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ELECTROMAGNET CONFIGURATIONS FOR EXT ATTITUDE TESTING IN MAGNETIC SUSPENSION AND BALANCE SYSTEMS

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APPENDICES

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1. INTRODUCTION

It is desirable that a large magnetic suspension and balance system (LMSBS) be capable of supporting and restraining typical models over a wide range of test attitudes under representative test conditions. Several fundamental difficulties arise, including:

i) Identification of electromagnet array geometries capable of generating, via field and field gradient components, forces and moments on the model in the required senses and magnitudes over the full range of model attitudes.

ii) Synthesis of control algorithms capable of accommodating large changes in model aerodynamic characteristics and magnetic couplings to the electromagnets.

iii) Design of position, attitude and other sensors to monitor wide ranges of model motion.

This report addresses part of (i), that is, the inclusion of adequate versatility into the electromagnet array configuration. Sizing the electromagnets thus specified to satisfy particular absolute force and moment requirements must be performed separately.

Magnetic performance of a permanent magnet model core, air cored electromagnet MSBS may easily and reliably be computed, such as by use of the Southampton University program FORCE (point field calculation and coil interface array processing segments derived from MIT program TABLE). FORCE calculates model forces and moments via representations of the model as an assembly of dipoles and the electromagnets as an assembly of line currents. A more detailed description of the program may be found in Appendix 1.

Some aspects of the performance of an ellipsoidal iron cored model may be inferred from the above under certain circumstances.

2. THEORETICAL BACKGROUND

2.1 Required field and field gradient components

Treating rolling moment as a special case for the moment, the remaining five forces and moments on the usual axially magnetized slender model core are predominantly created by the following field components:

$F_{x'}$	(axial force)	$H_{x'x'_o}$	
$F_{y'}$	(sideforce)	$H_{x'y'_o}$	
$F_{z'}$	(normal force)	$H_{x'z'_o}$	
$T_{y'}$	(pitching moment)	$H_{z'_o}$	(Refer to Appendix 3 for definition of axis system and subscripts.)
$T_{z'}$	(yaw moment)	$H_{y'_o}$	
Magnetizing field (soft iron cores only)		$H_{x'_o}$	

In normal suspension, model and balance axes coincide and these components correspond to:

$$H_{xx_o}\ ,\ H_{xy_o}\ ,\ H_{xz_o},\ H_{z_o}\ ,\ H_{y_o}\ ,\ H_{x_o}$$

Pitching or yawing the model through 90° translates these components into:

$$H_{zz_o}\ ,\ -H_{yz_o}\ ,\ -H_{xz_o}\ ,\ H_{x_o},\ H_{y_o}\ ,\ -H_{z_o}$$

and

$$H_{yy_o}\ ,\ -H_{xy_o}\ ,\ H_{yz_o}\ ,\ H_{z_o},\ -H_{x_o}\ ,\ H_{y_o}$$ respectively

It may immediately be noticed that all nine primary field components

$$H_x\ ,\ H_y\ ,\ H_z\ ,\ H_{xx}\ ,\ H_{xy}\ ,\ H_{xz}\ ,\ H_{yy}\ ,\ H_{yz}\ ,\ H_{zz}$$

are required independently at the origin for the full range of model attitudes to be useable. The effects of the spatial variations of these components about the origin are generally of second order. Restriction of gross attitude variation (ignoring roll) to one plane, say the xz plane, only reduces the requirement by one gradient component (H_{yy} here).

All existing MSBS were designed for limited model attitude excursions about the usual datum and their electromagnet configurations are unable to effectively generate all six independent primary field gradients. However,

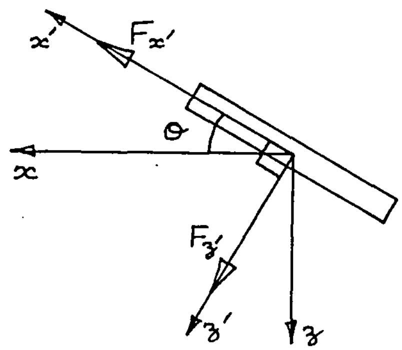
$$H_x\ ,\ H_y\ ,\ H_z\ ,\ H_{xx},\ H_{xy},\ H_{xz}\ ,\ H_{yy}\ ,\ H_{zz}$$

are generated straightforwardly and effectively, although frequently not independently, in most current MSBSs. In principle, therefore, the only radical alteration to conventional electromagnet layouts required to achieve extreme attitude capability is the provision for H_{yz} generation.

2.2 Changes in required gradient components in balance axes during model rotation

Whereas field components behave as vectors during model rotation, field gradient components do not. Evidence of this may be seen by examining the model forces in the vertical plane pitch rotation.

FIG.1 Model forces in vertical plane during pitch rotation



The required components for model normal and axial forces respectively are: $H_{x'z'}$, $H_{x'x'}$

$$H_{x'} = H_x \cos\theta - H_z \sin\theta$$

$$H_{z'} = H_x \sin\theta + H_z \cos\theta$$

$$\frac{\partial}{\partial x'} = \frac{\partial}{\partial x}\cos\theta - \frac{\partial}{\partial z}\sin\theta$$

$$\frac{\partial}{\partial z'} = \frac{\partial}{\partial x}\sin\theta + \frac{\partial}{\partial z}\cos\theta$$

$$\therefore\ H_{x'z'} = \frac{\partial}{\partial z'}H_{x'} = (H_{xx} - H_{zz})\sin\theta\cos\theta + H_{xz}(\cos^2\theta - \sin^2\theta) \quad \text{—(1A)}$$

$$H_{x'x'} = \frac{\partial}{\partial x'}H_{x'} = H_{xx}\cos^2\theta + H_{zz}\sin^2\theta - 2H_{xz}\sin\theta\cos\theta \quad \text{—(1B)}$$

These equations directly imply that B_{xx}, B_{zz} and B_{xz} must be generated independently during the rotation, and that null points occur for each field gradient with each force. A similar effect occurs with forces in the horizontal plane during yaw rotation, involving B_{xx}, B_{yy} and B_{xy}.

Using Euler angles to describe model rotation, roll orientation becomes unmeaningful for an axisymmetric core. Nevertheless, the coupling matrix from applied field gradients to forces in model axes is extremely complex when pitch and yaw occur simultaneously (Appendix 2).

