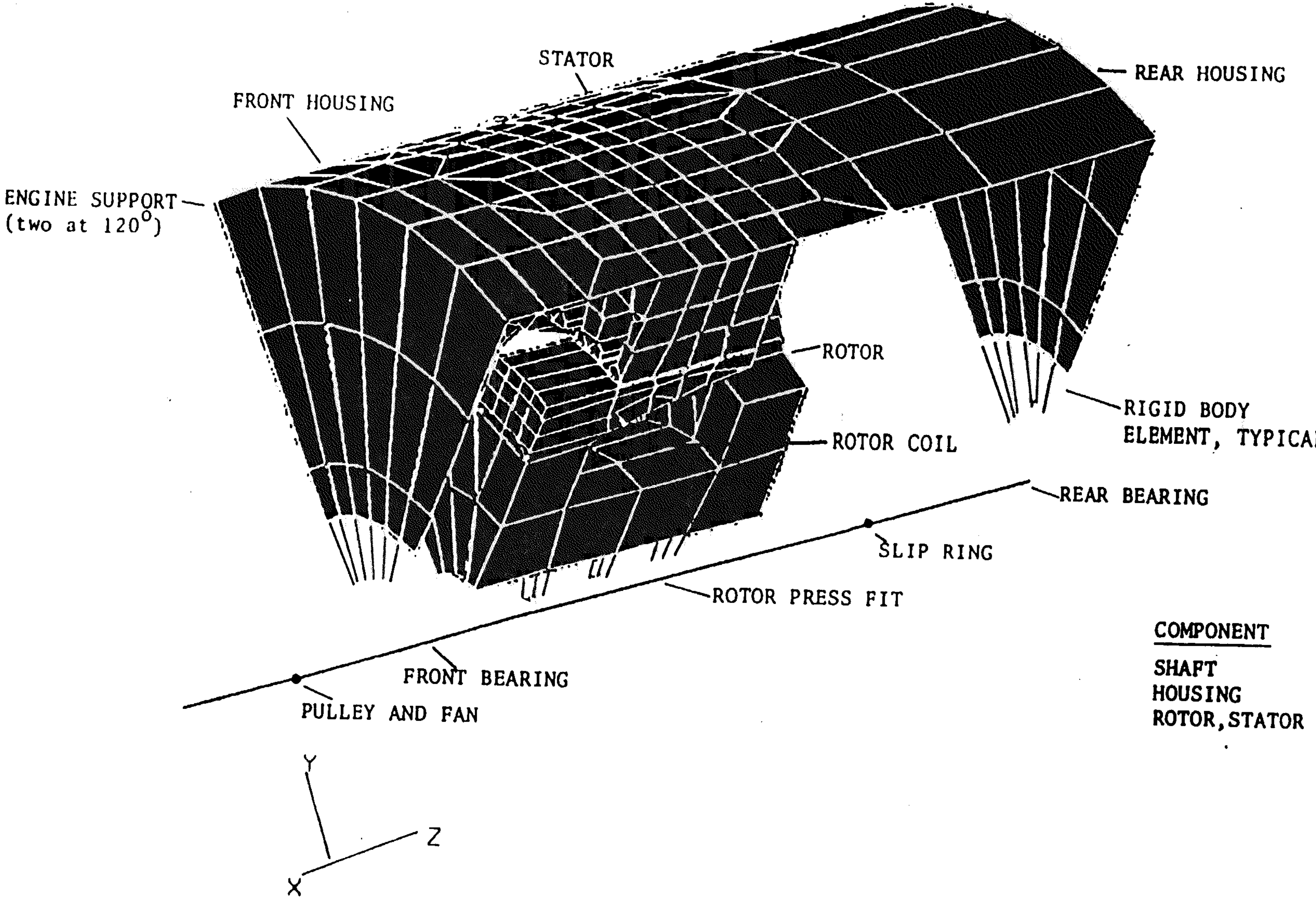


Figure 3c) stator



COMPONENT	ELEMENT
SHAFT	BAR
HOUSING	PLATES
ROTOR, STATOR	SOLID

Figure 4. A typical MSC/NASTRAN model