AIR CORED LINEAR MACHINES
FOR GROUND TRANSPORTATION

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APPENDIX I - BIBLIOGRAPHY

1. Scope of the Bibliography

This bibliography contains over 400 references to published literature relevant to linear synchronous machines. Since the development of this type of machine is so closely coupled to that of magnetic levitation, some of the more important EDS maglev references are included, particularly the Ford and Stanford reports for the US Department of Transportation. The earliest references are to essentially ac induction devices, which were suggested as forms of guided transport to assit or complement the existing rail systems. Linear induction motors are covered by Wagner's bibliography, the more general papers of Poloujadoff and Laithwaite, and the books by Laithwaite, Nasar and Yamamura. Also included are references to iron cored linear synchronous machines, and the homopolar and heteropolar variants. The linear dc machine or linear thyristor machine with iron cored field is similarly listed, as are the more relevant EMS papers.
Generally the majority of references are freely available. The exceptions are a few Warwick University internal publications, and the German Statusseminar proceedings. Special issues and IEEE Transactions on Magnetics (for INTERMAG and Applied Superconductivity Conferences) will find about 94 of the references, and the remaining listed conferences include a further 86 papers.

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5.3 Corporate Index

APPENDIX II

SOLENOID MAGNET DESIGN

APPENDIX II SOLENOID MAGNET DESIGN

1. Introduction

The design of adequate performance ACLM for propelling advanced ground transport vehicles ultimately relies on the assumption that the inductances and field profiles of the coils in the vehicle array can be correctly predicted. Fortunately the absence of ferromagnetic material means that the calculations involve linear field strength - flux density relationships, and superposition can be readily applied.

Design procedures for circular coils have been available for sometime(257), and parameter variation was investigated by Maxwell, who established inductance and maximum efficiency relationships. More recently field analyses of thick solenoids both on and off axis were performed under NASA sponsorship(258,259). Coil mutual and self inductance calculations were made easier by tabulations and simplified formulae assembled by Grover(260), and Fawzi later produced an algorithm that could be used for coaxial current sheets which meant that faster calculation cycle time was possible(261). Previous computing methods had generally stored Grover's tables, which leads to limited and uncontrolled accuracies at certain geometries.

For Maglev, circular coils do not necessarily represent an optimum geometry. For the Warwick system this is considered in Chapter 3. The common choice is for rectangular or even square coils with tight corner radii. The corners represent problem areas because the self field is concentrated by the rapid change in direction of the current, and the subsequently generated body forces must be accommodated by the coil structure and support. The corner field will also determine the load line of the coil and its intercept with the critical field locus. Field calculations then must be made for straight line filaments and bars, and the corner effects evaluated.

A racetrack winding is often used to provide a rectangular coil equivalent, and inductance matching is based on an equal area criteria. This configuration is more easily wound than a tight corner coil since there is reduced chance of the wire riding up and splaying on the corners, and migrating when energised. Montgomery has briefly looked at rectangular coil field analysis by approximating the coil with four straight bars, overlapping at the corners[262]. Unfortunately the published material is inconsistent in its notation, so reworking has proved to be necessary.

For a period of time the design procedure involving different coil geometries and their field distributions seemed only soluble by large mainframe computer programmes. The Rutherford Laboratory's GFUN and TOSCA represent quite complex software which can handle a wide range of intricate magnetic systems. A similar installation is General Atomics' interactive computer programme GMAN used in conjunction with the field analysis programme EFFI, developed by the Lawrence Livermore Laboratory[263]. These systems are necessary to work through a finished detailed design, but can prove costly in trying to just establish the basic configurations that need further study, and the parameter sensitivity to major changes in design strategy. This appendix sets out the techniques that can be used to produce reasonably accurate solutions to field problems for circular, rectangular and racetrack coils, both on and off the geometric axis. The solution to equations can be found using pocket or desk top programmable scientific calculators. This enables the design process to proceed rapidly, without the initial need to establish a large data and software base to accurately analyse coil structures which will then prove unsatisfactory and need to be discarded.