It is more convenient to consider model forces in balance axes, whence model magnetizations may be resolved into components in these axes and forces expressed as follows:

$$\delta \underline{F} = \underline{J} \cdot \nabla \underline{H} \delta V$$

$$\delta \begin{pmatrix} F_x \\ F_y \\ F_z \end{pmatrix} = \begin{pmatrix} H_{xx} & H_{xy} & H_{xz} \\ H_{xy} & H_{yy} & H_{yz} \\ H_{xz} & H_{yz} & H_{zz} \end{pmatrix} \begin{pmatrix} J_x \\ J_y \\ J_z \end{pmatrix} \delta V \quad \text{—(2)}$$

Using Euler angles

$$J_x = \cos\theta \cos\psi \, J_{x'} \, , \quad J_y = \sin\psi \, J_{x'} \, , \quad J_z = -\sin\theta \cos\theta \, J_{x'}$$

Thus with the usual origin of axes:

$$\begin{pmatrix} F_x \\ F_y \\ F_z \end{pmatrix} \simeq \begin{pmatrix} H_{xx_0} & H_{xy_0} & H_{xz_0} \\ H_{xy_0} & H_{yy_0} & H_{yz_0} \\ H_{xz_0} & H_{yz_0} & H_{zz_0} \end{pmatrix} \begin{pmatrix} \cos\theta \cos\psi \\ \sin\psi \\ -\sin\theta \cos\theta \end{pmatrix} J_{x'} V \quad \text{—(3)}$$

Equation 3 represents the idealised coupling between applied field gradient components and model forces. Real electromagnet and model configurations will depart from this somewhat due to the effects of the spatial distribution of field components.

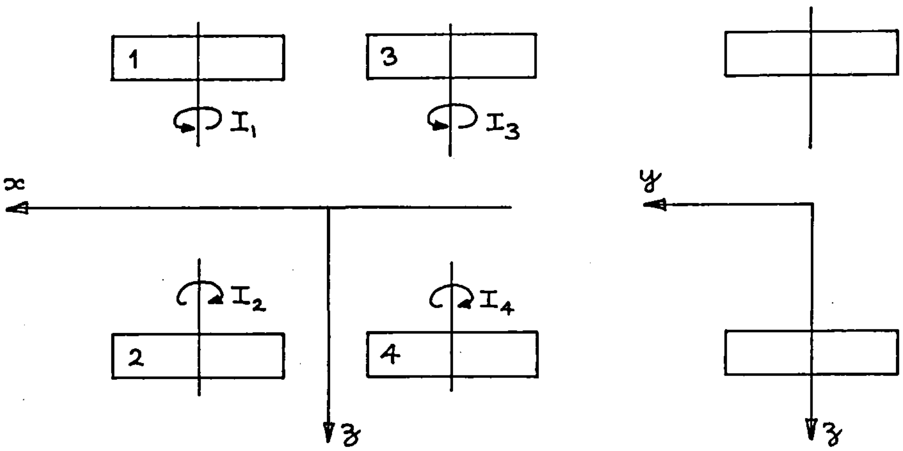
2.3 Electromagnet configurations for multiple independent field and field gradient component generation

The requirement to generate 9 components independently, necessitates at least 9 independent electromagnets. The desire for symmetry in the electromagnet array acts to increase this figure.

A straightforward quadruplet of electromagnets as shown in Fig.2

FIG.2 Symmetric Quadruplet

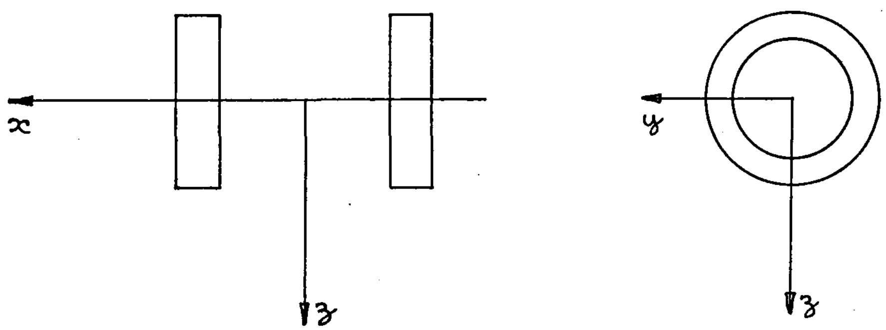
(I_n represents current in E/M n)



can generate three field gradient components at the origin, B_{xz_o} (I_1, I_4 = $-I_2$, I_3), B_{xx_o} (I_1, I_2, I_3 = I_4), B_{zz_o} (I_1, I_2, I_3 = I_4) but it is immediately seen that B_{xx} and B_{zz} are not independent. Two field components at the origin, B_{x_o} (I_1, I_2 = $-I_3$, I_4) and B_{z_o} (I_1, I_3 = $-I_2$, I_4) may also be generated. Depending on the geometry it is found that a quadruplet as shown can be relatively weak in B_{xx_o}. If B_{zz_o} were regarded as a prime component of field for this sub-configuration and the 'stray' component B_{xx_o} were countered by some other means, the quadruplet would be a useful generator of four independent field or field gradient components, B_{x_o}, B_{z_o}, B_{xz_o}, B_{zz_o}.

A pair of electromagnets can generate one field and one field gradient component independently at the origin, B_x and B_{xx} as shown below:

FIG.3 Symmetric Pair



Conventional electromagnet configurations can be considered as an assembly of quadruplets and pairs as defined above. B_{yz} can be generated by a quadruplet disposed in the yz plane but the geometry of the quadruplet may require modification to optimise its performance with particular test section cross sections.

2.4 '+' electromagnet configuration study

2.4.1 Geometry

The revised configuration for the Southampton University 6-component MSBS, (SUMSBS) not commissioned at the time of writing, falls into this category. The performance of this system cannot be computed by FORCE since the main electromagnets are iron cored; however, a system having similar proportions but arbitrary exact dimensions has been computed to yield an indication of the useable attitude range of SUMSBS. Since SUMSBS will commission with an asymmetric 'drag' electromagnet configuration, (E/M 10 below not yet existing) the first set of computations includes only electromagnets 1-8 below.

