NASA Contractor Report 172520

NASA-CR-172520
19850009759,

THE GENERATION OF ROLLING MOMENTS WITH
THE SUPERCONDUCTING SOLENOID MODEL

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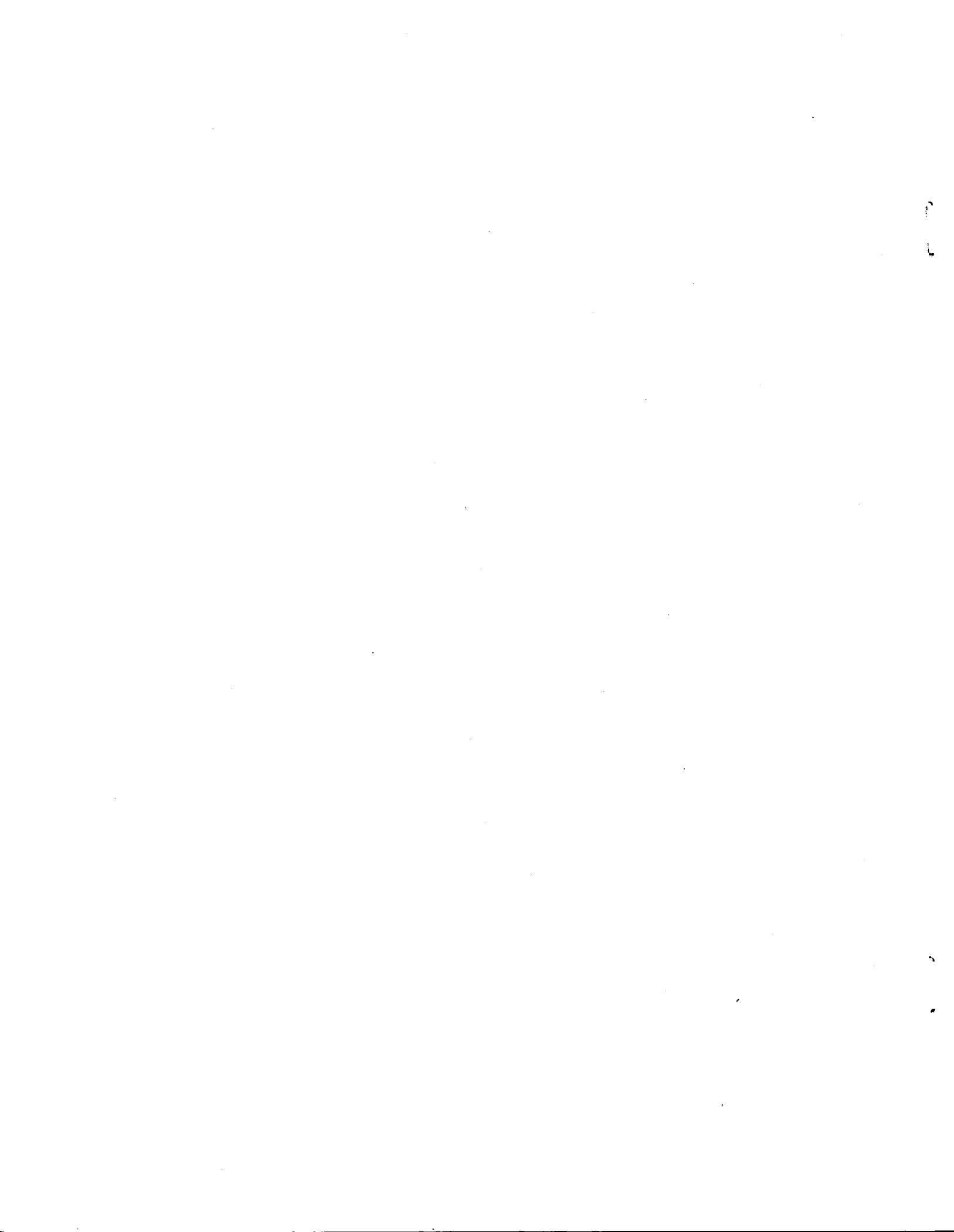
THE GENERATION OF ROLLING MOMENTS WITH THE SUPERCONDUCTING SOLENOID MODEL

M.J. Goodyer

1. INTRODUCTION

The SuperConducting Solenoid (SCS) model is a wind tunnel model for levitation in a magnetic suspension system, the model featuring the substitution of this solenoid for the usual permanent or soft magnetic core. As the design is relatively new a few words describing its features might be useful.

The model, which would typically be of an aircraft, contains within its fuselage a superconducting solenoid working in the persistent mode, the axis of the solenoid lying along the fuselage and behaving as a permanent magnet producing poles near each end of the model. The solenoid must be held near liquid helium temperature and is therefore housed within a cryostat. When in suspension there is a slow helium boiloff resulting in a finite superconducting lifetime because the model must be suspended free of umbilicals. For suspension purposes the solenoid is operated upon by a set of electromagnets (which themselves might be superconducting) surrounding the wind tunnel and supplied with variable currents to accommodate the demands of the wind tunnel test while holding the model in position. The principal advantage that the SCS has over the options of the various types of conventional magnets is a higher magnetic moment per unit volume in this application, which is reflected in a need for smaller suspension electromagnets. As the main part of the cost of such systems will lie in the suspension electromagnets there will be useful overall cost reductions despite the relative complexity of the model. With the model in the normal attitude the set of suspension electromagnets is able to exert magnetic forces resisting the aerodynamic drag, lift and side forces, and magnetic moments resisting pitching and yawing moments. A rolling moment cannot be resisted by the solenoid through any manipulation of the magnetic fields from the electromagnets.

In most cases the largest requirements for magnetic rolling moment occur on winged models such as transport aircraft or fighters. In these cases the most appropriate way[1,2] to produce the magnetic moment is to partially fill the wings with material magnetised in the spanwise direction and to provide the system with suitable roll control electromagnets around the test section. However there will be occasions, when suspending models such as missiles for example, where there are no flying surfaces suitable for exploitation for roll control but when control is required nevertheless. In these circumstances there is a need for some alternate source of control moment although it is evident that the required capacity is likely to be appreciably less than in the case of winged models when comparisons are based on equal fuselage lengths.

This report covers the work carried out to date on the subject of providing sources of rolling moment for use when the spanwise magnets are not available.

Several methods have emerged for generating a rolling moment based on the use of elements positioned around or within the solenoid. The methods fall into two categories: (i) superconducting loops added to the solenoid specifically for the purpose of roll control and (ii) magnetic poles added to a simple SCS model likewise specifically for roll control.

This report first introduces the various roll elements, then presents predictions of the moment capacities of superconducting loops in models sized for a large wind tunnel. An existing prototype SCS model[3-6] proved a suitable vehicle for demonstrating and calibrating at a smaller scale some of the other roll elements based on magnetic pole devices. Calibration data is included.