2. Circular Coils

2.1 Basic Field and Power Relationships

Figure 67 shows the simple elemental current loop for which the on axis field B_z is given by the Biot-Savart relationship. At a position z from the coil plane, and for a loop current of I amperes, the field is

$$B_z = \mu_0 \frac{I}{2} \cdot \frac{a^2}{(a^2 + z^2)^{3/2}} \tag{55}$$

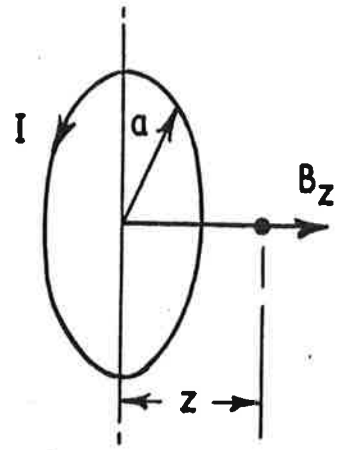


Figure.67. The Elemental Loop.

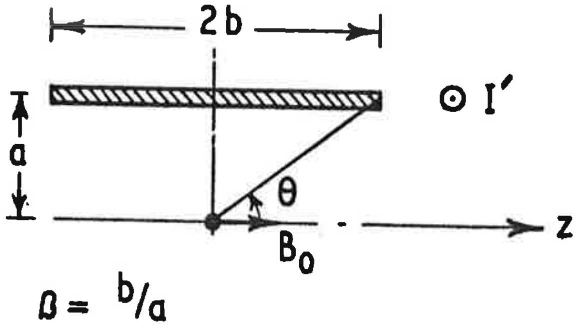


Figure 68. Current Sheet.

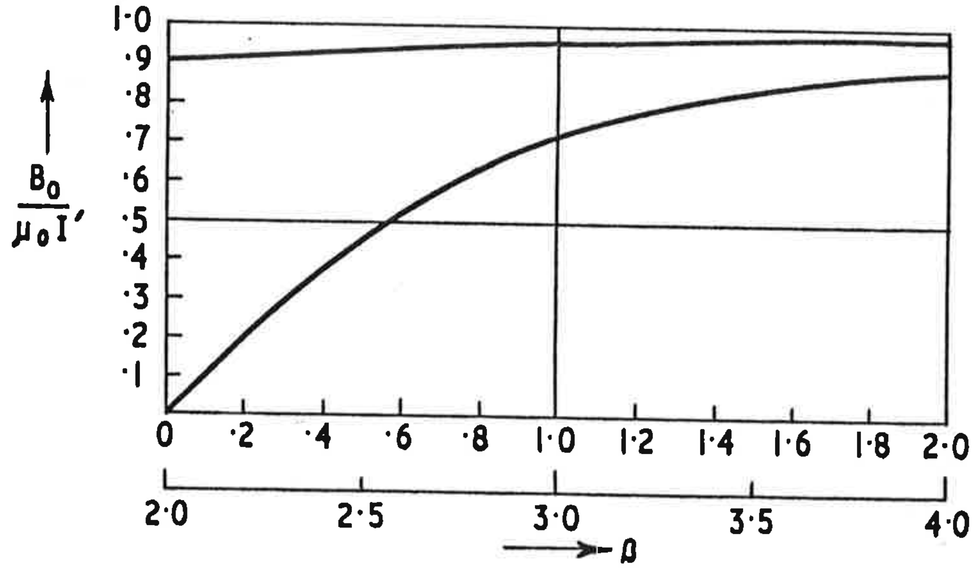


Figure 69. Saturation of Current Sheet Central Field.

where a is the loop radius. The central field is simply

$$B_0 = \mu_0 \frac{I}{2a} \tag{56}$$

so generally,

$$B_z = B_0 \frac{a^3}{(a^2 + z^2)^{3/2}} \tag{57}$$

The off axis field of a circular filament is given by expressions involving complete elliptical integrals of the first and second kind. For a loop radius a, carrying I amperes in an anticlockwise direction in plan, the field components in the vertical and radial direction are B_z and B_r. The field point below the coil plane is defined as being δa vertically and ϵa horizontally from the coil centre.