Without E/Ms 9 and 10, B_{xx} must be generated, where required, by the systems two quadruplets as described in section 2.3 above. Restriction of model attitudes to the vertical plane (yaw=0) enables the horizontal quadruplet to cancel the stray B_{xx} from the vertical quadruplet since the B_{yy} component is not now required (Eqn.3).

2.4.2 Maximum force capabilities

For any particular model attitude and force/moment requirement there is not generally a unique solution for electromagnet currents. The systems maximum force and moment capability as a function of model attitude is not, therefore, directly analytic. However, the symmetry existing in the '+' configuration may be used to simplify the problem somewhat.

With the model limited to movement in the vertical plane, it is possible to identify several electromagnet sets which, if their currents remain in certain fixed relationships to each other, produce only forces or moments. For the '+' configuration these include:

Set	E/Ms	Current sense (Fig.4)	Action
A	1,7	+ve	Forces in vertical plane only
B	3,5	+ve	"
C	2,4,6,8	+ve	"
D	1	+ve	Moments in vertical plane only
	7	-ve	
E	3	+ve	"
	5	-ve	
F	2,4	+ve	"
	6,8	-ve	

Note that sets A,B,C and D,E,F are each mutually exclusive.

If the required pitch and yaw moments are zero(they will generally be small about the model C.G.) two equation in three variables may be formed as follows:

$$F_x = aI_A + bI_B + cI_C \qquad (4a)$$

$$F_z = dI_A + eI_B + fI_C \qquad (4b)$$

Where a-f are constants depending on the geometry of the system.

It may be argued that for given current limits, say I_A' etc., the maximum force capability occurs with at least one current at its limiting value (+ve or -ve). Let that current be I_A for example. Choosing a fixed relation between F_x and F_z, say $F_z = kF_x$ and eliminating I_B from equations 4, we have

$$F_x = \left(a + \frac{b(ka-d)}{(e-kb)}\right) I_A' + \left(c + \frac{b(kc-f)}{(e-kb)}\right) I_c \quad \text{—(5)}$$

Since this is a simple linear equation in I_C it follows that for maximum F_x, I_C must be at some limiting value. This value might be set by the current limit of I_C or I_B (via the relation between I_B and I_C).

FORCE may be used to evaluate parameters a-f which can then be processed on the assumption that for maximum force in any given direction with the model in any fixed attitude, at least two of the available three currents must be at their limiting values.

The results of this study are summarised in Figs.5-6. The discontinuities in slope of the maximum resultant force lines are due to changes in the distributions of electromagnet current limiting, for example, sets A and B may initially be limited whilst C is not, transforming to sets A and C limited whilst B is not, with small change in θ.

2.4.3 '+' configuration with axial electromagnets

It is argued that the requirement for (n-1) electromagnet sets to be at their current limits for a maximum force in a given sense with n independent sets available may be extended to the case of n=4. The computations in 2.4.2 may thus be extended to include electromagnets 9 and 10. Results are summarised in Figs.7-9.

Moment and sideforce calibrations are presented in Figs.9-12.

2.4.4 Discussion of results

The absolute magnitudes of forces shown in Figs.5-9 are of somewhat limited significance. They do not represent the minimum attainable forces for the chosen configuration, merely the forces attainable within the constraints of given electromagnet current limits. The absolute maximum attainable forces with a permanent magnet model core are principally set by the magnetic behaviour of the core (demagnetization). Relevant magnetic data for high coercivity permanent magnet materials was not available at the time of writing. The corresponding limits for a soft iron core will be set by the behaviour of the induced magnetization as the core material enters its saturation region.

The features in Figs.5-12 which are intended to be highlighted are:

1) The variations of force capability with angle of attack.
2) Some indication of the variations of force capability at any particular angle of attack as the demand force vector rotates.
3) Illustration of the changes in magnetic coupling between electromagnet sets and model forces and moments.
4) Via (1), (2) and (3) identification of weaknesses, if any, in the candidate E/M configuration vis-a-vis requirements for extreme attitude capability.

It is seen from Figs.5-9 that two local minima occur in the curves for model normal force and for worst case β's. These correspond approximately to the attitudes where electromagnet sets A and B lie perpendicular and parallel to the model axis respectively. Addition of axial E/Ms considerably improves performance at these points. Fig.6 may be considered to illustrate an unsatisfactory performance insofar as model normal force capability falls rapidly as angle of attack increases from zero. Again, addition of axial E/Ms alleviates the difficulty.