2. THE FIELD COMPONENTS AVAILABLE FOR ROLL CONTROL

2.1

The first roll control devices to be employed in magnetic suspension systems[7-10] exploited a field component in the y-direction (refer to Figure 1) symmetric about the x-axis which would develop a roll torque, but no other force or moment, on a suitably shaped model. The essential feature of the roll field is a component B_y anti-symmetric about

the x-axis. In practice at small values of x, y, and z relative to the dimensions of the electromagnets this field component is proportional to y (B_y = ky where k = f(x)) and independent of z at a particular x. The field was produced by pairs of identical electromagnets, numbered 2, 4, 6 and 8 in Figure 1, positioned along each side of the wind tunnel. To produce a rolling moment, electromagnets 2 and 4 were given one polarity and 6 and 8 the opposite polarity. The model carried either small wire coils to react with the field component to produce the roll torque, or a suitably shaped magnetic core, or magnetic material in the wings magnetised through the thickness. The same field component may be used with the SCS model when it carries suitable roll elements, and essentially the same electromagnet array was used in the tests reported here but with one important innovation. The array has been improved since the pioneering work on roll control by the addition of a pair of electromagnets, 1 and 5 in Figure 1, to complete the symmetry in the vertical plane[2], a change which introduced the possibility of exploiting in roll control a second field component similar to that just outlined but in the z-direction and created by electromagnets 1, 3, 5 and 7. By suitably selecting the sign of the field this component will add to the roll torque from the same roll elements on the model. Magnetic pole devices were tested in fields of this type.

It seems likely that identically the same field components may be used to produce roll torques from forces on loops of superconducting wire of suitable shape inside or around the superconducting coil of an SCS model. The suspension system at the University of Southampton could in principle be used this way, but modification of the existing SCS model has not yet been undertaken.

2.2

Another roll control field is that used in the spanwise magnet system. The required field is one in the z-direction, at right angles to wings lying in the xy plane[1]. The field may be produced by four electromagnets devoted to the function. However a recently designed set of electromagnets for an eight-foot square test section[11] is used in calculations, presented later, of the rolling moment available from current-carrying roll loops in an SCS type of model.

Figure 2(a) shows the relevant electromagnets[11] in simplified form. Just the centrelines are shown for clarity with the current directions required for one sign of rolling moment on a suitably designed model suspended in the position shown, which is with the model on the origin of the axis system. The four electromagnets are identical and are supplied each with the same current. The model is assumed in this report to be in the normal attitude for wind tunnel testing, that is with the axis of the model aligned with the x-axis which is also the wind axis.

Illustrated on Figure 2(b) is the pattern of the field computed by the program FORCE[2] in the y-z plane, which may be taken as representing the field along the whole model since although the model extends some way along the x-axis (perhaps from x = -0.4m to +0.4m), with this particular design of electromagnet the field is practically independent of x in this range.

The area covered by the figure is chosen to encompass the likely diameters of SCS model roll loops and does not therefore extend any significant distance along the wings. Despite this the field component which produces a rolling moment on spanwise magnetised wings is evident: that is the z-component across the y-axis which is seen increasing (in fact linearly) with y.

The force produced by this field on a conductor crossing the y-axis and lying parallel to the x-axis will not contribute to roll torque. In contrast such a conductor lying on the 45-degree line OA experiences a force contributing directly to roll as will be discussed later. Four such current-carrying conductors disposed symmetrically about the x-axis can produce a pure roll couple.

3. ROLLING MOMENT ELEMENTS

3.1 Superconducting rolling moment loops

Rolling moments have been produced in the past by incorporating small coils of wire into models, the coils carrying D.C.[8,9] or A.C.[12] currents. The coils are operated upon by suitably controlled components of the suspension magnetic field, components which affect only roll. The

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former version is suitable for exploitation by the SCS model since it also carries a D.C. current which can be diverted through roll windings.

Figure 3 shows the essentials of the proposed geometry. The main model solenoid is shown in outline only while the roll loops are highlighted. As drawn they lie inside the solenoid but there is the option of winding the roll loops on the outside. It is proposed that they be connected in series with the solenoid for simplicity in the external connections required during charge-up. The current flow directions are those which, when interacting with the fields from the racetrack coils of Figure 2, produce a rolling moment. The loops are shown in the normal attitude, that is with the planes of the loops horizontal leading to one of the long arms lying on line OA of Figure 2(b). Section 4 contains a summary of computed torque capacities.

3.2 Magnetic pole devices

From among the rolling moment devices already developed for conventional magnetic suspension models[7-10] two types were chosen for exploration on the existing SCS model, along with a new quadrupole device. They are all sketched on Figure 4. The mild steel saddle pairs and the shaped pole were intended to be magnetised by the field from the solenoid. In the event the shaped pole proved to be too far from the solenoid for there to be a measurable roll torque, and the device is not discussed again. The permanent magnet quadrupole (comprising four samarium cobalt magnets of dimensions 30mm x 10mm x 6mm magnetised parallel to the 6mm dimension and arranged in the manner shown on Figure 4(b)) was calibrated for rolling moment capacity under the action of roll field components from their nearest electromagnets, those numbered 5, 6, 7 and 8 on Figure 1.

The mild steel saddle pairs were 1 inch long 45 degee segments cut from tube of inside diameter 2.5 inches and outside diameter 3 inches. They were clamped to the outside of the existing cryostat near to the ends of the solenoid and magnetised to some extent by its field. In the tests of these devices the rolling moment was produced by the eight

electromagnets numbered 1-8 on Figure 1. Calibration data on each of these rolling-moment elements is in the following section.

4. ROLLING MOMENT

4.1 Computations for roll loops in an SCS model suspended in a large balance

In these computations the suspension electromagnets are taken to be those proposed by Boom et al[11] working up to the current limits proposed in that reference, that is a maximum current density based on the cross-section of superconductor of 1500 amps per square centimeter.

4.1.1 Model in nominal attitude

Nominal attitude is the model suspended with its longitudinal axis along the x-axis centered on the origin and with zero displacement in roll. The four long sections of the model's roll loops lie parallel to the x-axis but in 45 degree planes between the y and z axes.

With the four roll racetrack coils equally energised to the maximum, the field generated is that shown on Figure 2(b). The ampere-turn product for each of these coils is 3.9 million. A feature of the field near to the model is strength proportional to radius. A current-carrying conductor anywhere on line OA running into the figure will experience a force at right angles to OA and therefore contributing to rolling moment about the origin. Four conductors symmetrically placed and carrying the same curent, suitably directed, will produce a pure couple.

The roll torque produced by such a set of roll elements (that is the roll loops shown on Figure 3 combined with the racetracks shown on Figure 2(a)) is given by

$$\text{Torque} = k.r.^2.\ell.i_m.i_r$$

where   k is a constant dependent on the racetrack geometry,

i_m is the ampere turn product in each of the two roll loops in the model,

i_r is the ampere-turn product in each racetrack,

ℓ is the length of a long arm of a roll loop measured along the x-axis,

r is the radius of a long arm of a roll loop measured from the x-axis.