The fields and modulus, k, are given by

$$B_z = \frac{\mu_0 I}{2\pi a} \cdot \frac{1}{[(1+\epsilon)^2 + \delta^2]^{1/2}} \cdot \left[K + \frac{1 - \epsilon^2 - \delta^2}{(1-\epsilon)^2 + \delta^2} E \right] \tag{58a}$$

$$B_r = \frac{\mu_0 I}{2\pi a} \frac{\delta}{\epsilon[(1+\epsilon)^2 + \delta^2]^{1/2}} \left[K - \frac{1 + \epsilon^2 + \delta^2}{(1-\epsilon)^2 + \delta^2} E \right] \tag{58b}$$

$$k^2 = \frac{4\epsilon}{(1+\epsilon)^2 + \delta^2} \tag{58c}$$

K and E are the complete elliptic integrals and can be either evaluated by calculation using a series expansion, or simply looked up in a suitable set of tables.

The elemental loop can be used to generate the field expressions for current sheets by integrating between the beginning and ends of the single layer coil equivalent. The sheet is defined by the strength I′, ampere turns per metre, and axial aspect ratio β , the ratio of sheet length to diameter (Figure 68). It can be shown that the central field B_o is given by

$$B_0 = \mu_0 I' \cos\theta = \mu_0 I \frac{\beta}{(1+\beta^2)^{1/2}} \tag{59}$$

where $$I' = \frac{NI}{2b}, \quad \beta = \frac{b}{a} \tag{60}$$

I is the turn current and N the number of turns. Figure 69 shows the saturating effect of length on the central field; for $\beta = 2$ the central field is already at ~ 90% of its infinite length value.

Integrating the effect of the current loop over a finite build coil (Figure 70), with inner and outer radii a_1 and a_2 such that

$$\alpha = \frac{a_2}{a_1} \quad \text{and} \quad \beta = \frac{b}{a_1} \tag{61}$$

produces a central field given by

$$B_0 = \mu_0 j\lambda a_1 \beta \ln \left[\frac{\alpha + (\alpha^2 + \beta^2)^{1/2}}{1 + (1 + \beta^2)^{1/2}} \right] \tag{62}$$

or $$B_0 = \mu_0 j\lambda a_1 \beta \left(\sinh^{-1}\left(\frac{\alpha}{\beta}\right) - \sinh^{-1}\left(\frac{1}{\beta}\right)\right) \tag{63}$$

$j\lambda$ is the overall current density per unit cross section,

i.e. $$j\lambda = \frac{NI}{2b(a_2 - a_1)} = \frac{NI}{2a_1\beta(\alpha - 1)} \tag{64}$$

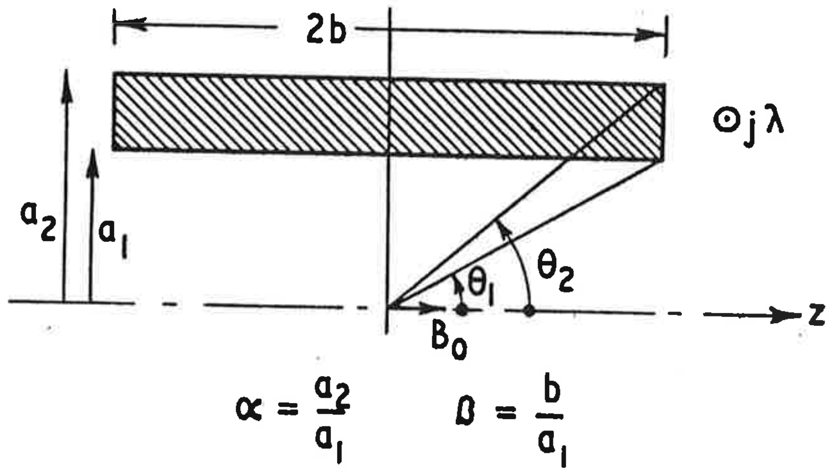


Figure 70. Finite Thickness Uniform Current Densisty Solenoid.

