SUPERCONDUCTING ELECTROMAGNETS FOR LARGE WIND TUNNEL MAGNETIC SUSPENSION AND BALANCE SYSTEMS*

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Abstract--This paper presents a new design study of a Magnetic Suspension and Balance System (MSBS) for airplane models in a large 8 ft x 8 ft wind tunnel. New developments in the design include: use of a superconducting solenoid as a model core instead of magnetized iron; combination of permanent magnet material in the model wings along with four race-track coils to produce the required roll torque; and mounting of all the magnets in an integral cold structure instead of in separate cryostats. Design of superconducting solenoid model cores and practical experience with a small-scale prototype are discussed.

INTRODUCTION

Magnetic Suspension and Balance Systems (MSBS) have been used for over a quarter of a century to support aircraft models in wind tunnels. The principal advantage of MSBS is the complete elimination of the disturbance of the aerodynamic flow over the model caused by the presence of mechanical support systems, such as struts or stings. Other advantages include the ease with which the suspended model may be positioned and oriented within the wind tunnel test section, including forced oscillatory motions if desired. To date, MSBS's have been restricted to small physical sizes, specifically wind tunnel test sections ranging from around 10 to 30 centimeters diameter.[1] Requirements for test Reynolds number, model detail, accuracy and instrumentation necessitate considerably larger test section sizes for the majority of aerospace research and development.[2] As MSBS's are scaled to larger sizes, considerations of power economy force the choice of superconducting electromagnets to create the magnetic fields that support and restrain the test model. Since the aerodynamic loads on the model are typically unsteady, the applied magnetic fields will have a strong AC component.

This basic design is for an MSBS for an 8 ft x 8 ft Mach 0.9 wind tunnel.[3] Inside the suspended airplane model is a superconducting solenoid which is suspended with 6 degree of freedom control by the magnetic forces from 14 external electromagnets, see Fig. 1. The airplane model magnet is a high performance persistent solenoid whose magnetic moment and equivalent pole strength can be 70% larger than magnetized iron at this scale. The 14 external magnets are large cryostable coils using 755 MAm of 11kA cable wound at 1500 A/cm^2 current density and storing 906 MJ of energy. The outermost diameter of the system in Fig. 1 is 8.2 m and the extreme system length is about 6.3 m. Split metal coil forms reduce AC loads by eliminating the major eddy current paths. Eleven power supplies with total power of 100 MW can achieve the required simultaneous 10 Hz variation of 0.1% on all forces and torques for control purposes. The maximum AC loss to LHe is 405 W from the coils and 1560 W from structure. The structure loss is unavoidable for this single dewar design with internal steel intermagnet cold structure. Design features such as selection of cable, forces, torques, cool down and safety are included.

There are two major improvements in this new design over previous designs.[2] First, the use of a compact potted superconducting coil, pioneered at Southampton,[4] instead of magnetized iron in the suspended model. This eliminates the need for external magnetization coils and reduces the size of the X coils (drag), Y coils (sideforce and yawing moment), and Z coils (lift force and pitching moment). The second improvement is the use of 4 race-track R (roll) coils, shown in Fig. 1 along with rare earth permanent magnet material in the models wings which combine to produce roll torque. Table I is a comparison of the Madison Magnetics design with a previous General Electric design for the same suspension requirement.[2,3] The ampere meters and stored energy are 44% and 47% less for Madison Magnetics.

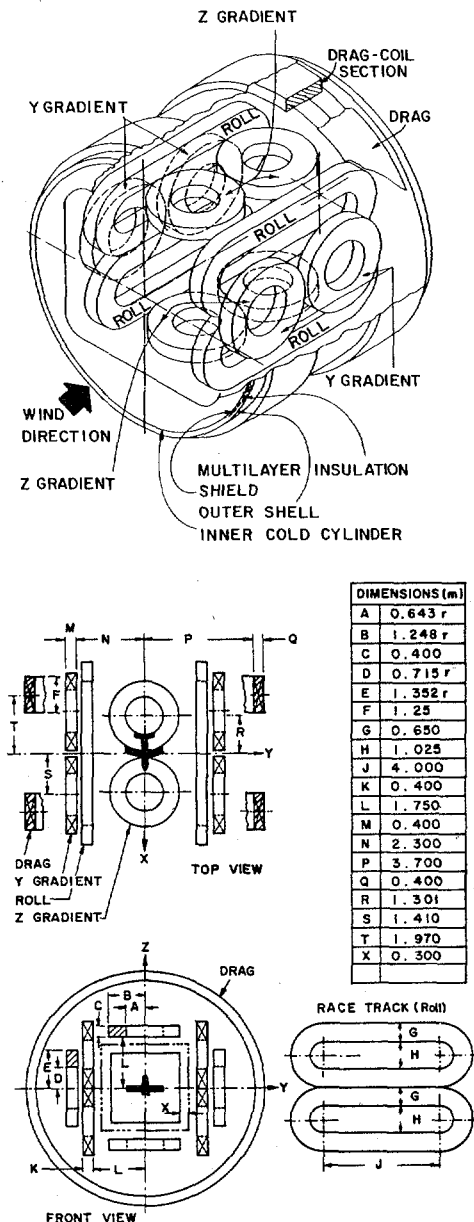| DIMENSIONS (m)	
A	0.643 r
B	1.248 r
C	0.400
D	0.715 r
E	1.352 r
F	1.25
G	0.650
H	1.025
J	4.000
K	0.400
L	1.750
M	0.400
N	2.300
P	3.700
Q	0.400
R	1.301
S	1.410
T	1.970
X	0.300

