# SUPERCONDUCTIVE SOLENOID FOR THE NAL 60CM MSBS

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## SUMMARY

The model position sensing system at the NAL 60-cm MSBS has been improved to provide a more accurate measurement of lateral positions by using an additional sensing camera mounted at the upper side of the test section. The MSBS is equipped with a model holding system in order to establish safe model release and capture. The holding system has a balance to monitor the load on the model while the system holds it. Suitable dimensions of the cylindrical model core for the MSBS are estimated. A larger MSBS for the 1.25 m high Reynolds number supersonic wind tunnel is designed by scaling up the dimensions of the 60-cm MSBS. A superconductive solenoid core is inevitable if suspending a model magnetically in the high Reynolds number supersonic wind tunnel. The proposed goal of the cylindrical core is 0.9m long and 74mm in diameter, with 80kA/cm$^2$ current density. In order to examine its feasibility, a superconductive solenoid model core of 300mm long and 45kA/cm$^2$ current density has been designed and built.

## INTRODUCTION

Magnetic Suspension and Balance Systems (MSBS) provide an ideal way of supporting a model for wind tunnel tests because the force to support the model is generated by a magnetic field which is controlled by coils arranged outside the test section. Any mechanical support system is not needed in the flow field inside the test section. Then the support interference problem does not exist except for very special test conditions like hypersonic flow containing ionized atoms. Besides the fact that the MSBS is an interference free support system, it is very suitable to carry out difficult tests like dynamic tests. It is much easier to change the model attitude over a wide range by the MSBS than by mechanical support systems. This feature of the MSBS will improve tunnel data productivity. Many MSBSs have been built up to 1970s but only a few are in operation presently.

The NAL 10-cm MSBS was developed in 1985 and the 60-cm MSBS was developed in 1991 at the National Aerospace Laboratory (NAL).[1] The 10-cm MSBS has been used for basic research like rolling moment control [2] and dynamic calibration tests with measured magnetic field intensity around the test section[3,4] A specially designed model is controlled in 6 degrees of freedom in the 10-cm MSBS. The 60-cm MSBS has the largest test section in the world in the sense of the dimensions. The coil arrangement in the 60-cm MSBS is the same as in the 10-cm MSBS as shown in Figure 1. The coil drive units are 5 for the MSBS. The model can be suspended in 5 degrees of freedom with the exception of its rolling motion about the model body axis.

The model size is large enough to allow some type of apparatus to be installed inside it. A rolling motion suppression system inside the model has been developed, which has a fiber optic gyro for the motion. The model attitude and its motion will be measured with sensors installed inside the model in the near future.

Another merit of the bigger model is the potential use of the superconductive solenoid model core. In order to generate large magnetic forces balancing the aerodynamic load, both a strong magnetic field and large magnetic moment of the model core are needed. The permanent magnet or ferromagnetic material like soft iron is used as a model core in the small MSBSs. In the case of large wind tunnel models, there is sufficient room inside the model. Then, the superconductive solenoid core can be mounted inside the model, which can generate a much larger magnetic moment than permanent magnet cores. A superconductive solenoid model core was designed and was suspended successfully in a MSBS at Southampton University supported by NASA.[5,6] A detailed feasibility study of a superconductive solenoid model core to meet a large transonic wind tunnel was carried out[7] and a large model core was designed and built[8]. But the model core has not been used in a large MSBS. There is not a large enough MSBS in the word such that the performance of the core may be tested in it.

The feasibility of the superconductive solenoid as a model core for the high Reynolds number supersonic wind tunnel has been studied with the 60-cm MSBS since 1996 at NAL. The improvements of the 60-cm MSBS in order to examine the superconductive solenoid core and goals of the core for the high Reynolds number supersonic wind tunnel and the specifications of the prototype model core, which was ordered and was built by a manufacturer, will be described in this paper.