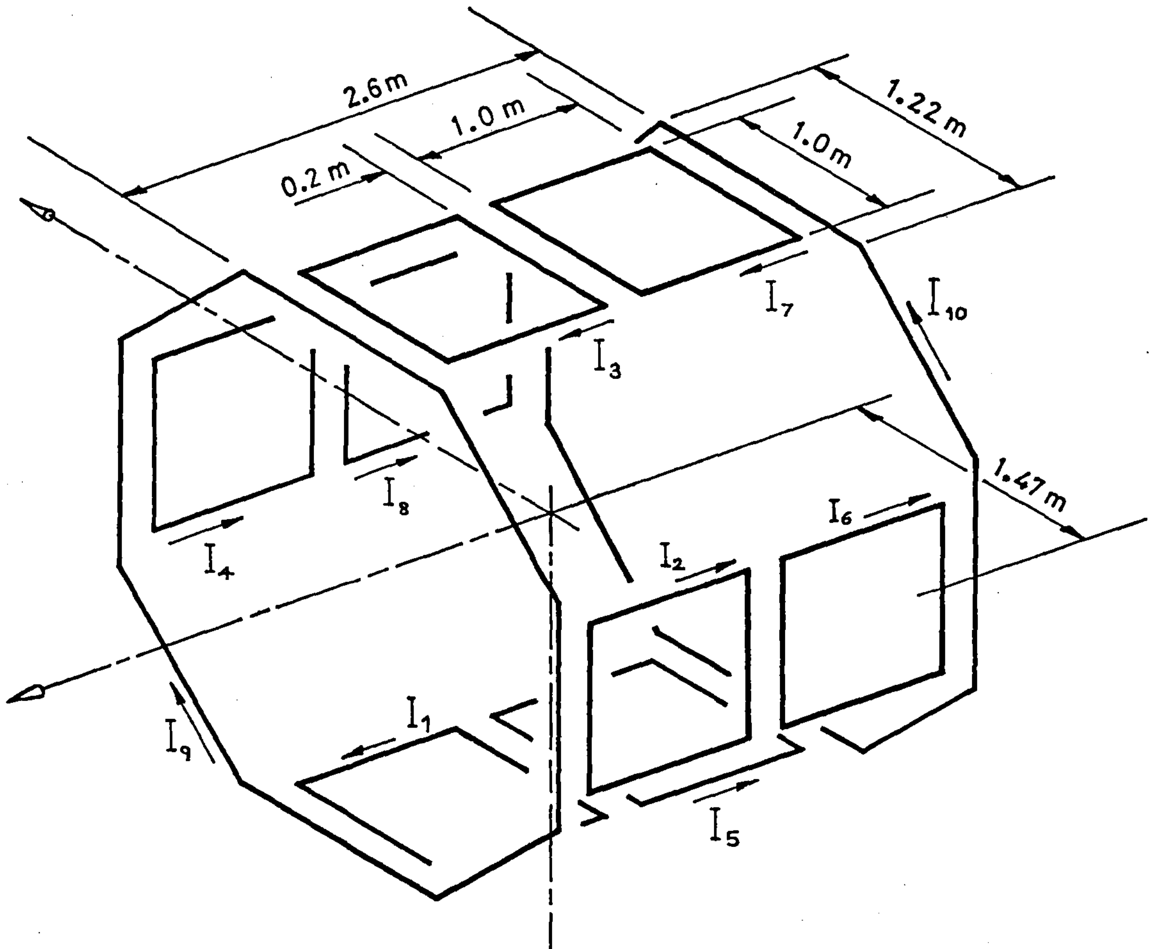


Fig.4 "+" configuration geometry and dimensions

All E/Ms line conductors.

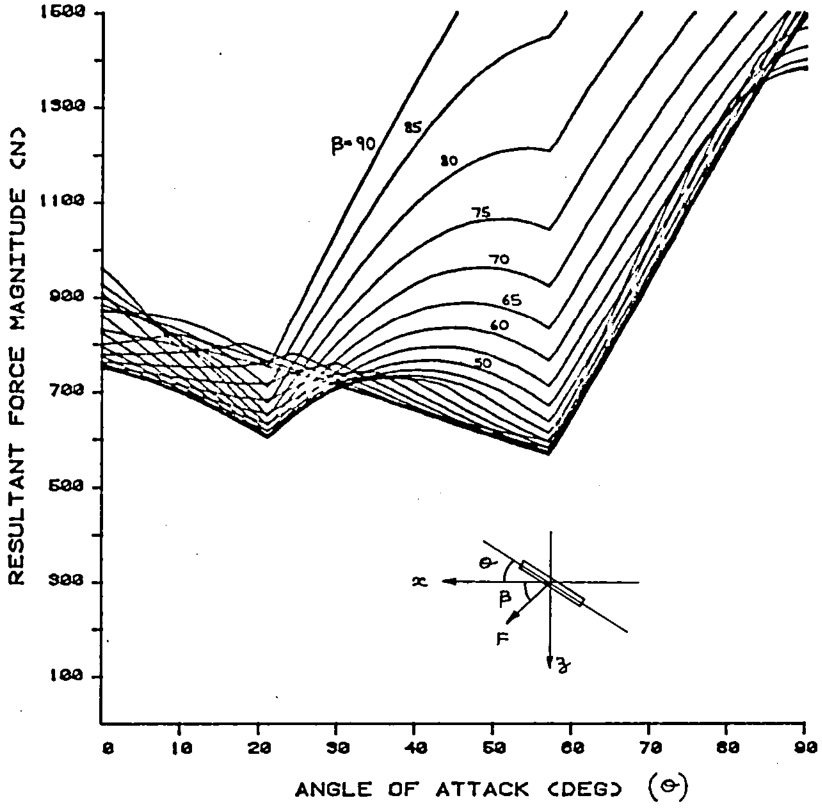


FIG.5 Maximum attainable forces

"+" configuration as FIG.4

E/Ms 1-8 limited at 10^6 amps

E/Ms 9-10 limited at 0 amps

β as Appendix 3

Cylindrical model core:

1.0m × 0.1m ∅

1 Tesla polarization

24 elements.

FIG.6 reproduces some of the content of this graph in a simplified manner.

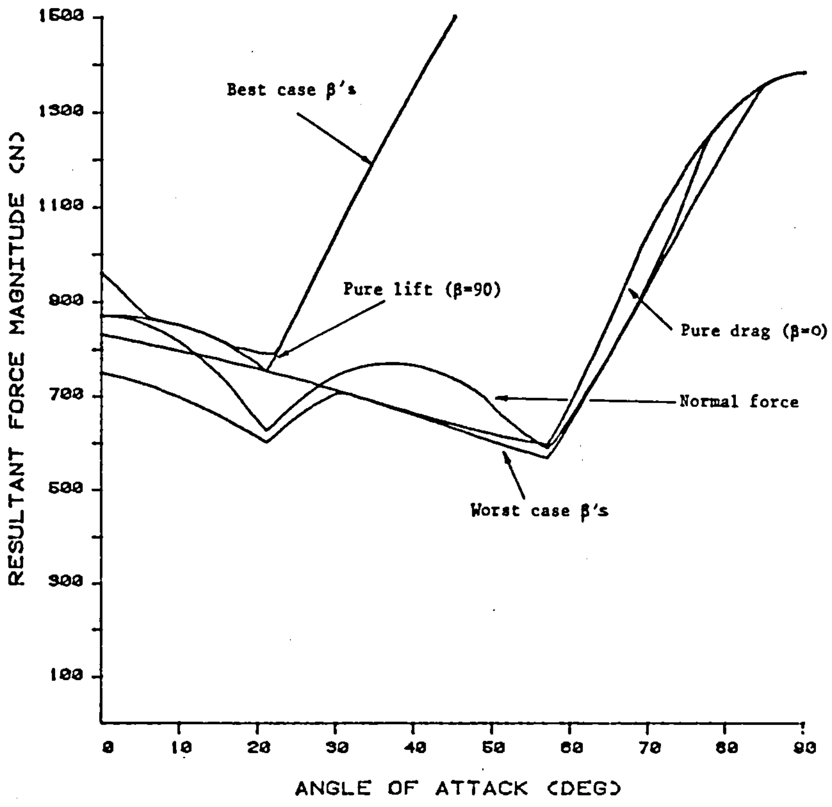


FIG.6 Maximum attainable force envelope

"+" configuration as FIG.4

E/Ms 1-8 limited at 10^6 amps.