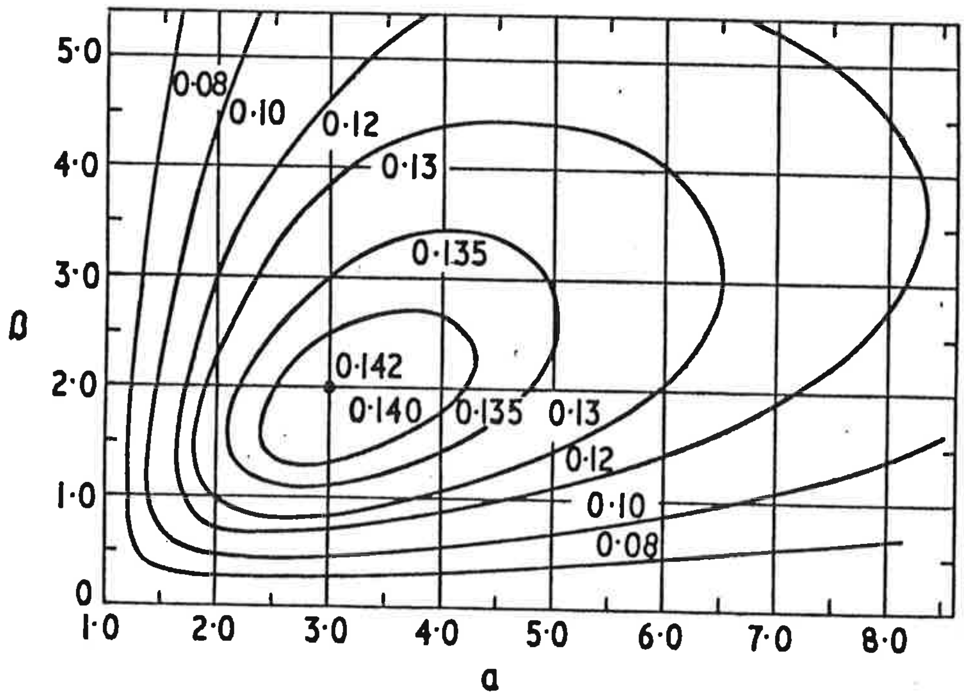


Figure 71. Constant Fabry Factor $G = (\alpha, \beta)$ Contours for a Uniform Current Density Coil.

j is the current density and λ the space factor.

Examination of 62 and 63 reveals that the central field is in fact given by the product of overall current density, inner coil radius and a geometry dependent factor. This factor is defined by

$$F(\alpha,\beta) = \beta(\sinh^{-1}(\frac{\alpha}{\beta}) - \sinh^{-1}(\frac{1}{\beta})) \tag{65}$$

so the central field expression becomes

$$B_0 = \mu_0 j \lambda a_1 F(\alpha,\beta) \tag{66}$$

For a resistive coil, the power required for a particular magnetic field can be evaluated, knowing the conductor resistivity and coil volume. The total power absorbed is

$$W = j^2 \varrho \lambda a_1^3 2\pi\beta(\alpha^2 - 1) \tag{67}$$

where the constant conductor current density j A/m^2 flows in the conductor of resistivity ϱ ohm - metre. Rearranging,

$$j = J(\alpha,\beta) \left[\frac{W}{\varrho \lambda a_1^3}\right]^{\frac{1}{2}} \tag{68}$$

where $$J(\alpha,\beta) = \left[\frac{1}{2\pi\beta(\alpha^2-1)}\right]^{\frac{1}{2}} \tag{69}$$

$J(\alpha,\beta)$ is the coil current density factor, relating conductor current density to the coil total power. The central field can be derived as a function of W, J and F such that

$$B_0 = \mu_0 F(\alpha,\beta) J(\alpha,\beta) \left[\frac{W\lambda}{\rho a_1}\right]^{1/2} \qquad (70)$$

or

$$B_0 = \mu_0 G(\alpha,\beta) \left[\frac{W\lambda}{\rho a_1}\right]^{1/2} \qquad (71)$$

$G(\alpha,\beta)$ is the totally geometrically dependent term known as the Fabry Factor, and links the field produced by a coil to the power input required. G has a maximum of 0.142 near $\alpha = 3$ and $\beta = 2$. Figure 71 shows the contours of Fabry Factor for various α and β of a uniform current density coil, and the moderate gradient allows some choice in α and β with minimal degradation of G.