segment of an automotive alternator

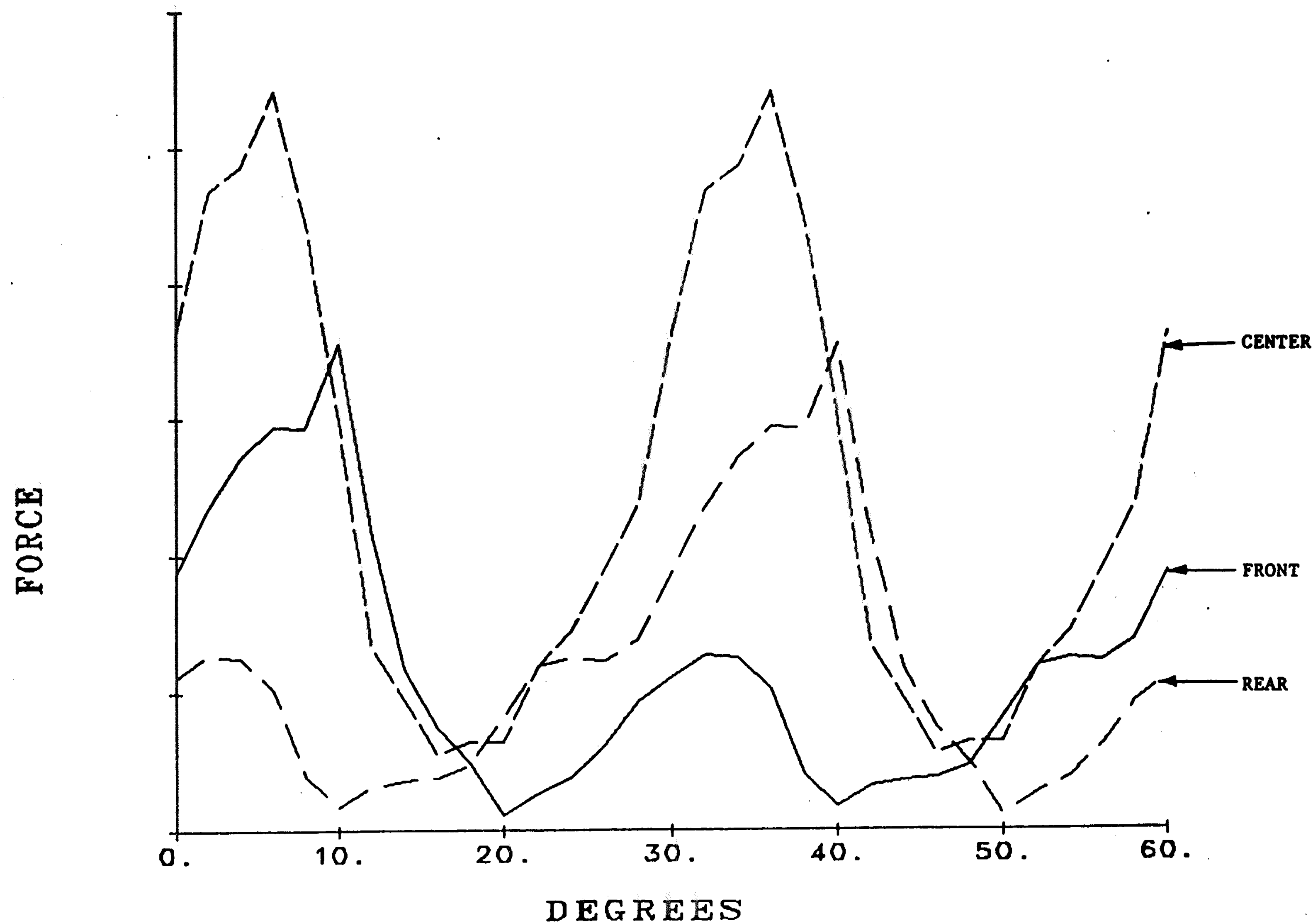


Figure 5. Alternator stator loads for typical grid points over 60 mechanical degress