E/Ms 9-10 limited at 0 amps.

β as Appendix 3

Cylindrical model core:

1.0m × 0.1m ∅

1 Tesla polarization

24 elements.

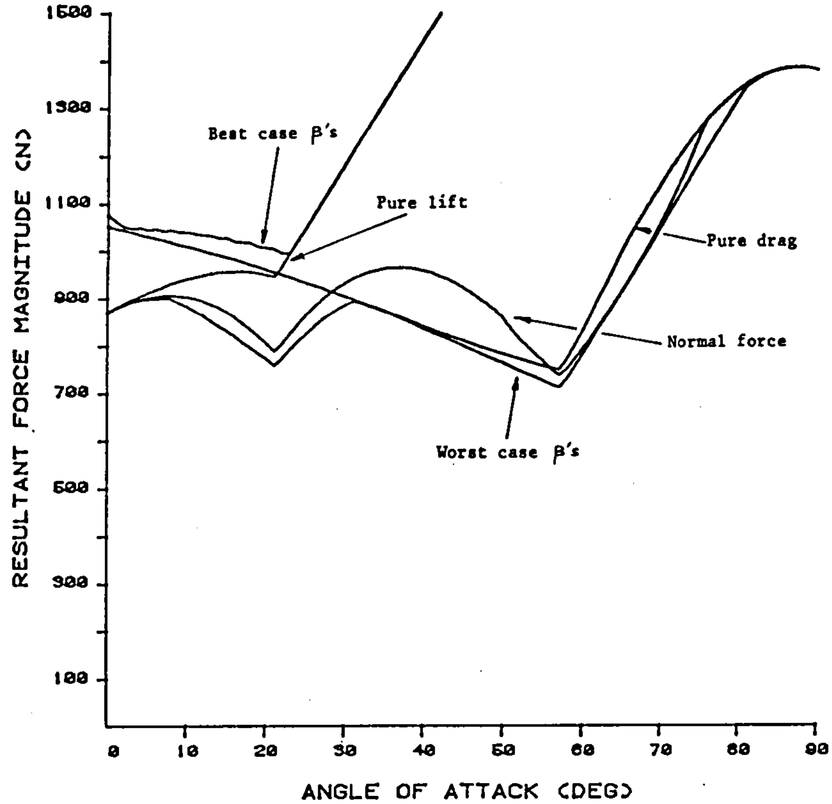


FIG.7 Maximum attainable force envelope

"+" configuration as FIG.4

E/Ms 1-8 limited at 10^6 amps.

E/Ms 9-10 limited at 10^5 amps.

β as Appendix 3

Cylindrical model core:

1.0m × 0.1m ø

1 Tesla polarization

24 elements

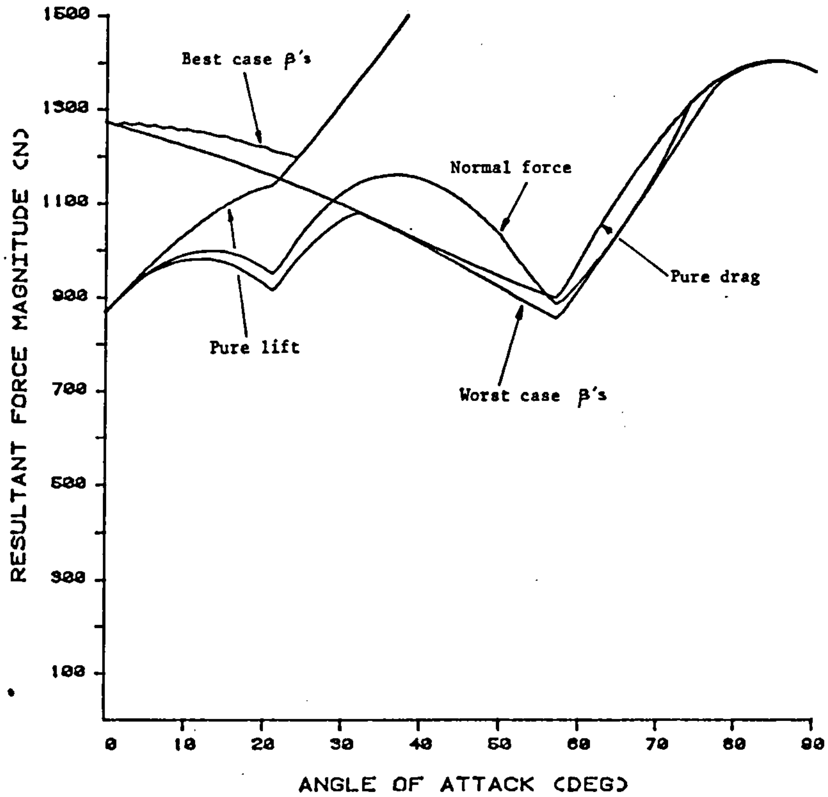


FIG.8 Maximum attainable force envelope

"+" configuration as FIG.4

E/Ms 1-8 limited at 10^6 amps.

E/Ms 9-10 limited at $2 \cdot 10^5$ amps.