2.2 Off-Axis Field of a Finite Solenoid

Calculating the off axis field of a finite solenoid is possible by integrating the effect of a current carrying element such as is shown in Figure 72, throughout the solenoid. This technique is most successful off-axis and at medium distance from the coil, but can be complicated for regions within the coil itself because of discontinuities in the functions encountered.

A more simple method is to break down the solenoid into a set of four semi infinite solenoids as shown in Figure 73. The advantage of the semi infinite solenoid, which has a zero inner radius and a uniform current density extending from the axis to the outer radius, is that the field at a point can be represented by only two nondimensional variables, the normalized radial and axial coordinates of the field point. Reference 259 shows how

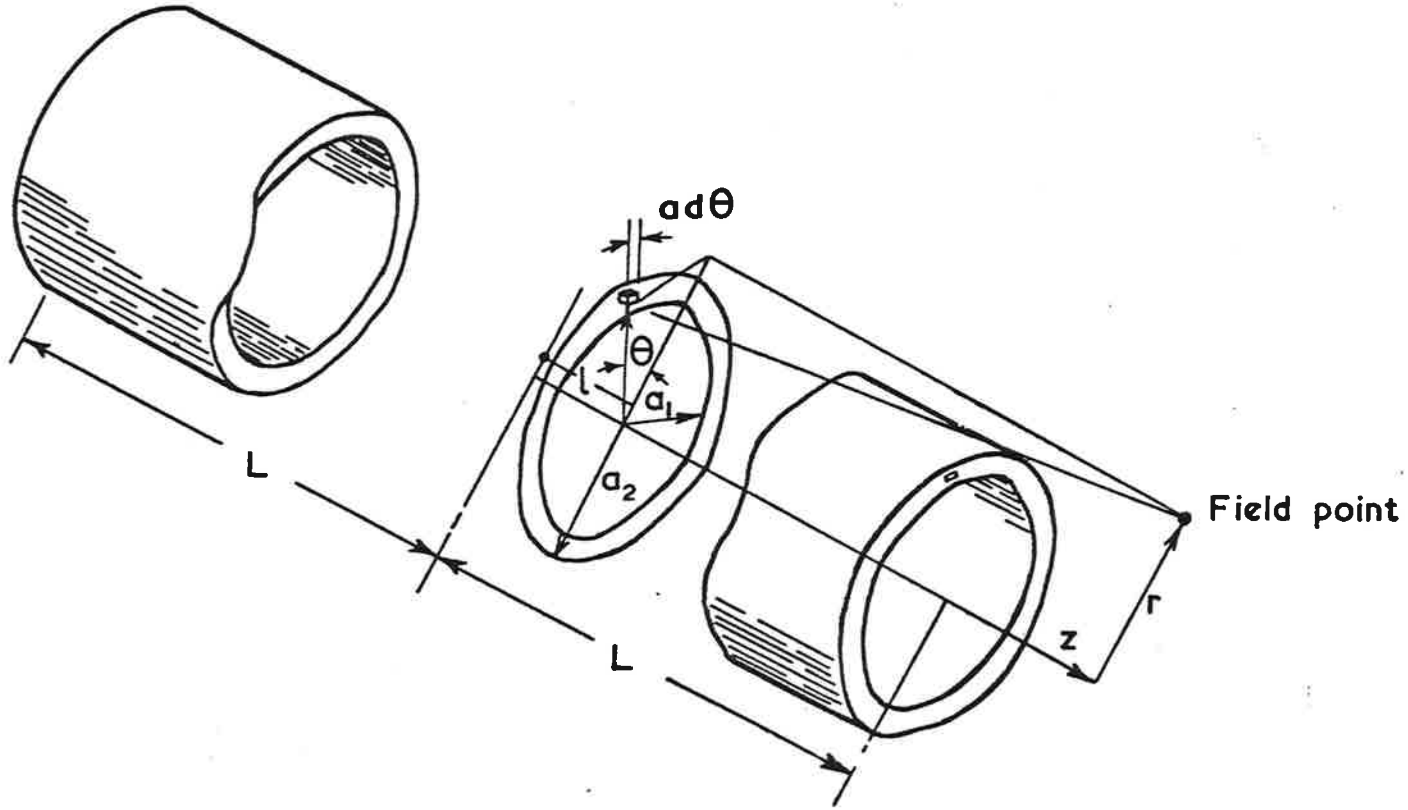
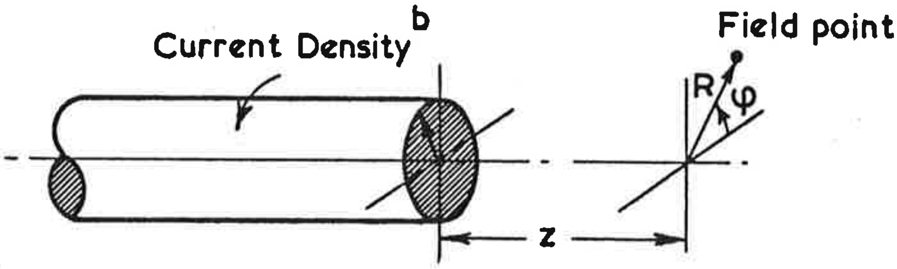
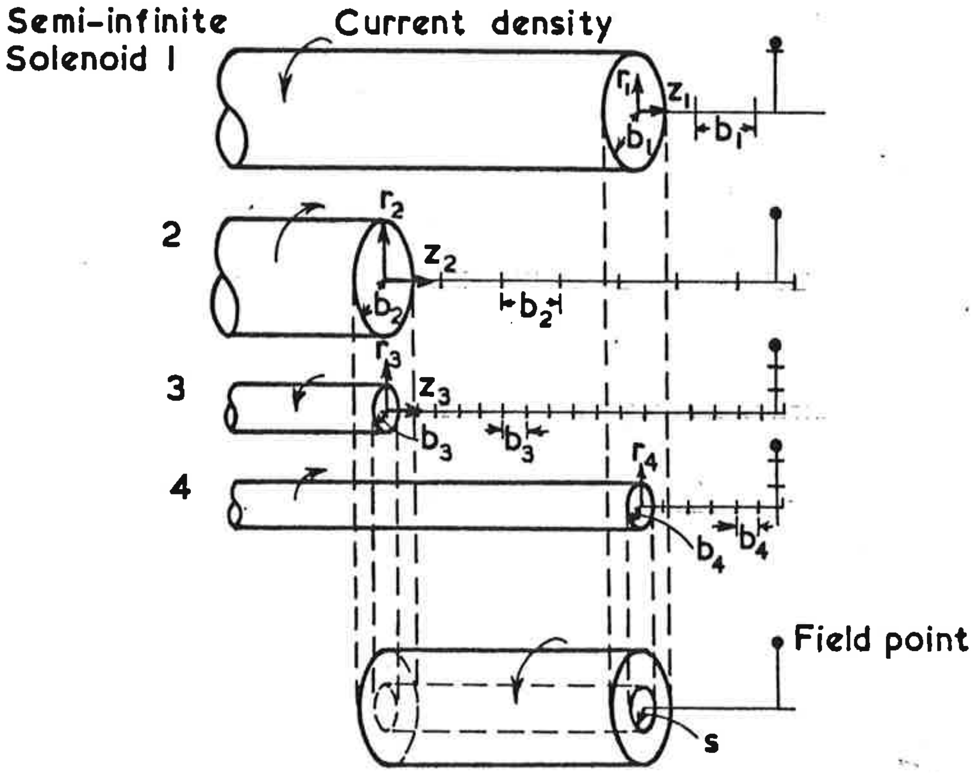


Figure 72. Coil geometry for calculating off axis field for a thick coil.



a) Semi-infinite solenoid with zero inner radius. Current density extends from axis to R=b, and from z=O to z=-∞.



b) Formation of finite solenoid from four semi-infinite solenoids.

Figure 73. Superposition of semi-infinite solenoids.