The value of the constant k is $7.77/10^7$ T/Am for these racetracks.

The maximum rolling moment to be expected from a model may be estimated if assumptions are made for the geometry of the roll loops and current density. Two model design studies have been published[13] which allow estimates to be made of appropriate dimensions for roll loops which might be added to them. The studies indicate that a model might contain a cryostat having internal dimensions allowing loop lengths of 700mm. The rolling moment is sensitive to the assumed rdius and it is important not to overestimate this dimension. The design studies indicate that a radius of 30mm might correspond to roll loops mounted inside the solenoid and 45mm to loops outside. It should be noted that the latter option, while giving the higher moment, detracts from the performance of the solenoid as it must be reduced in size to create room for the roll loops because of space limitations in the model. The current density assumed for the windings of model solenoids is 300 amps/mm^2, a figure adopted here also for roll loop windings. The moment capacities become 0.573 and 1.289Nm respectively per mm^2 of winding in each of the two roll loops. It is anticipated that loop winding cross-sectional areas of at about 50mm^2 should be reasonable (perhaps more in the case of loops mounted on the inside and less on the outside) giving maximum rolling moments of about 28Nm and 65Nm respectively, 20% and 46% of the value chosen for winged models[11] and perhaps adequate for missile-like models.

4.1.2 Model displaced in roll

The maximum rolling moment capacity varies as sin2R where R is the angular displacement in roll, which leads to zero capacity when the

model is rolled 45 degrees from the nominal attitude. This might be an undesirable feature in missile testing where complete rotation could be required. For this reason some schemes have been considered which exploit alternative modes of energisation of the suspension electromagnets in order to recover some control of roll specifically at the 45 degree attitude.

The array of electromagnets which has been adopted is that proposed by Boom[11] illustrated here schematically on Figure 5 but with drag coils omitted for clarity as these can play no part in the generation of rolling moment when the model is at zero incidence. Electromagnets are represented by single turns.

Eight of the electromagnets are in two groups of four. The primary functions of 1, 3, 5 and 7 are to resist aerodynamic lift force and pitching moment and the primary functions of 2, 4, 6 and 8 are to resist side force and yawing moment. If either of these groups is not fully extended in carrying out its primary functions then its reserve power can be used in principle to generate a rolling moment. It is usual for the loads on a missile-like geometry to be much lower than those on an aircraft model of similar body size. The electromagnets have been sized for the latter and therefore are likely to have quite considerable reserves in missile testing. Here it is arbitrarily assumed that half of the maximum ampere-turn product of each electromagnet 1-8 is available for roll control.

The geometries of the two groups differ but the mechanism by which they can produce a rolling moment is the same, which is as follows. The current levels which happen to be in use for the primary functions of a group are perturbed in order to create field components which interact with the long arms of the roll loops (which for this discussion lie two in the x-y plane and two in the x-z plane) to produce forces which sum to create a rolling moment. The perturbations are of the same sign and magnitude in all electromagnets of the group, that is they are perturbed towards north poles or towards south poles depending on the required sign of rolling moment, a pattern which avoids any change in the magnitude of the force and moment constituting the primary functions.

Current perturbations of this type produce field components of the required sense across the long arms of the roll loops. For example the roll

loop elements which lie in the x-y plane (for these, z = 0 at the 45 degree attitude) are exposed to field components B_y. The elements which lie in the x-z plane (y = 0 at the 45 degree attitude) are exposed to B_z components. The forces arising from the field-current interactions combine to produce a pure roll couple.

If the currents in the other set of electromagnets are perturbed simultaneously in the opposite sense their effect on rolling moment is additive but not necessarily of the same magnitude because of differences in geometry.

These current perturbations produce an unwanted axial force on the model, of opposite sign from each set and therefore tending to cancel. The cancellation is not perfect because of the geometry differences and will need countering with the drag coils. Preceding arguments on the subject of reserve power apply also to the drag coils.

The roll racetracks (numbered 9-12 on Figure 5) can also contribute to rolling moment on a model when it is in this attitude if the current is reversed in two of the racetracks. The designed current directions are shown on Figure 2 (or all reversed for the opposite rolling moment). It is suggested here that the currents be modulated for optimum roll capacity perhaps in a progressive manner as a function of roll attitude, leading to the current directions shown on Figure 5 for the 45 degree roll attitude. This change will not induce any unwanted force or moment when the currents are equal in magnitude in all racetracks. The current perturbations shown on the figure, coupled with the current directions in the model's roll loops, produce a clockwise moment as viewed.

The magnitudes of the contributions of these three sets of electromagnets to roll torque again have been estimated from field calculations using FORCE[2]. Adopting 50% of current capacity for roll from electromagnets 1-8 and full capacity from 9-12 leads to the following contributions to rolling moment:

Rolling moment on elements positioned:	inboard	outboard of solenoid
From group 1,3,5,7:	5.1	11.5
group 2,4,6,8:	3.5	7.9
group 9-12:	6.9	15.6
Totals:	15.5Nm	35.0Nm

based on roll loop conductor cross sectional areas of $50mm^2$. These figures are just over half of those available in the nominal attitude, but nevertheless constitute what might be useful levels of moment. The scheme, if admissible on superconducting grounds, opens up the possibility of *"all round"* control in roll, that is a measure of control in roll at any roll attitude.

4.2 Rolling moment measurements

4.2.1 Samarium cobalt quadrupole

This device was first tested under open-loop control while supported mechanically on the centreline of the electromagnet array of the MSBS at the University of Southampton, which has been described in its current form by Britcher[2]. Rolling moments were applied to the quadrupole by weights hung from short arms attached to the device and the resultant displacement in roll was nulled by adjustments to the currents in electromagnets 5-8 of Figure 1 in the sense required to resist the rolling moment. The currents were fed to the electromagnets in the directions required to produce the polarity pattern shown on Figure 4(b) for a clockwise moment, and vice versa. Calibrations were carried out at various positions along the x-axis with the results shown on Figure 6. For this calibration and the subsequent calibration while magnetically suspended the quadrupole was mounted in a downstream position. Three values of position were used as indicated on Figure 6. These are the values of x measured to the downstream face of the quadrupole. The calibrations show good linearity but a strong sensitivity to x. The sensitivity is a feature of this model/electromagnet combination and is not

generally fundamental to quadrupoles of this type, partly because the SCS model which was to be used was large for the MSBS and partly because of the use of only electromagnets 5-8 in the calibrations instead of the complete set 1-8.

The quadrupole was later mounted on the downstream end of the SCS model[3-6,13] for further calibration while magnetically suspended. Following cooling with liquid helium the solenoid was charged with the usual 15 amps and magnetically suspended under closed-loop control by digital computer in five degrees of freedom. The model was positioned nominally on the axis of the MSBS. Roll was under open-loop control by the operator who could demand perturbations in the currents in electromagnets 5-8 of the same magnitude through a single keyboard entry. The signs of the current changes were those required to produce a rolling moment. The model was loaded in roll while in suspension and the roll attitude nulled by the operator as before. The resultant roll calibration is shown on Figure 7 again exhibiting good linearity. The slope of this line was as expected from the preceeding calibration indicating that the permanent magnets were not affected by, and operated independently of, the superconducting solenoid. Further, the ease with which the operation was carried out promises that closed-loop control of roll with superconducting solenoid models carrying this type of roll element will prove to be trouble-free.