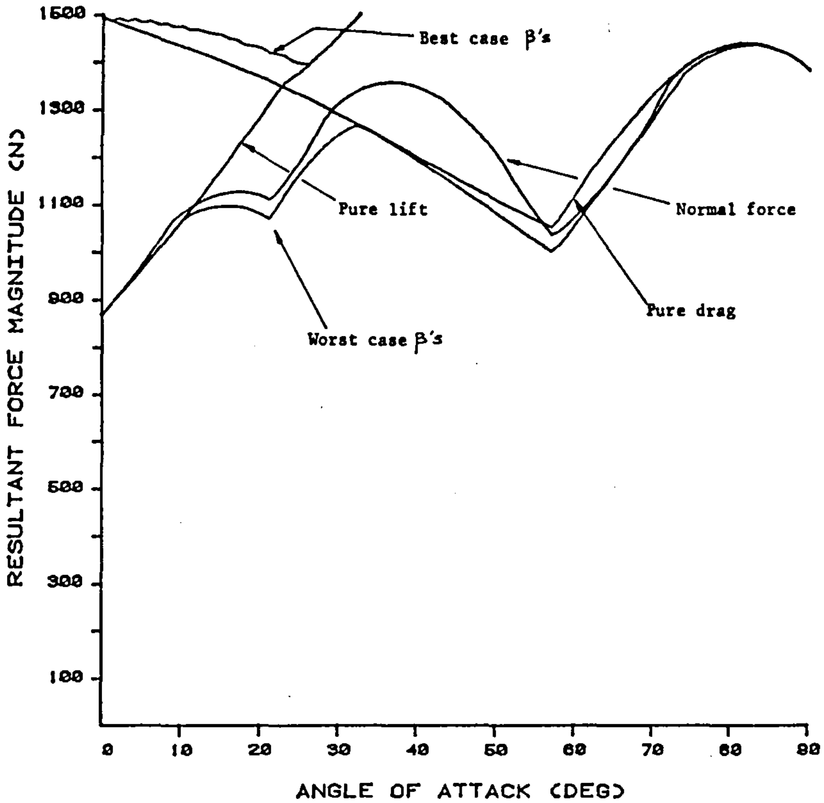
β as Appendix 3

Cylindrical model core:

1.0m × 0.1m ø

1 Tesla polarization

24 elements.



<u>FIG.9 Maximum attainable force envelope</u>

"+" configuration as FIG.4

E/Ms 1-8 limited at 10^6 amps.

E/Ms 9-10 limited at 3×10^5 amps.

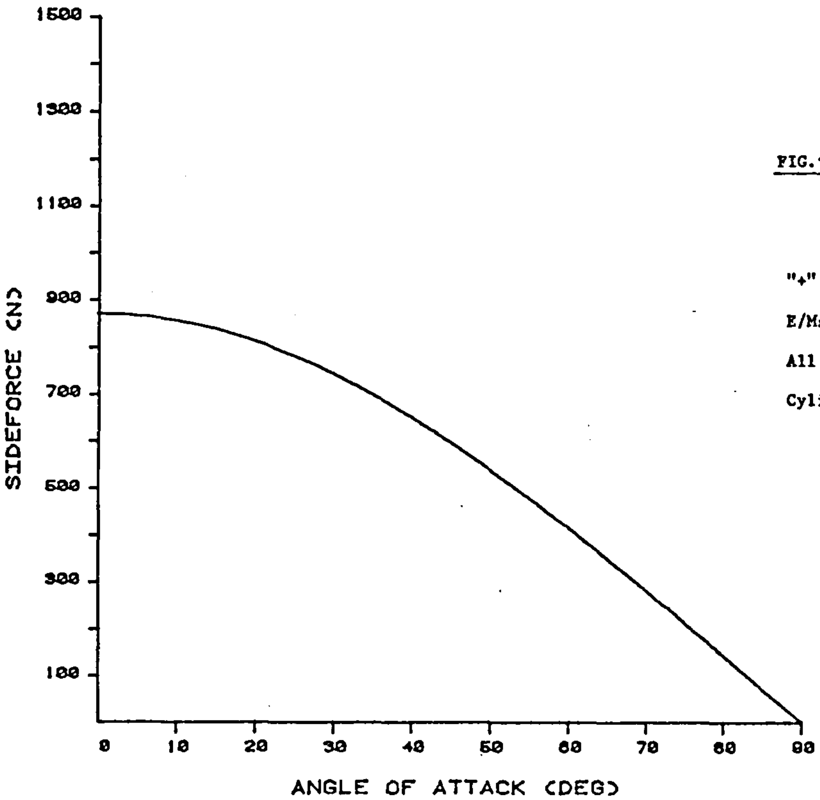
β as Appendix 3

Cylindrical model core:

1.0m × 0.1m ∅

1 Tesla polarization

24 elements



<u>FIG.10 Sideforce variation, currents constant</u>

"+" configuration as FIG.4

E/Ms 2,4,6,8 limited at 10^6 amps.

All other E/Ms zero current.

Cylindrical model core:

1.0m × 0.1m ∅

1 Tesla polarization

24 elements.

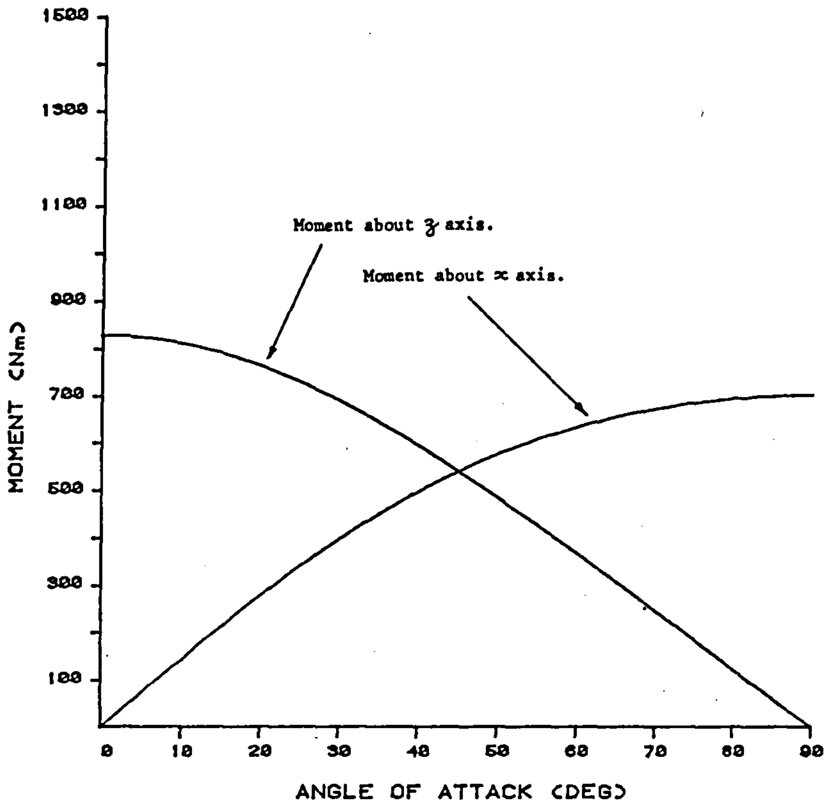


FIG.11 Yaw moment variation,

currents constant.