## SYMBOLS

$(x,y,z)$ ... coordinate system, See Figure 1.
$(\phi,\theta,\psi)$ ... rolling, pitching , and yawing angles of a model
$H$ ... magnetic field intensity $(Hx,Hy,Hz)$
$M$ .... moment (Nm) $(Mx,My,Mz)$
$F$ ... force (N) $(Fx,Fy,Fz)$

## IMPROVEMENTS OF THE 60-CM MSBS

A model with a cylindrical permanent magnet core inside it was successfully suspended in 3 degrees of freedom at the NAL 60-cm MSBS in 1993. Presently, a model with the same core can be suspended in 5 degrees of freedom except for rolling motion about the axis of the core. In order to get more stable control in the lateral direction, an additional model position sensing camera was mounted on the upper side of the test section together with the original sensing camera. Before a model is suspended, it sometimes becomes very unstable near its stand. The complete model suspension was confirmed by inspection. This was a potential danger. The MSBS was equipped with a model holding system to avoid the unexpected unstable motion and the danger. The MSBS was also equipped with a monitoring system for the model load and the contact between the model and the system.

### Description of the NAL 60-cm MSBS

Details of the NAL 60-cm MSBS are described in References 1 to 4, so only the main features of it will be described here. There are two iron rings perpendicular to the wind axis ($x$ axis) as shown in Figure 2. Each has four pole surfaces. The coils 1 to 4 are attached asymmetrically to the upstream iron ring. The coils 5 to 8 are attached to the downstream ring similarly. The magnetic field surrounded by the four pole surfaces in each ring can be controlled by the coil currents. The four coils are always excited in pairs, for example, coils 1 and 3. For pure vertical force the pair coils of (1,3) and (5,7) are excited so that a vertical field exists between the vertical pair poles of each ring. Similarly, for horizontal force the pair coils of (2,4) and (6,8) are excited. A pair of air cored coils, (0, 9) causes drag force along $x$ axis. The distance between the poles of the coil pairs is 640 mm. The specifications of the coils are listed in Table 1. $Hz$ and $Hy$ of the magnetic field intensity and their derivatives with $x$ can be controlled by adjusting the four pair coil currents. $Hx$ derivative with $x$ can be controlled with the two air cored coils.

| coil # | turn number | dimensions | purposes |
|---|---|---|---|
| 0,9 | 50 | 620 x 620 | drag |
| 1,3,5,7 | 97 + 97 | 200 x 200 | lift, pitch moment |
| 2,4,6,8 | 100 | 200 x 200 | side force yawing moment, and rolling moment |

| | | |
|---|---|---|
| coil drive units | 60V, 75A | 5 units |
| bias coil drive units | 1000 W | 2 units |
| model core | $300^{\Phi}$ x 600 cylindrical permanent magnet (Fe-Cr-Co) | |
| control | 5 degree of freedom except for rolling motion control | |

Table 1 Specifications of the NAL 60-cm MSBS

A model core of the 60-cm MSBS is a permanent cylindrical magnet magnetized along its principal axis. It is 50 mm in diameter and 300 mm long and a TOKIN K-5 type Fe-Cr-Co magnet. Five coil drive units for the coil pairs range from -75 to 75 A at 60V. A bias coil for generating additional lifting force is driven by two constant current power units of 1000 W, which range from 0 to 100 A. The coils are cooled with ambient air and they can be operated for about 1 hour.

The magnetic field was measured with an F.W.BELL Co. type 9903 gauss-meter using coil currents required to magnetically suspend the model. The measured $Hz$ is plotted with respect to $x$ coordinate in three lift coil current cases as shown in Figure 3. The figure suggests that the derivative of $Hz$ with $x$ is proportional to the current. $Hx$ is also plotted with $x$ in three drag coil currents as shown in Figure 4.