4.2.2 Mild steel saddles

These are notionally the same devices as used earlier[7-9] on models fitted with permanent magnet cores. They were positioned over, and were magnetised by, the poles of the cores at 45 degree positions. At that time rolling moments were generated by just the lateral magnets numbered 2, 4, 6 and 8 on Figure 1.

Essentially the same procedure described in Section 4.2.1 was followed in this calibration with the exception that a demand by the operator for change in roll current was arranged to cause the roll component of current to change in the eight electromagnets 1-8. The calibration curve is shown on Figure 8 and is non-linear. No complete explanation is available for the non-linearity, but it is likely to be

associated with change in magnetisation of the saddles. The mean slope of the curve is lower than experienced before, indicating the arrangement to be a more powerful source of rolling moment. However it must be bourne in mind that twice as many electromagnets were contributing, and the saddles had a relatively large radius. Experience has shown that rolling moment capacity is a strong function of the radius of a roll element.

5. DISCUSSION

The work reported here probably represents the first attempt to devise and evaluate theoretically and experimentally various devices for allowing the rolling motions to be controlled of magnetically suspended superconducting solenoid models. Advantage has been taken of two existing tools: the program FORCE to indicate the performance of superconducting roll loops in the model under the action of roll fields produced by an array of superconducting suspension electromagnets, and an existing superconducting solenoid model to allow the practical demonstrations of, and measurements of, rolling moments.

The theoretical work has shown that it should be possible to design models incorporating roll loops which contribute sufficient roll torque for missile-like models for a large balance, that is a rolling moment very roughly one-third of that deemed necessary for winged models having the same fuselage size. Of course if the loops are used in a winged model they would supplement the rolling moment available to that model from other sources. It is also shown that it might be possible to control the rolling motion of a model through the full 360 degrees in roll.

The experimental work has shown that it is possible to devise elements from magnetic material which will allow rolling moments to be produced on a magnetically suspended superconducting solenoid model. The model so fitted was controlled in roll open-loop, showed good stability and every sign that it could be controlled closed-loop in roll, which is the ultimate aim of such devices.

The next logical step will be to design and demonstrate, in a convenient model magnetically suspended in a conventional balance, the action of superconducting roll loops, preferably under closed-loop control.

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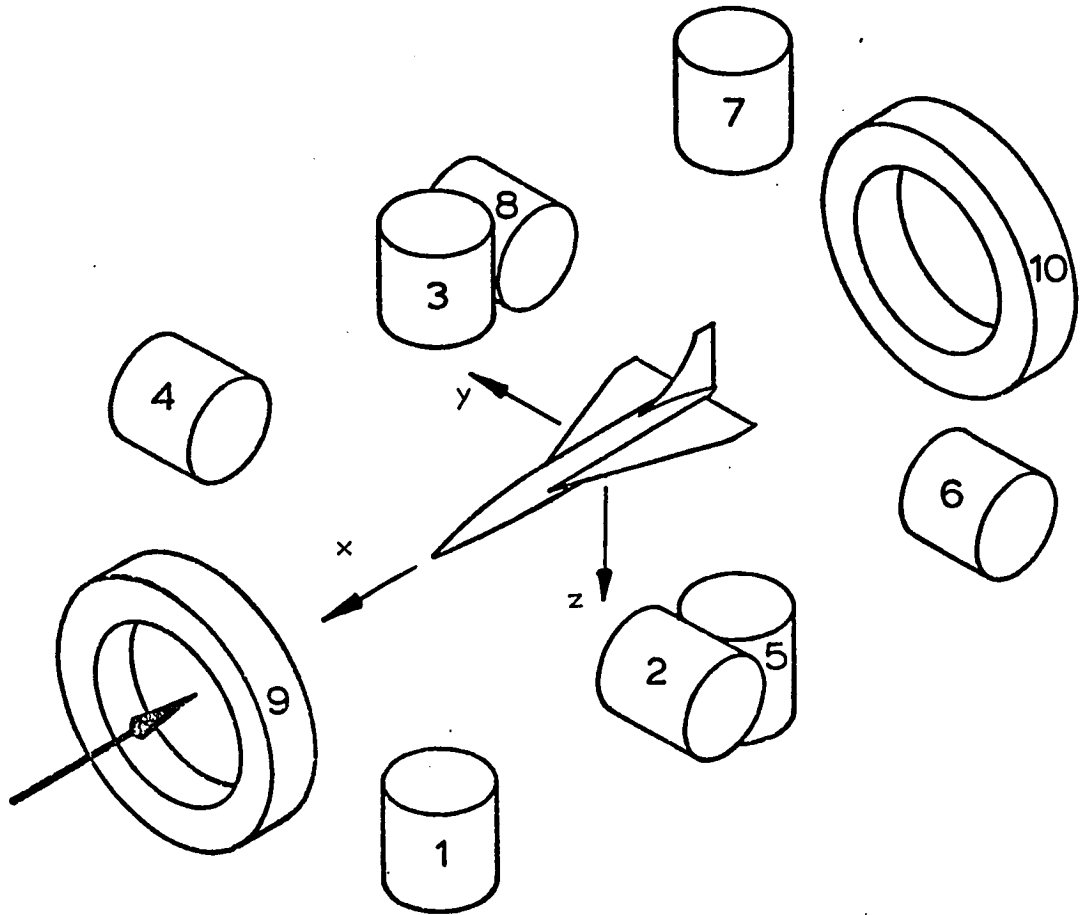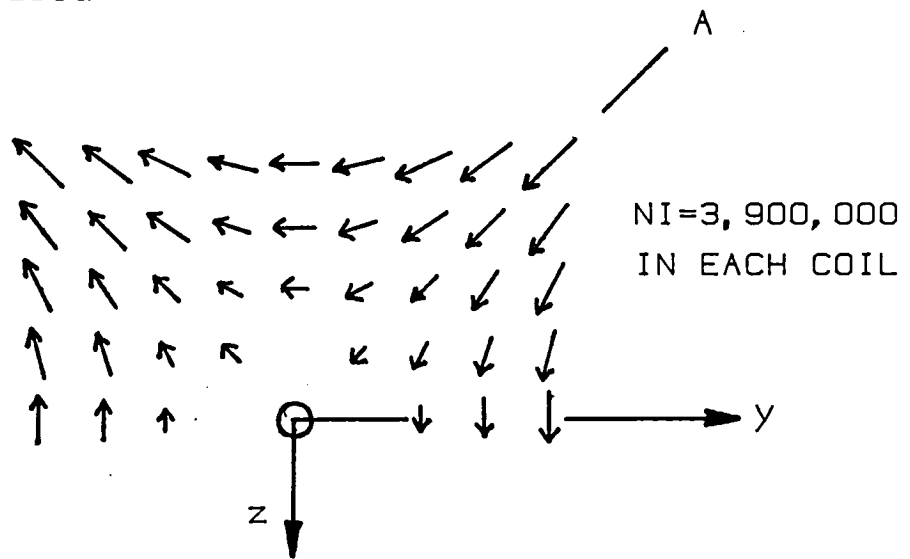
FIGURE 1. SCHEMATIC OF THE 6-COMPONENT MAGNETIC SUSPENSION AND BALANCE SYSTEM AT THE UNIVERSITY OF SOUTHAMPTON.
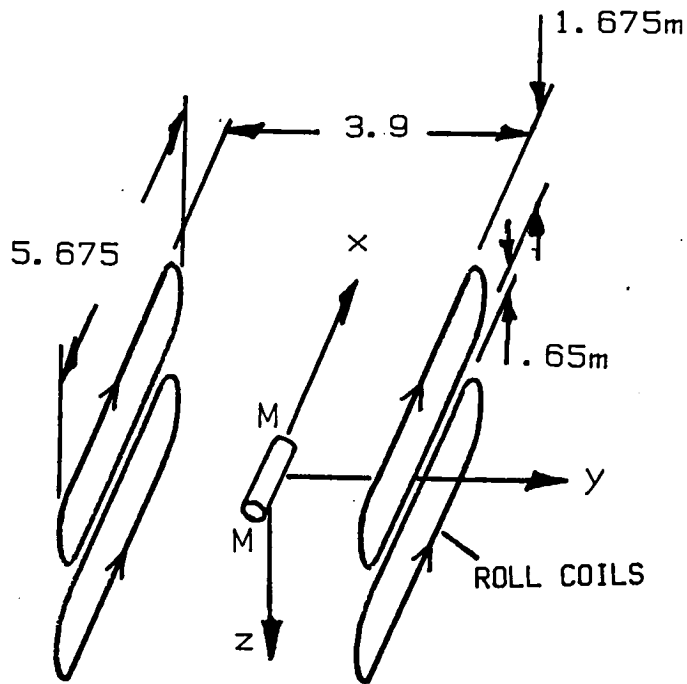
(a) CENTERLINES OF ROLL COILS OF REFERENCE 11, THE
AXIS SYSTEM AND LOCATION OF MODEL MM.