"+" configuration as FIG.4

E/Ms 2,4,6,8 limited at 10^6 amps.

All other E/Ms zero current.

Cylindrical model core:

1.0m × 0.1m ø

1 Tesla polarization

24 elements.

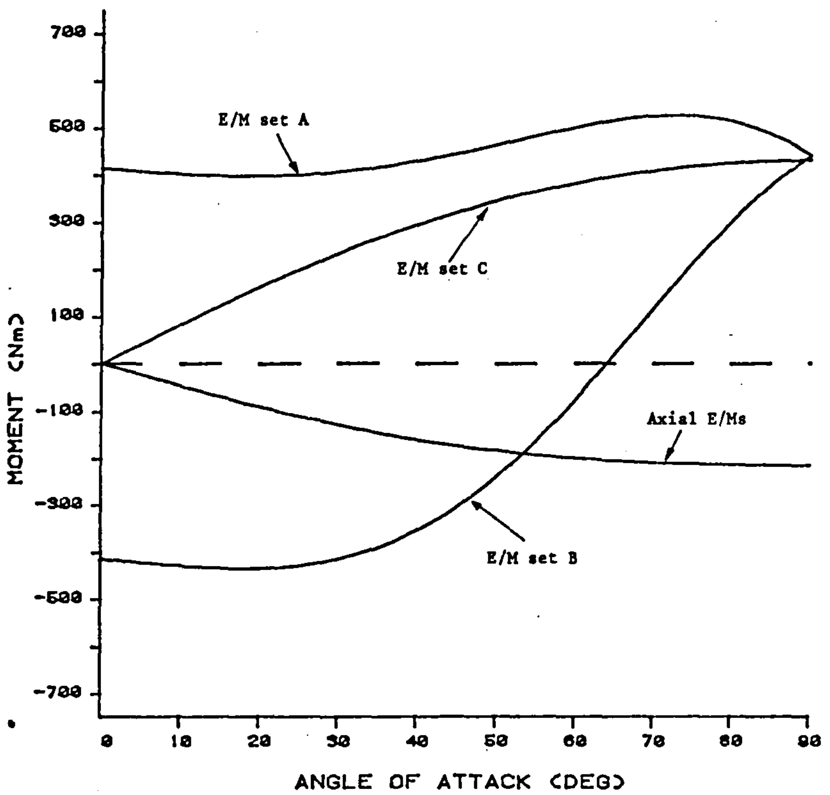


FIG.12 Pitching moment variation,

currents constant.

"+" configuration as FIG.4

E/M sets A,B,C limited at 10^6 amps.

E/M set C limited at 10^5 amps.

Only one set activated per curve.

Cylindrical model core:

1.0m × 0.1m ø

1 Tesla polarization.

24 elements.

Only one catastrophic flaw remains in this configuration, that is the inability to generate sideforce at 90° pitch. This is due, as predicted, to the lack of Hyz capability.

3. MSBS SCALING LAWS

For absolutely constant balance geometry, model magnetization, E/M current densities[1] and model aerodynamic characteristics:

Magnetic forces $\propto \ell^3$ (moments $\propto \ell^4$)
Aerodynamic forces $\propto \ell^2$ (moments $\propto \ell^3$)

where ℓ is some reference length of the configuration.

For change in model magnetization:

Magnetic forces and moments $\propto$ J

The strict condition of constant geometry may be relaxed somewhat. For small changes in the cross-section of the magnetic core, length held constant:

Magnetic forces and moments $\dot{\propto}$ cross sectional area.

Magnetic performance of MSBS configurations can be sensitive to changes in the length of the magnetic core. For large changes in the current density in the E/Ms or small changes in E/M cross sections:

Magnetic forces and moments $\dot{\propto}$ E/M cross section
Magnetic forces and moments $\propto$ current density

4. GENERAL DISCUSSION AND CONCLUSIONS

The results presented show that SUMSBS should be useable over a pitch attitude range of at least -45° to +45° with this attitude measured in its usual sense. If symmetric axial E/Ms become available it is thought that this range may be extended if the plane of pitching is inclined at 45° to the vertical, effectively converting the E/M configuration to a "X" type. A supplement to this report is under preparation with analysis of a "X" configuration, extension of the "+" and "X" types to cover simultaneous yaw and pitch and analysis of other configurations more appropriate to the requirements of the NASA LMSBS.

1. Infinite in Figs.5-12

In the design of an extreme attitude capable MSBS it is probably more appropriate to consider the electromagnet array simply as a generator of field and field gradient components in the test section, rather than an assembly of "lift" and "drag" E/Ms etc., as has been common previously. Useable model attitudes (ignoring roll again) are unlimited if all components can be generated effectively and independently. It is advantageous that the fields are relatively pure and uniform in the region of the model (the central volume of the test section) in order to minimise cross coupling effects. This requirement may perhaps be met by use of Helmholtz pairs and corresponding optimised geometries for multiple arrays.

The field or field gradient component most commonly absent from contemporary MSBSs is Hyz. The spanwise magnet rolling moment generation system under development at Southampton University utilises Hyz as the prime source of rolling moment with the model at normal attitudes. For this and other reasons it would appear that the application of MSBSs to extreme attitude testing should not require a drastic departure from conventional E/M array configurations.

APPENDIX 1 Program FORCE, background and description

The major features of any MSBS for wind tunnel applications are a suspended model composed largely of magnetic material surrounded by an array of electromagnets. It is necessary to predict the magnetic behaviour of candidate systems but unfortunately only the very simplest geometries yield to wholly analytical treatment. The inherent complexity of most geometries of MSBS makes the use of some numerical and/or finite element approach essential. Calculation for realistic configurations when soft magnetic materials are present in the model or E/Ms is extremely difficult. Where the electromagnets are air cored and the model is composed of high coercivity permanent magnet material or where the magnetization of the model is already established, calculation can be comparatively straightforward.