Fig. 1. Magnet system isometric and dimensions.
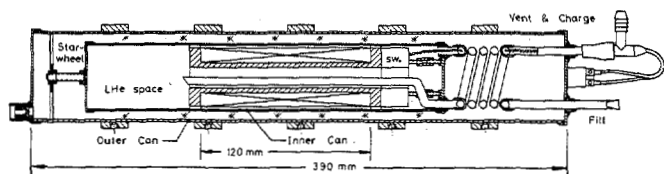
Fig. 2. Prototype superconducting solenoid model core.

Operating current	15A (21 max)
Current density	23kA/cm^2 (32)
Peak field	3.8T (5.3)
LHe capacity	≈200 cc's
Superconducting life	≈30 mins

(Usual operating parameters shown, maximum design values in parentheses.)

Fig. 3. Prototype superconducting solenoid (components and suspension).

TABLE I. MSBS design comparison.

Madison Magnetics Design	Z	Y	Roll	Drag	Total
			Electromagnets		
Ampere-Meters (MAm)	86	100	207	362	755
Energy Stored (MJ)	50	60	140	656	906
Maximum Field (tesla)	5.8	6.3	6.1	4.4	

General Electric Design	Z	Y	Roll	Drag + Magnetize	Total
Ampere-Meters (MAm)	374	51	233	508 + 180	1346
Energy Stored (MJ)	592	56	248	758 + 52	1706
Maximum Field (tesla)	7.7	4	4	4	

The first superconducting coil operated in a wind tunnel model is a 12 cm x 4.6 cm OD solenoid developed at the University of Southampton.[4] This proof-of-concept model has been successfully suspended in the small MSBS at the University of Southampton and subjected to fairly extensive testing and calibration. Design studies of larger model cores are now underway.

EXPERIENCE WITH SUPERCONDUCTING SOLENOID MODEL CORES AT THE UNIVERSITY OF SOUTHAMPTON

Figs. 2,3 show the internal design and technical specifications of the proof-of-concept model. Over 4 hours of suspension time (Fig. 4) have been accumulated to date, under a variety of conditions, including application of vertical loads up to 2.5 kg.,
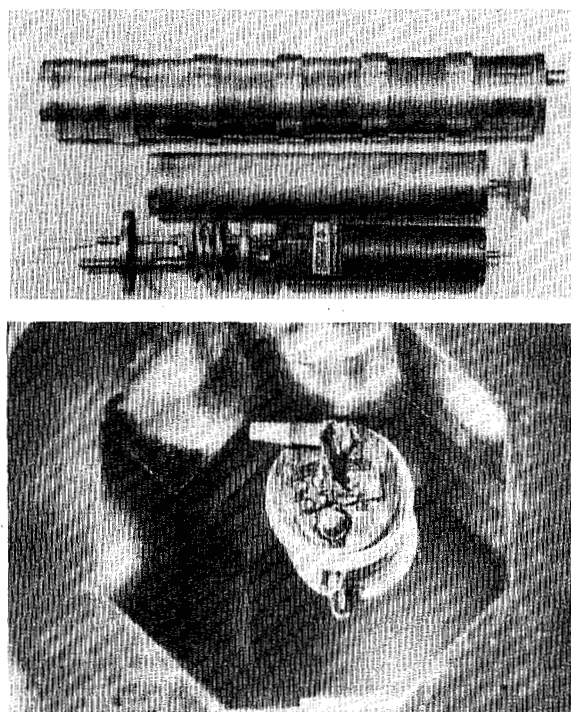
changes of pitch attitude within a range of ±4.5 degrees and forced oscillations up to 16 Hz. No unexpected coil quenches were encountered. Some force and moment calibration data has been taken, such as shown in Fig. 4. Roll torque was generated using permanent magnet quadrupole roll elements attached to the ends of the solenoid. The linearity of the plots permits relatively simple calibration procedures, using a matrix of calibration constants. Most of these constants are dependent on the current in the solenoid, which must therefore be accurately set during energization. However, since the solenoid is largely insensitive to the temperature of its environment and is free from magnetic hysteresis or saturation effects, it is felt that the in-service calibration of this type of model may be more straightforward than with conventional ferromagnetic cores. Operation of the model has become somewhat routine.