(b) FIELD VECTORS IN y-z PLANE AT x=0

FIGURE 2. RACETRACK ROLL COILS WITH THE MODEL'S
LOCATION AND THE ROLL FIELD IN THE
REGION OF ITS FUSELAGE.

16

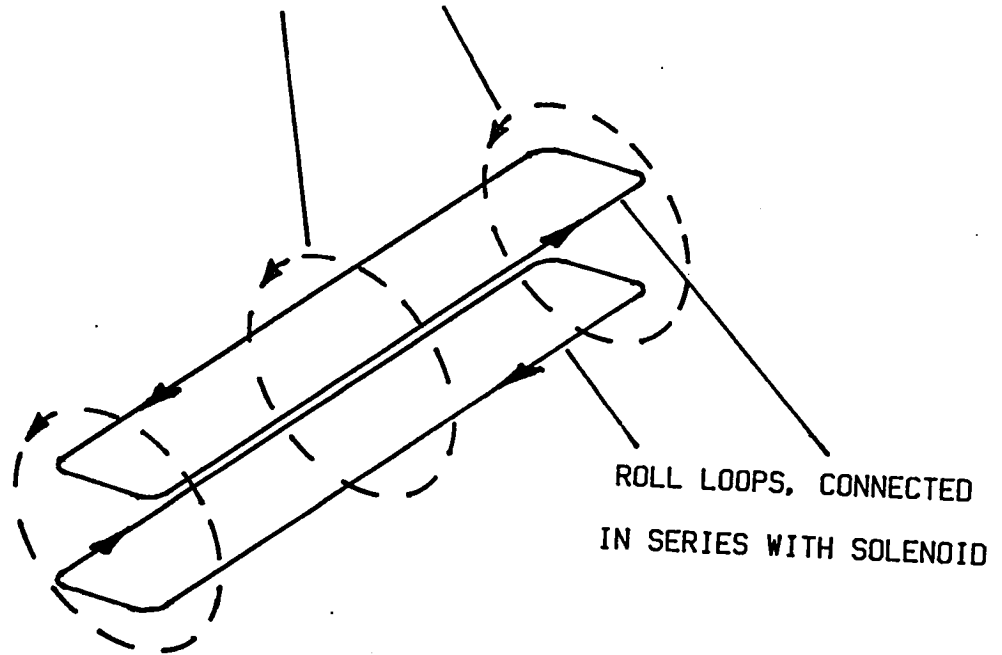SOLENOID PROVIDING THREE FORCE COMPONENTS,
AND PITCHING AND YAWING MOMENTS

ROLL LOOPS, CONNECTED
IN SERIES WITH SOLENOID

FIGURE 3. SUPERCONDUCTING SOLENOID WITH ADDED
ROLLING MOMENT LOOPS.
LOOPS SHOWN HERE INSIDE SOLENOID.