## Improved Model Position Sensing System

The model position sensing system developed at NAL had poor accuracy in the lateral position because the position was evaluated with the model image size focused on the 3 CCD line sensors. The measured lateral position was worse in its accuracy than the longitudinal position by about 1 order as described in Ref. 1. The response speed of the lateral motion was much slower than of the longitudinal motion due to the poor accuracy of the position when the model position was measured with only one camera mounted at the side of the MSBS. In order to improve the lateral motion control, another model position sensing camera was mounted at the upper side. The camera measures $y$ coordinate and yaw angle, $\psi$ of the model. The expected accuracy of the measured $y$ coordinate and yaw angle, $\psi$ with the additional camera is the same as those measured with the original camera. The calibration test results show good resolution as shown in Table 2. Some examples of the results are also shown in Figure 5.

Each camera is connected to a computer and both measured data sets are gathered synchronously in a computer. The computer evaluates the model position based on these data sets and adjusts the coil currents accordingly. Large noise radiated from the power units affects the accuracy of the measured position significantly. All position data are modified with low pass filters of 10Hz cut-off frequency before evaluating the model position.

| | resolution |
|---|---|
| x | 0.07 mm |
| y | 0.06 mm |
| z | 0.04 mm |
| $\theta$ | 0.02° |
| $\psi$ | 0.02° |

Table 2 Resolution of the Improved Model Position Sensing System

## Model Holding System

Before a model is suspended, it is laid on a stand made of wood. After suspending the model completely without any contact to the stand, the stand is removed by hand. The process is very dangerous when the model starts to move suddenly for some reason. The model was occasionally balanced on an edge of the stand. If the model was lifted rapidly to clear the stand, the model started to move with a periodical motion or dropped down from the stand during the early tests. It was very difficult to determine a way of lifting up the model safely from the stand in the early stages.

In order to avoid model damage and personnel accidents, the 60-cm MSBS was equipped with a model holding system. The system can suppress unexpected model motion byholdingit strongly and can release the model gradually by monitoring the model position and load on it.

The system was designed to hold the model horizontally at the center of the test section as shown in Figure 6. The held model position can be changed by 200 mm vertically about the center while the system holds it. The model can be moved to the positive *y* direction from the center. The arm part of the system can be moved out from the test section completely after releasing the model. The arm can also be moved back to the holding position automatically through sequential procedures. In order to establish accurate positioning repeatability, 5 photo switches are used. The system is driven by 5 hydraulic actuators. All parts are made with non-ferromagnetic materials. The arm can hold the model solidly even if 98 N vertical or horizontal forces and 30 N axial force act on it, respectively. The shape of the part holding a model was designed specially not to prevent the two sensing cameras from measuring the model position. The system can hold the model up to 93mm in diameter. The system works well during MSBS operation presently.

## Force Monitoring System

When the model holding system holds a model in the 60-cm MSBS, various forces act on the model. After confirming the model is in balance, the model can be released. In order to know that the model is in balance, the model holding system is equipped with a force balance as shown in Fig. 6. The specifications of the balance are listed in Table 3. The force and moment acting on and about the model gravity center can be estimated from the obtained data. If the output from the balance vanishes, it suggests that the model has left the system completely. After the model is released from the system completely, the arm is moved out of the test section quickly.

shape : $67^{\phi}$ x $27^{h}$, mass : 180 g
fx, fy < 100 N, fz < 200 N
Mx,My,Mz < 6.3 Nm
data rate : 0.4883 Hz

Table 3 Specifications of the Balance for the Magnetic Force Monitoring System

Calibration tests for the balance were carried out with an empty model shell at the 60-cm MSBS. The magnetic field effect on the balance output was measured. If the effect is negligible small, aerodynamic load will be measured accurately after the wind tunnel test as has been mentioned in Reference 9. The temporal results obtained show there is little effect as shown in Figure 7.

## MODEL CORES FOR THE NAL 60-CM MSBS

### Permanent Magnet Cores

The original model core for the NAL 60-cm MSBS is a cylindrical permanent magnet since the design stage of the system. The MSBS is not equipped with magnetization coils. As a result, a soft iron core cannot be used with the MSBS.