THE MADISON MAGNETICS DESIGN

The magnet system configuration for the 8 ft x 8 ft tunnel shown in Fig. 1 provides the magnetic fields to produce the static forces and torques needed to control the model in the six degrees of freedom. The force and torque requirements are listed in Table II.

The system configuration is summarized as follows.

• A 70 cm long potted persistent superconducting solenoidal coil, 11.5 cm O.D., and 6.1 tesla is the model core.
• The model wings are 85% permanent magnet material with 15% of the wing volume high strength stainless steel, see Fig. 5.
• Z and Y (direction) gradient coils are symmetric arrays of four solenoid magnets each, controlling vertical and lateral motions of the model.
• The X (drag) coils to counterbalance model aerodynamic drag force are two large diameter solenoids.
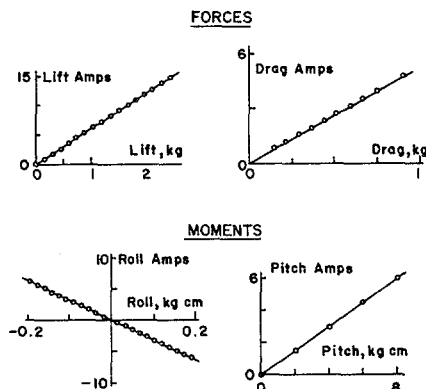• The roll coils are four race-track coils.

FORCES

Fig. 4. Examples of calibrations of a magnetically
suspended superconducting solenoid model.

TABLE II. MSBS requirements, for an 8 ft x 8 ft test
section.

A.	Static Force Requirements	
	Lift	9790 N
	Side	1380 N
	Drag	4180 N
B.	Static Moment Capability	
	Pitch	420 Nm
	Yaw	140 Nm
	Roll	140 Nm
C.	Angular Displacement Range	
	Angle of Attack (α)	± 30°
	Angle of Sideslip (β)	± 10°
	Angle of Roll (ϕ)	± 20°

The conductor in all coils, except the model coil, is
the 11-kA low-loss cryostable cable conductor devel-
oped by Argonne National Laboratory.[5] The cable is 24
basic cables twisted around an insulated stainless
steel strip with a twist pitch of 22.5 cm. The basic
cable is three seven-strand conductors (triplex cable)
with a twist pitch of 2.2 cm. The seven-strand
conductors are six OFHC copper wires twisted around a
superconducting center conductor and soldered with
Staybrite.

Model Core Solenoid

The model core solenoid is an adiabatically stable
epoxy impregnated solenoid. Such coils contain little
copper and cooled surfaces, and their ability to
tolerate thermal disturbances is limited by the
adiabatic heat capacity of the conductor material.
However, the absence of much copper and helium in the
windings allows current densities up to ten times
larger than for cryostable coils. Based on experience
and technology, a field of 6.1 tesla and current
density of 30,000 A/cm^2 are proposed.

Cryogenic and structural design of these large-
scale models is complicated by the conflicting re-
quirements of high load capacity (Table II), low
helium boil-off rates and maximum utilization of
volume for superconducting windings. Independent
design studies at Madison Magnetics and Southampton
presently promise similar overall performance, though
with different design choices for coil support

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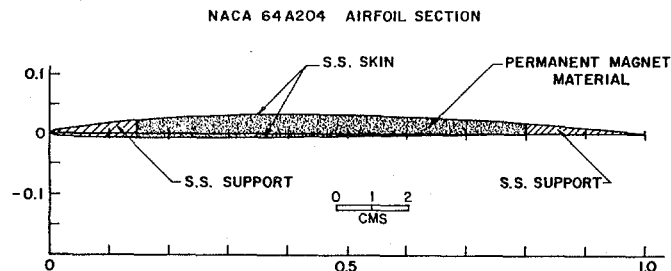
Fig. 5. Typical wing cross-section.

systems, etc. For either design, the model coil is
wound with 10 to 40 A wire for an effective magnetiza-
tion, based on overall model volume, of 3.4 to 3.5
tesla. Helium capacity is 3.0 to 3.5 ℓ with idling
boil-off rate predicted at 0.14 to 0.2 ℓ/h. For an
AC loss at 10 Hz, full load of 0.03W, the time to 50%
helium boiloff would be 4 to 7 hours.