17

Cryostat

Mild steel
saddle pairs

Mild steel
shaped pole

Samarium cobalt
quadrupole
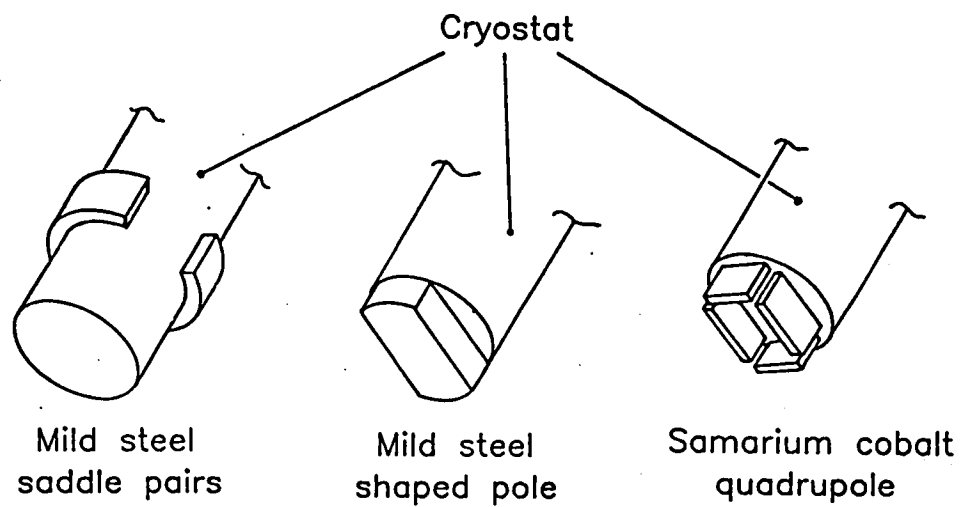
FIGURE 4(a) ROLLING MOMENT ELEMENTS APPLIED
TO CRYOSTAT OF EXISTING SCS MODEL
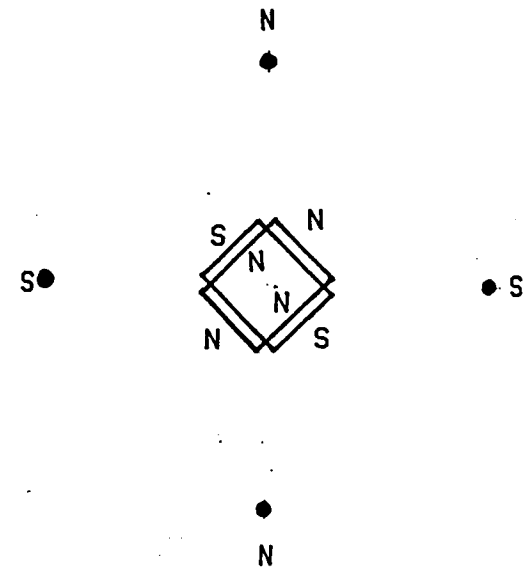
(b) POLARITY OF QUADRUPOLE AND
ADJACENT ELECTROMAGNETS FOR
A CLOCKWISE MOMENT.
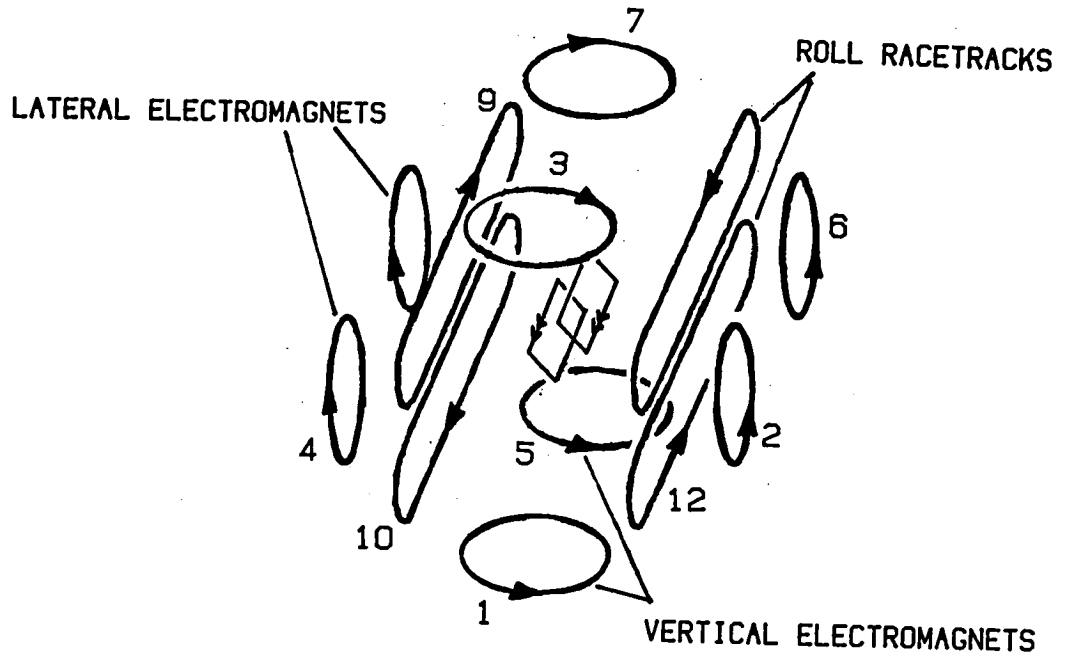
FIGURE 5. ELECTROMAGNETS CAPABLE OF GENERATING A
ROLLING MOMENT ON ROLL LOOPS IN AN SCS MODEL
WHEN ROLLED 45 DEGREES AWAY FROM NOMINAL.