Magnetic force acting on a cylindrical permanent magnet core is proportional to its magnetic moment. The magnetic moment is approximated by the product of the residual magnetic induction and the core volume. However, the available residual magnetic induction is limited to around 1.2 to 1.4T at present. The model must be suspended against the gravity force by the magnetic force. In addition to the gravity force, the vertical upward magnetic force component, *Fz*, must be as large as possible. In the case of the 60-cm MSBS, Figure 8 predicts that Alnico magnets are the most suitable for the size of the model core for the 60-cm MSBS. If the shape is changed, the suitable magnet will be other magnetic material like the Nd-Fe-B magnet. Figure 9 shows the net lifting force of the cylindrical magnet for the 60-cm MSBS with respect to its diameter. There is a suitable diameter for each cylindrical magnet of constant length. The present magnet core is near the most suitable shape. The net lifting force will be up to 17N at the MSBS even if the shape is designed very well. If a tunnel model is aircraft shaped, the model mass including the wing and control surfaces must be less than 1.7kg plus the magnet mass. Although the aerodynamic force acting on a tunnel model reduces the lifting coil currents, the model must be supported in no flow by the magnetic force. Then, the model mass must be less than 1.7kg. If the model does not contain any instrumentation, it will be possible to build such a light model. If the model includes some control system inside it, it will become impossible to build a model lighter than 1.7kg. So, the net lifting force must be as large as possible.

### Superconductive Solenoid Core

In place of the permanent magnet, the superconductive solenoid can be used as a model core for the 60-cm MSBS. The solenoid can generate a much larger magnetic moment than the permanent magnet if the sizes are the same. This means that the solenoid core can generate a magnetic force several times larger than a permanent magnet core. However, the coil must be thermally insulated with a light and strong special cryostat because the current mode is established at very low temperature around liquid helium temperature. The discovery of high temperature superconductive materials will make the superconductive solenoid core more feasible.

By adjusting the coil current, the magnetic moment of the solenoid can be adjusted easily. It is very convenient to control the coil currents because the power units for driving the coils can be operated in similar conditions independently of the aerodynamic load. This means that the aerodynamic load can be measured accurately independent of the load magnitude.

A superconductive solenoid model was successfully suspended in the Southampton University's MSBS. The cryostat for the coil looks very complicated because it contains the solenoid plus various apparatus for gaseous helium exhaust and protection diodes against the quench and leads for large current and a switch for the permanent current mode change and support system for the solenoid inside the cryostat against the large magnetic force.

Because the required thickness of thermal insulation remains independent of scale, the solenoid diameter in the cryostat must become smaller rapidly as the cryostat diameter decreases. Then, the magnetic moment of the model core will be small at a small MSBS. If the model core diameter is 50 mm, the solenoid diameter is expected to be about 35 mm at most. If the core is 300 mm long, the solenoid length will be about 150mm at most. The attainable magnetic moment of the solenoid is not large enough that the magnetic force can suspend the model for the 60-cm MSBS. As a result, the cylindrical permanent magnet core is much better than the superconductive solenoid core for the 60-cm MSBS if the shape is limited to a suitable scale for aeronautical wind tunnel tests. In case of wind tunnel models like aircraft, the superconductive solenoid core will be suitable for a larger MSBS whose test section is above 1m at least. In the case of a thick body, the superconductive solenoid can still be available as a wind tunnel model core in smaller sized MSBSs.

## MODEL CORES FOR THE HIGH REYNOLDS NUMBER SUPERSONIC WIND TUNNEL

### The High Reynolds Number Supersonic Wind Tunnel

It is necessary to conduct wind tunnel tests at the same Reynolds number as in flight conditions in order to predict airplane performance from the obtained wind tunnel tests. Many wind tunnels have been designed to meet the conditions of Reynolds number match. Higher wind tunnel pressure provides higher Reynolds number flow generally. However, the aerodynamic load on the model becomes large in a highly pressurized wind tunnel, especially at transonic and low supersonic speeds. The load could exceed the limits of even mechanical support systems. The load also causes some distortion of the model shape.