The program FORCE is designed for analysis of permanent magnet model core, air cored E/M MSBSs. The program runs semi-interactively on a minicomputer and is heavily modularised in order to restrict its main memory requirement. The main features and capabilities of the program are summarised below:

1) Simple representations of E/Ms as assemblies of line current elements.
2) Symmetry options to allow generation of an array of E/Ms from one input data set.
3) Finite element representations of simple model core geometries.
4) Calculation of magnetic fields of E/M.
5) Calculation of forces and moments on the model core (unit polarization).
6) Model and E/M configuration storage in data files.
7) Output routing to data files.

APPENDIX 2 Coupling from applied field gradients to forces in model axes

$$\begin{pmatrix} F_{x'} \\ F_{y'} \\ F_{z'} \end{pmatrix} = J_{x'}V \begin{pmatrix} p^2q^2 & 2p^2qs & -2pqr & p^2s^2 & -2prs & r^2 \\ -pqs & p(q^2-s^2) & rs & pqs & -qr & 0 \\ pq^2s & 2pqrs & q(p^2-r^2) & prs^2 & s(p^2-r^2) & -pr \end{pmatrix} \begin{pmatrix} B_{xx} \\ B_{xy} \\ B_{xz} \\ B_{yy} \\ B_{yz} \\ B_{zz} \end{pmatrix}$$

Where $p = \cos\theta$ $q = \cos\psi$ $r = \sin\theta$ $s = \sin\psi$

V = Model element volume $J_{x'}$ = Polarization(axial)

APPENDIX 3 Magnetic units and definitions.

Units

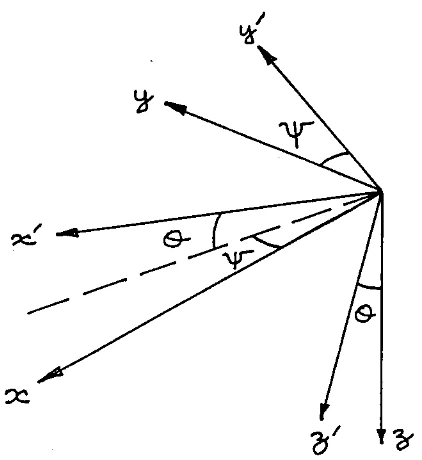
All equations are given in the SI system of units, whence $B = \mu_o H$ in free space ($\mu_o = 4\pi \times 10^{-7}$). However, there are two alternative subsystems, the Kennelly and Sommerfeld systems. The Kennelly system is used in this report, in the belief that it is somewhat more convenient where only permanent magnetic material is present. The key definitions of this system are:

$\underline{B} = \mu_o \underline{H} + \underline{J}$ (flux through permanent magnet material)

$\delta\underline{F} = \underline{J}.\nabla \underline{H}\ \delta V$ (force on a dipole)

$\delta\underline{T} = \underline{J} \times \underline{H}\ \delta V$ (torque on a dipole)

Model and tunnel axis system



Tunnel axes - x, y, z

Model axes - x′, y′, z′

Sequence of rotations - Yaw, pitch

Roll orientation not significant for axisymmetric core.

o subscripts (e.g. x_o) imply the origin of axes

Field property subscript notation

The first subscript to the field property indicates the component under consideration, the second (where present) specifies the gradient direction, e.g.

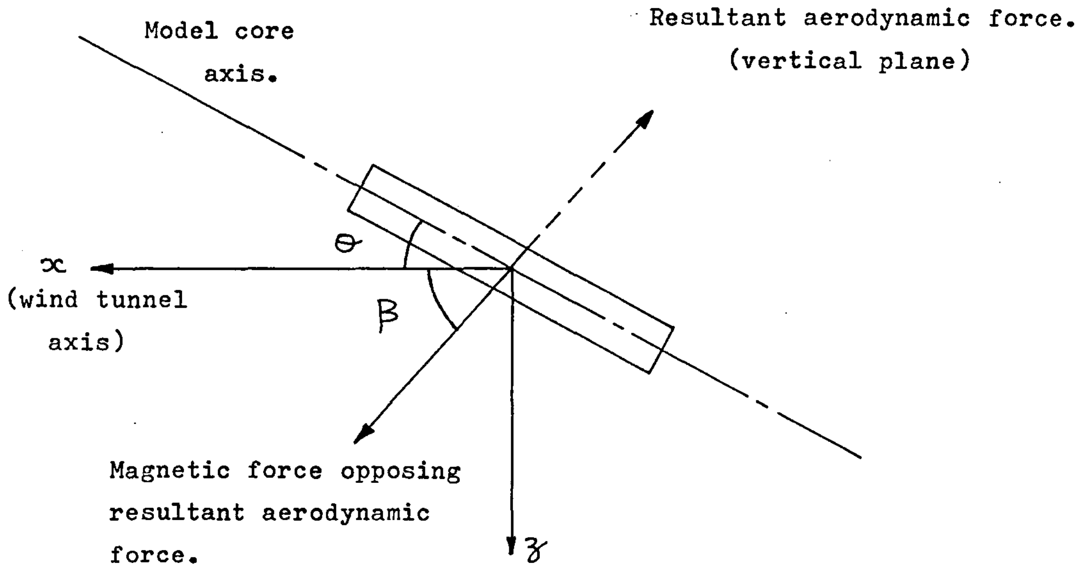
$H_a \equiv$ field strength in direction a (a=x,y,z,x′,y′,z′)

$$H_{ab} \equiv \frac{\partial}{\partial b}(H_a)$$

In free space $H_{ab} = H_{ba}$

As above $H_{ab_o} \equiv H_{ab}$ evaluated at the origin of axes.

Definition of θ and β .



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15. Supplementary Notes

Principal Investigator was Dr. M. J. Goodyer.
Langley Technical Monitor was Richmond P. Boyden.

16. Abstract

A preliminary examination is made of the impact on conventional wind tunnel magnetic suspension and balance system configurations of a requirement to suspend models over a wide range of attitudes relative to the balance system. The problem of gross changes in the systems magnetic couplings is addressed. Computations concerning a ten electromagnet system in the classical "+" arrangement, representative of the system under construction at Southampton University, indicate that a permanent magnet model could usefully be suspended to approximately 45° angle of attack in the vertical plane. The study continues towards the exploration of higher angles of attack.

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