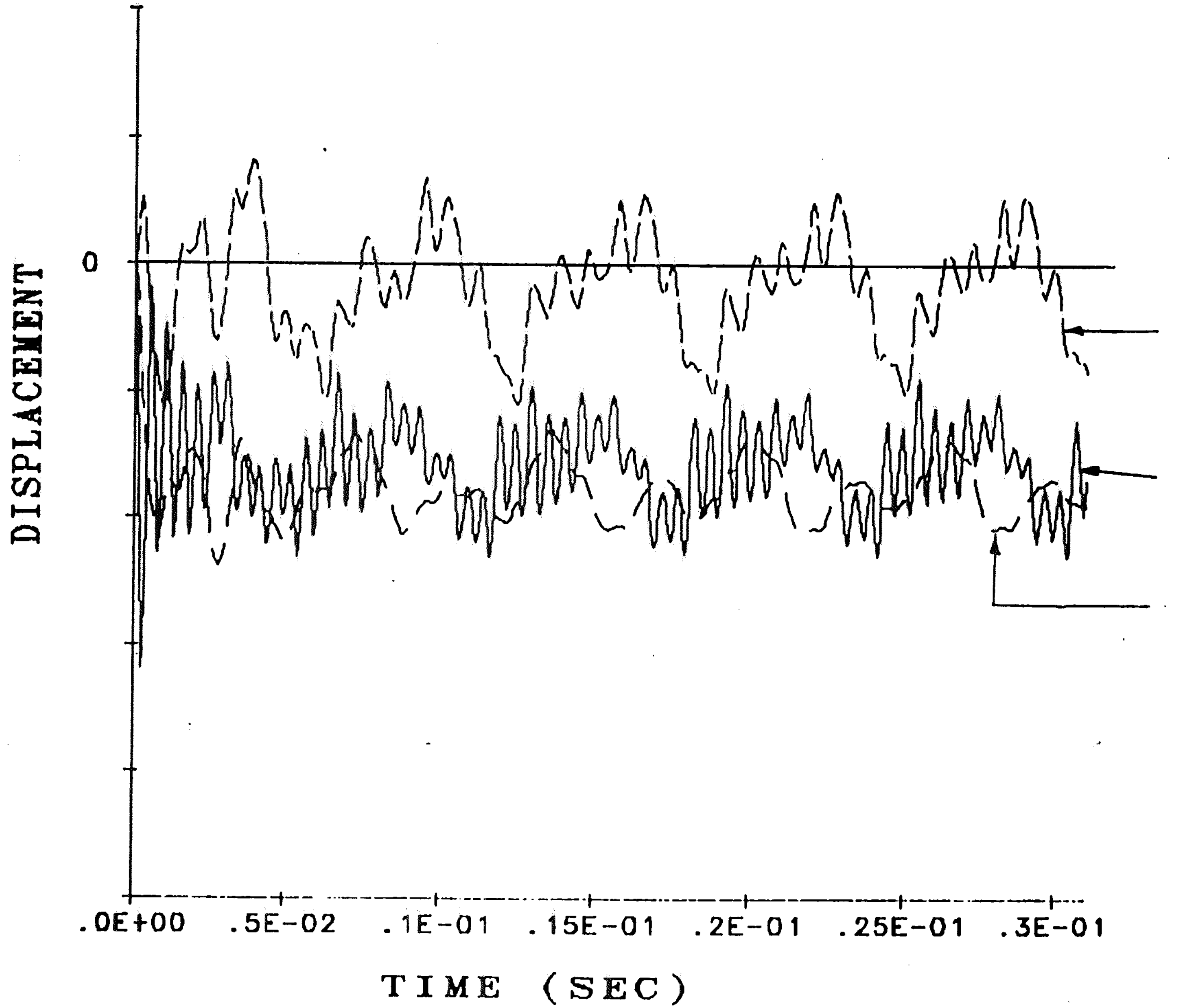


Figure 6. Time history response for typical grid point on alternator stator

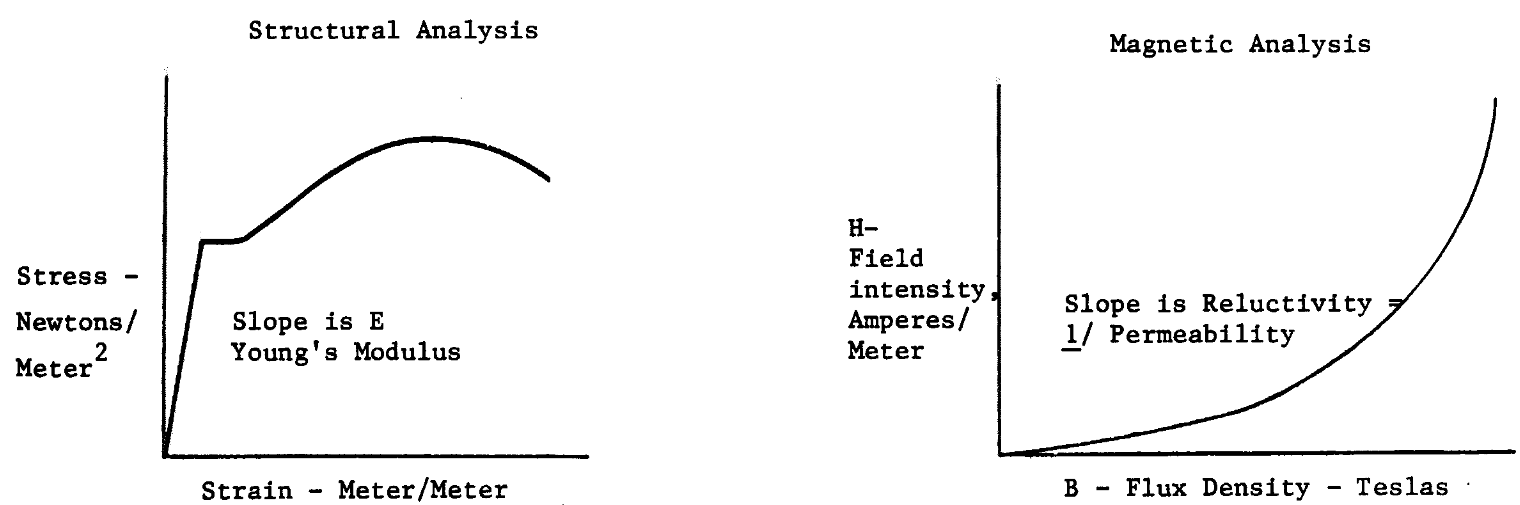


Figure 7. Material Properties