Cryogenic wind tunnels were successfully designed and operated which can generate high Reynolds number flow by decreasing the fluid temperature in smaller test sections than ambient temperature wind tunnels. The dynamic pressure, which is proportional to the model load, remains independent of the temperature. Then cryogenic wind tunnels are very suitable for MSBSs. For example, in a low speed cryogenic wind tunnel, the fluid temperature is cooled to around 100K. Then the density becomes about three times as large as the ambient one at constant pressure. The viscosity of the fluid will become 0.38 times smaller than the ambient one. As a result the Reynolds number will become about 8 times as large as at ambient at the same flow speed if the pressure remains constant. However, the dynamic pressure will remain constant. So, the cryogenic wind tunnel is better in the sense of the model load than the pressurized wind tunnel. The fluid temperature ranges from 90 K to 150 K in the cryogenic wind tunnel. The low fluid temperature makes the cryostat thermal insulation thinner or the operation time of the cryostat longer in case of using the superconductive solenoid core. Also, the high temperature superconductive material will exaggerate the tendency much more because the temperature is around 100 K.

## Magnetic Force Required at the Proposed Wind Tunnel

There are no high Reynolds number supersonic wind tunnels in the world presently. The Society of Japanese Aerospace Companies, Inc. proposed a high Reynolds number supersonic wind tunnel with a 1.25 m x 1.25 m test section.[10] This tunnel is a cryogenic one and the tunnel pressure ranges from 1 to 5 bar. The tunnel temperature is about 170 K at Mach number 2.0. Supposing a supersonic transport model for this tunnel, the fuselage will be 2000 mm long and about 91 mm in diameter. The attainable largest Reynolds number in the tunnel is still much lower than that of a proposed huge supersonic transport in flight.

We investigated the feasibility of a suitable superconductive solenoid core for this model. The aerodynamic load on the wind tunnel model will be 6000 N in lift and 900 N in drag. The aerodynamic moment about the model gravity center is estimated to be small because the core gravity center can be located at the aerodynamic load center. These values are estimated from the aerodynamic coefficients during the cruising flight. They are not so definite because the model attitude will be changed during the tests.

## A Superconductive Solenoid Core

If the MSBS for the tunnel is two times as large as the 60-cm MSBS, the gradient of $Hz$ and $Hx$ with $x$ will reduce to a quarter of the $Hz$ and $Hx$ of the 60-cm MSBS, respectively. Because the model is 2000 mm long, the winding length could become 900 mm at least. It is reasonable to be subdivided into three 300 mm long solenoids to avoid a single long solenoid. Judging from the fuselage diameter of 91 mm, the cryostat for the solenoid is about 87 mm in diameter. The solenoid diameter is 72 mm because thermal insulation must be installed between the solenoid and the cryostat shell. The cryostat is still 1200 mm in overall length because various apparatus for the superconductive solenoid and the gaseous helium exhaust system and so on must be included completely in a space of 300 mm long.

Supposing the NbTi superconductive solenoid of 900 mm long and 72 mm in outer diameter and 43 mm inner diameter and 45 kA/cm$^2$ current density, the magnetic forces are 550 N lift and 135 N drag forces in the 1.3-m MSBS, which is scaled up by two times of the 60-cm MSBS and the same coil turn number of electromagnets and power units. The obtainable forces are about 1/11 in lift and 1/7 in drag of the required magnitudes. More efficient magnetic circuits, larger power units, and larger numbers of coil turns are required as the specifications of the new MSBS for the 1.25-m supersonic wind tunnel in addition to the higher performance of the superconductive solenoid core.