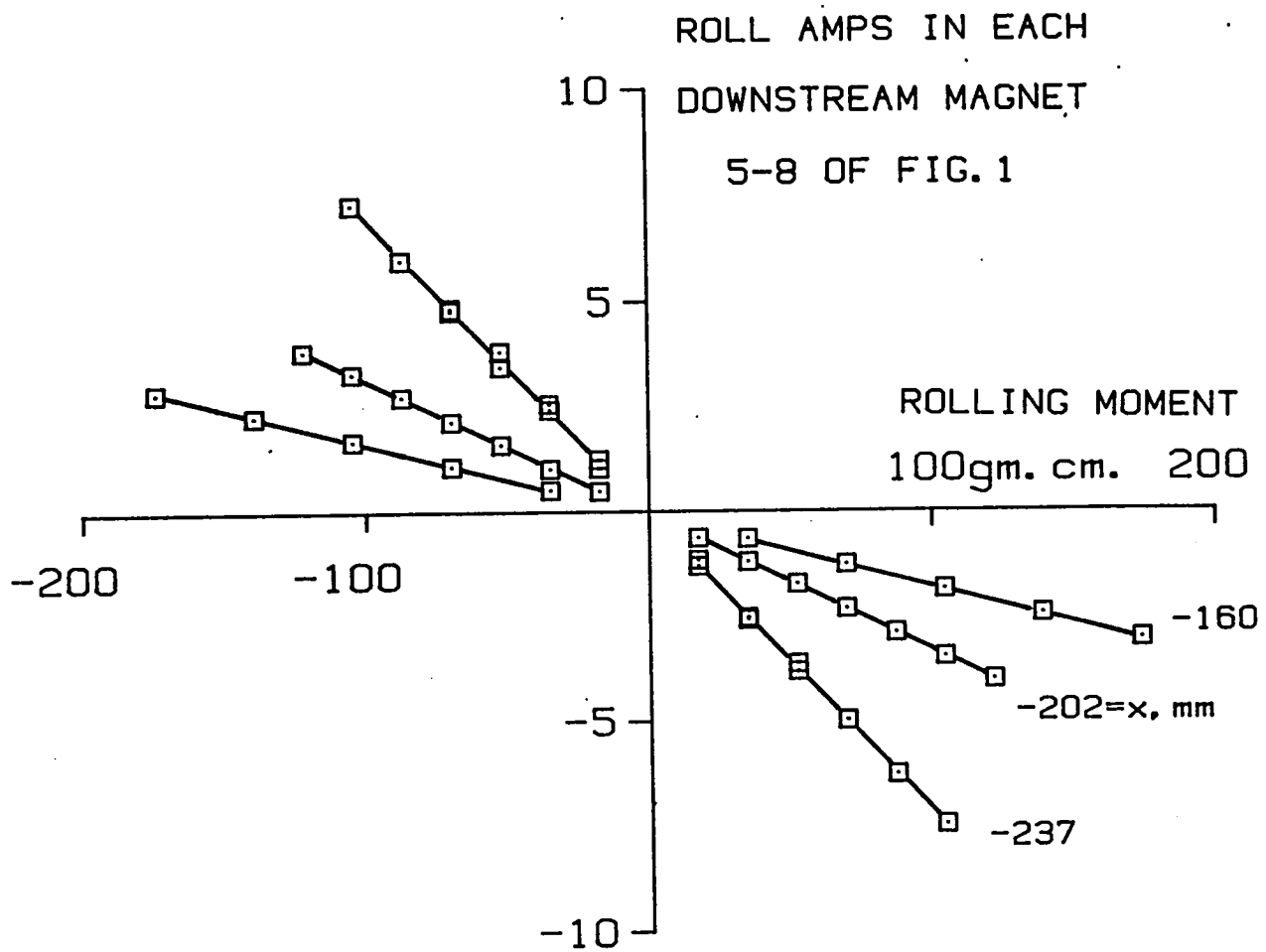FIGURE 6. INITIAL CALIBRATION OF MECHANICALLY SUPPORTED
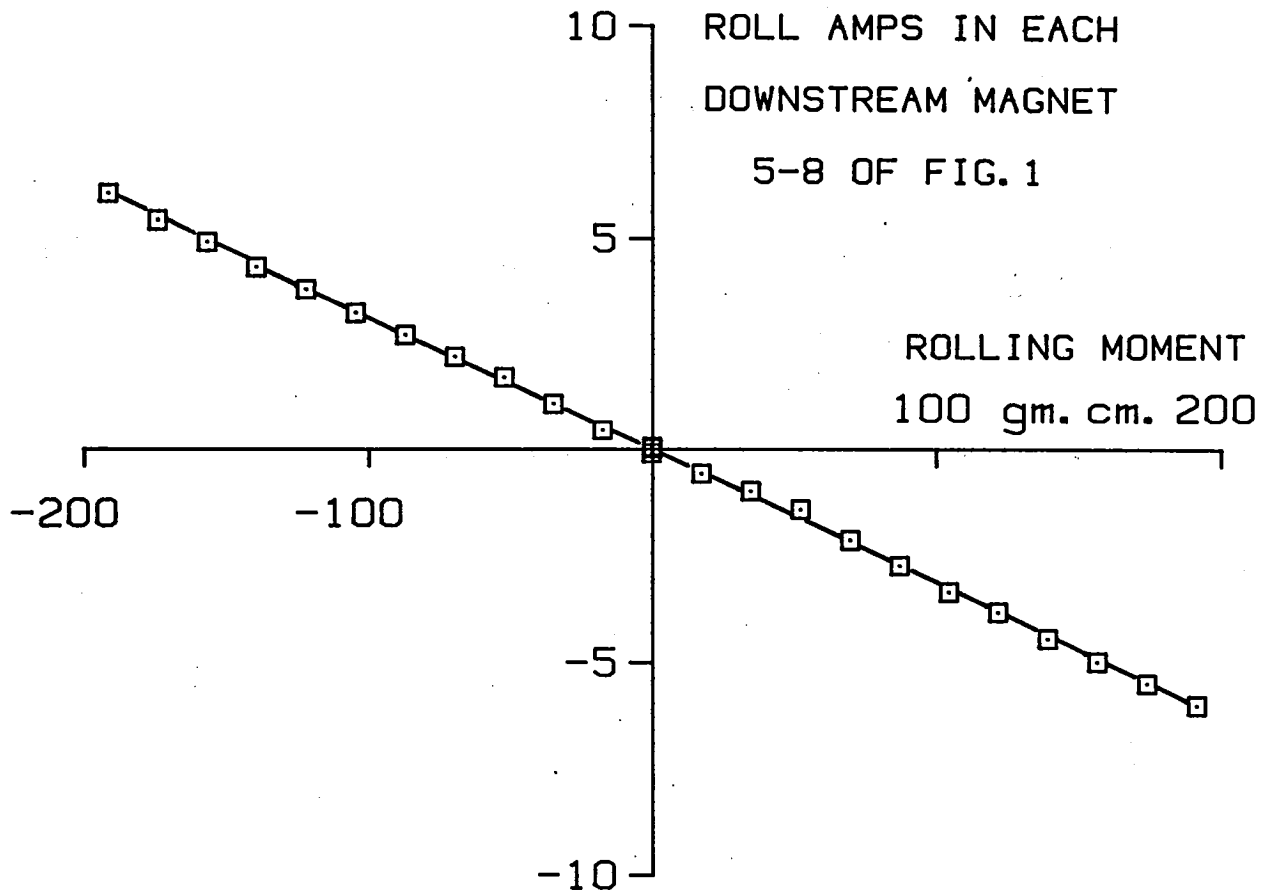SAMARIUM-COBALT ROLLING MOMENT ELEMENT FOR
SCS MODEL.