X, Y, and Z Coils

The two 8.2 m OD drag (X) coils provide an axial
field gradient on the model coil. The X coils enclose
the lift (Z) coils, the side (Y) coils, and the roll
(R) coils, see Figs. 1 and 6. The sizes and positions
of all external coils are optimized to minimize both
the ampere meters and the stored energy listed in
Table I.

R Coils and Wing Design

The R coils provide a Z field on the wing. The
field is an odd function of Y to produce zero field at
the fuselage (the model core) for minimum cross
couplings. This field is best produced by the 4 race-
track coils shown in Fig. 1.

The model wings are of high coercive force perma-
nent magnet materials with remanent magnetization on
the order of 0.9 tesla, such as ReCo.[6] The externally
applied field on the wing will range from 0.0 at the
center to 0.30 tesla at the tip. The magnetic materi-
al in the wing is Sm Co$_5$ "RECOMA 20" or ReCo. The
wing is covered with a strong skin of non-magnetic
stainless steel alloy as shown in Fig. 5. For stain-
less steel and 85% SmCo$_5$ the average magnetization is
0.7 to 0.75 tesla.

Cross Coupling

When the model pitches (from Z coils) yaws (from
Y coils), or rolls (from R coils) there are cross
couplings between the different coils in the system.
All coils have extra ampere-turns to override the
worst case unwanted couplings.

Coil Structural Design and AC Losses

The system structure sketched in Fig. 6 meets all
the specified functional requirements with 304 N
stainless steel designed at 20,000 psi working stress.
In lower stress areas 304 and 304 L are used. The
system structure provides for and reacts gravity
loads, steady state forces and 10 Hz control forces,
vacuum pressures, thermal cycling contraction forces,
and accurate coil positioning with acceptable flexure
during pulsing.

The design includes a load-bearing thermal-vacuum
enclosure immediately surrounding the wind tunnel, a

Fig. 6. Structure cross-section.

large rectangular box with rounded corners for mounting the R, Y and Z coils, the principal structural elements which incorporate the two large X coils, a cylindrical outer cold surface, multilayer insulation space with liquid nitrogen shield, and a stiffened outer vacuum jacket. The helium container around each X coil is a thin non-structural stainless steel liner which includes a separate electrical break. The use of a thin liner to contain helium removes the requirement to seal against helium leakage at insulated flanges in the heavy structural walls which are subject to large mechanical torques. The internal coil structure is a bifilar 304 stainless steel strip slightly higher than the conductor. All axial and radial forces are taken by this interleaved strip. The forces are spread between each layer by radial insulating separator slats.

Eddy current losses in the steel structure at 10 Hz are the major operating loads on the cryogenic system. The AC losses in the structure comprise about 70% of the 4.2K helium requirement at full 10 Hz load. To reduce X coil eddy current losses, the inner cold 4.2K structure stainless steel surfaces of the X coil are slotted to eliminate the major closed circuit. However, these surfaces still couple to all other coils. To the R, Y, and Z coils the inner heavy surfaces of the X coils, on which the X turns are wound, appear as large, thick flat plates, which therefore must be segmented to avoid resultant eddy current losses.

Cryogenics

The key features of the cryogenic system are: 560 liter/h helium liquefier; 47,500 liter helium storage dewar; 40,000 m³ gas storage facility; 1150 cfm helium recovery compressor; LN$_2$ heat exchangers; and 354 m³ helium gas bag. Design of the system is based on the following criteria:
 • Reasonable cool down time of eight to ten days.
 • Adequate liquid storage to fill the magnet cryostat with reserve to meet daily or five-day week operating deficits.

 • Available liquid storage capacity sufficient to empty the cryostat without loss of helium.
 • Liquefaction capacity to maintain scheduled operations on either a continuous or five-day week basis.
 • Sufficient compressor capacity to handle the maximum planned rate of gas evolution without helium loss.
 • Helium gas storage for all of the helium in the system to permit an indefinite shutdown.

AC losses for the system for 1/4 and full load conditions along with the static heat leak, lead losses and conductor joint losses are listed in Table III. These losses determine the size of the liquefier and cryogenic system.

TABLE III. Magnet cryostat operating losses.

Loss	Zero Load	1/4 Load	Full Load
Conductor (AC)	--	187.78	379.4
S.S. Strip (AC)	--	1.58	25.44
Structural Eddy Current	--	97.52	1560
Conductor Joints	--	5.13	82
Leads	78.6	81.2	120
Static Heat Leak	45	45	45
Total Losses - W	123.6 W	418.21 W	2211.84 W
Helium Consumption--ℓ/h	175	590	3120

CONCLUSIONS

A new design for a large 8 ft x 8 ft wind tunnel MSBS indicates overall reductions of the system size, weight and cost by over 50%. The improvements are due to: superconductive model cores, successfully demonstrated at small scale; single dewar with cold internal structure; and race-track roll coils.

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