From the experience of designing the two MSBSs at NAL, the temporal goals of the improvement of the MSBS performance are chosen as shown in Table 4. The large increase in the coil turn number may cause some trouble in the cooling system of the coils and a huge inductance problem. A 600 ampere power unit for coil drive is sold by a company presently. The improvement of the magnetic circuit of the MSBS by 20% in its efficiency seems possible according to magnetic field simulation results. The remaining goal is the superconductive solenoid core with higher current density. The goals except the last one look very promising with commonly available technology.

**the new MSBS for the proposed wind tunnel**

coil turn number of the lift coil : 200 + 200
coil turn number of the drag coil : 200
maximum current of the lift coil : 600 A
maximum current of the drag coil : 300 A
derivative of *Hz* with *x* at 600 A lift coil : 91000 AT/$m^2$
derivative of *Hx* with *x* at 300 A drag coil : 19800 AT/$m^2$

**goal of the solenoid performance**

dimensions : $72^{\phi}$ mm x $42^{\phi}$ mm x 300 mm x 3 pieces
current density : 75 kA/$cm^2$

**goal for the cryostat performance**

lifetime : 2 hours

Table 4 Goals of the Model Core for the Proposed Wind Tunnel

## A Prototype Superconductive Solenoid Core

A 900 mm long solenoid is too long for the MSBS. A superconductive solenoid core was designed and built in 1997 by Cryogenics Co., which is the same shape as the required one except its length as shown in Figure 10 and Table 5. The new cryostat is 600 mm long and the solenoid is 300 mm long. By examining the performance of the prototype solenoid core, the feasibility of the long core for the new MSBS will be studied. The solenoid is limited to 300mm which is as long as the permanent magnet core. The diameter of the core is 87mm which is the goal in Table 4. The superconductive material is NbTi and works at 4.2 K. The maximum magnetic moment is above 0.0047 Wb·m. The duration time of the persistant current mode is above 1 hour. For about 20 minutes, the operator must establish the permanent current mode and disconnect the liquid helium transfer tube and current leads. It will take 20 minutes to suspend the model magnetically and carry out some tests and capture the model by the model holding system. Next, the operator must connect the current leads and sink the current from the solenoid. The duration time seems long enough for the above mentioned procedure.

Magnet

| | | |
|---|---|---|
| Field achieved in test at 4.2K | Specified: 6.5 T | Actual: >6.5 T |
| Coil inductance: | Specified: N/A | Actual: ~7 H |
| Current density at 6.5T: | Specified: >25 kA/cm2 | Actual: 45.1 kA/cm2 |
| Calculated magnetic moment at 6.5T: | Specified: >0.0047 Wb.m | Actual: 0.0057 Wb.m |
| Magnet bore: | Specified: 35 mm | Actual: 43 mm |
| Overall diameter: | Specified: 75 mm | Actual: 72 mm |
| Overall length: | Specified: N/A | Actual: 348 mm |
| Winding length: | Specified: 300 mm | Actual: 300 mm |
| Distance from base to field center: | Specified: N/A | Actual: 156.5 mm |

Cryostat

| | | |
|---|---|---|
| Cryostat length: | Specified: 600 mm | Actual: 600 mm |
| Cryostat outside diameter: | Specified: 87 mm | Actual: 87 mm |

Table 5 Superconductive solenoid core specifications for the 60-cm MSBS

All parts for the solenoid operation are installed completely inside a cylindrical region of 87 mm in diameter. This condition is necessary to install the cryostat into a wind tunnel model easily. The vaporized gas from the liquid helium is exhausted through a slender pipe periodically. During exhausting the gas, the aerodynamic forces cannot be measured because the flow around the model is disturbed by the exhausted gas jet. The solenoid will be immersed in the liquid helium. The pressure in the cryostat remains around 1 bar by exhausting the excessive gas. The mass of the cryostat is about 8 kg.