FIGURE 7. CALIBRATION OF SAMARIUM-COBALT ROLLING
MOMENT ELEMENT MAGNETICALLY SUSPENDED ON
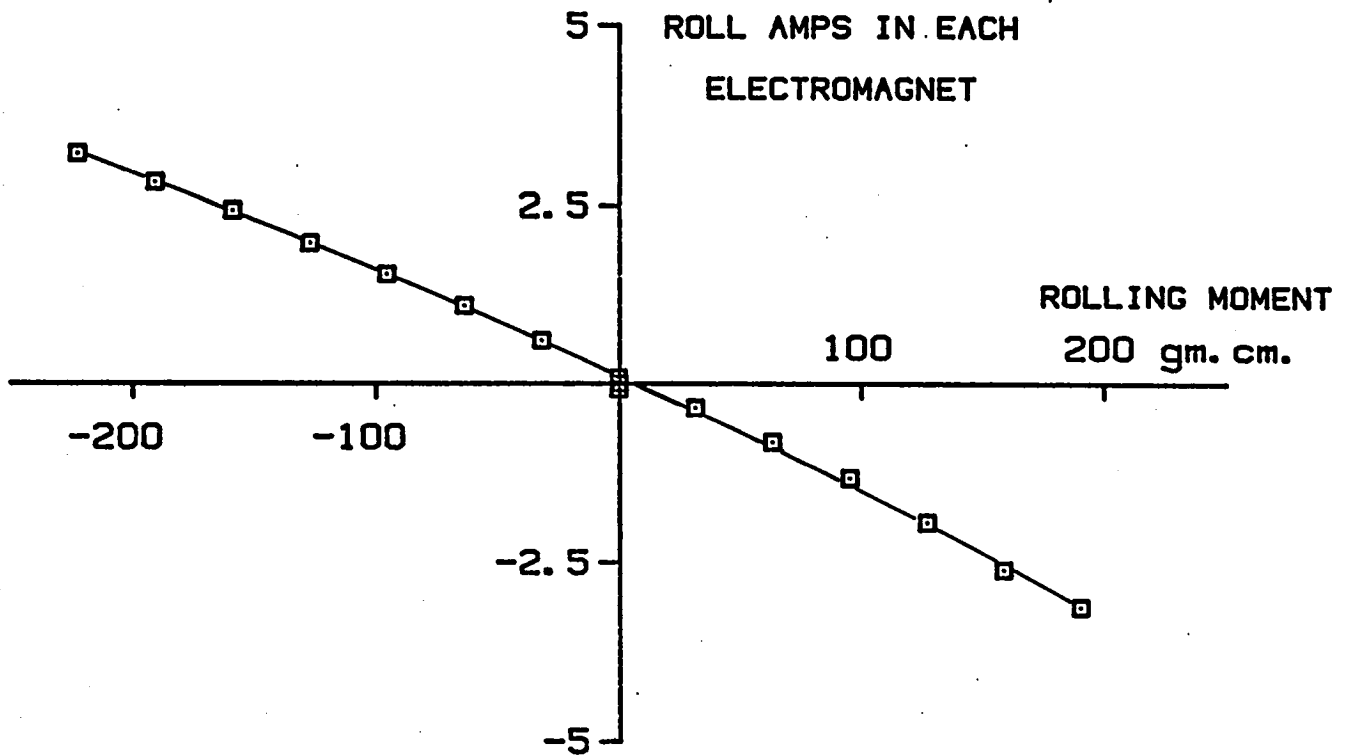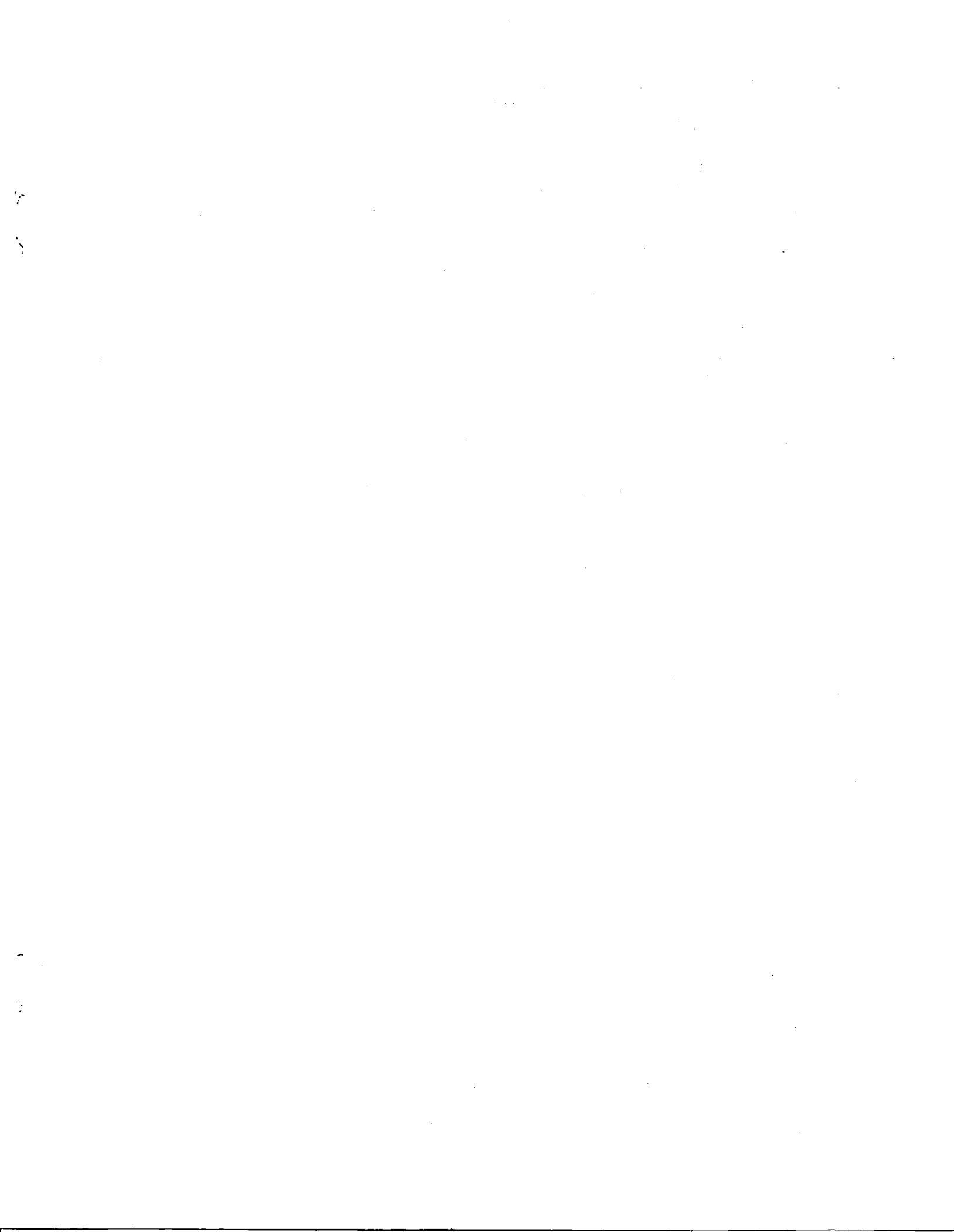SUPERCONDUCTING SOLENOID MODEL.

FIGURE 8. CALIBRATION OF MILD STEEL SADDLES
ROLLING-MOMENT ELEMENTS MAGNETICALLY
SUSPENDED ON SUPERCONDUCTING SOLENOID MODEL.

1. Report No. NASA CR-172520	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle THE GENERATION OF ROLLING MOMENTS WITH THE SUPERCONDUCTING SOLENOID MODEL		5. Report Date January 1985
		6. Performing Organization Code
7. Author(s) *Michael J. Goodyer		8. Performing Organization Report No.
		10. Work Unit No.
9. Performing Organization Name and Address Vigyan Research Associates, Inc. 28 Research Drive Hampton, VA 23666		11. Contract or Grant No. NAS1-17919
		13. Type of Report and Period Covered
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		Contractor Report
		14. Sponsoring Agency Code 505-31-53-10

16. Abstract

The superconducting solenoid model is a pilot model core for levitation in a wind tunnel magnetic suspension system. This type of core would replace the ferromagnetic core typically installed in the model fuselage. For suspension purposes, the solenoid is operated upon by a set of electromagnets surrounding the wind tunnel which are to support and restrain the model at required positions and orientations under the influence of powerful aerodynamic disturbances. This report covers the work carried out, to date, on the subject of providing sources of magnets rolling moment for use when spanwise magnets, which can be used for winged models, are not available. Several methods have emerged for generating a rolling moment based on the use of additional superconducting loops or magnetic poles positioned around or within the solenoid. The report presents predictions of the moment capacities of superconducting loops in models sized for a large wind tunnel. An existing prototype superconducting model proved a suitable vehicle for demonstrating and calibrating, at a smaller scale, some of the other roll elements based on magnetic pole devices. Calibration data are included.

17. Key Words (Suggested by Author(s)) Superconducting Solenoid Rolling Moment Magnetic Suspension	18. Distribution Statement Unclassified - Unlimited Star Category - 09	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 23	22. Price A02