The magnetic force on the solenoid can be evaluated from the measured magnetic field in the 60-cm MSBS. The obtained results are plotted in Figure 11. Even at the very low current density of the solenoid, the magnetic lifting force is enough to lift up the cryostat as shown in the figure.

## Next Step for the Superconductive Solenoid Core.

As mentioned as goals for the solenoid performance in Table 4, the required solenoid is 3 times as long as the present solenoid and the current density is also 3 times as large as the present one. The elongation of the solenoid seems easy because the three present solenoids can be lined up in a new long cryostat. The goal of the current density is 75kA/cm2. It appears impossible to accomplish this value by using the NbTi superconductive material. Other material like Nb$_3$Sn or Nb$_3$Al will be needed. However, just improving the material is not enough to reach the goal. One of the solutions may be to operate the solenoid at a much lower temperature, around 1K, by the use of $^3$He. Other is to redesign the cryostat to make the solenoid as large as possible.

The strong magnetic field generated by the solenoid may magnetize the iron rings of the MSBS unexpectedly if it is too strong. It could be very dangerous for the suspended model because the magnetic field may become uncontrollable by the unexpected magnetization. The estimated magnetic field induced by the solenoid will change by concentrating the magnetic flux at the ferromagnetic materials in the magnetic field. In order to avoid this phenomenon, it is best not to use the electromagnets for the MSBS. Much iron material is used for the iron rings at the 60-cm MSBS. The magnetic field induced by the solenoid must be sufficiently weak around the ferromagnetic materials like the iron coil cores not to be magnetized strongly. This means there is an upper limit value of the current density for the solenoid of the 60-cm MSBS. This effect will be much reduced for the larger MSBS because the magnetic field intensity induced by the solenoid reduces rapidly in inverse proportion to the square of the distance between the solenoid and the ferromagnetic material.

## CONCLUDING REMARKS

The original model position sensing system was improved by adding another sensing camera mounted at the upper side of the 60-cm MSBS. Measured $y$ coordinate and yawing angle, $\psi$, of the model are as accurate as the other measured positions like the $z$ coordinate with the original sensing camera mounted on the side of the MSBS.

The 60-cm MSBS is equipped with a model holding system in order to release safely and hold the suspended model. This system is inevitable for tests of a superconductive solenoid core because it is very dangerous to put the excited solenoid on a stand in the MSBS manually. The system is used to hold and release a permanent magnet cored model presently.

The model holding system is equipped with a model load monitoring system. The system can measure the load at various coil currents at various model positions.

It is impossible to build a suitable sized superconductive solenoid for the 60-cm MSBS because the solenoid inside the cryostat must be too small.

A cylindrical model core of Alnico magnet is the most suitable of available permanent magnets for the 60-cm MSBS. The attainable net lifting force is up to 17N with 130A lifting coil current. A model must be designed within the gravity force of 17 N except for the core weight.

The cryogenic wind tunnel has a much smaller test section and smaller dynamic pressure than other ambient temperature wind tunnels when they generate the same Reynolds number flow in their test sections. These features of the cryogenic tunnel is very suitable for the MSBS. Besides, the low temperature of the fluid is good for the cryostat of the superconductive solenoid. The MSBS is a very attractive system, especially for the cryogenic high Reynolds number supersonic wind tunnel.

A superconductive solenoid core for the cryogenic high Reynolds number supersonic wind tunnel is specified. As a first step to make the solenoid, a 300 mm long superconductive solenoid core was designed and built in 1997. The dimensions of the cryostat are 87 mm in diameter and 600 mm long and below 8 kg in mass. The NbTi superconductive solenoid is 72 mm in diameter and 300 mm long and 45 kA/cm$^2$ at highest current density. The solenoid is immersed in liquid helium at around 4.2 K. The lifetime is about 1 hour. The largest magnetic lifting force is estimated at 500 N at the 60-cm MSBS although it has not been examined at NAL.

We plan to examine the performance of the superconductive solenoid and the cryostat and the suspension performance in the near future.

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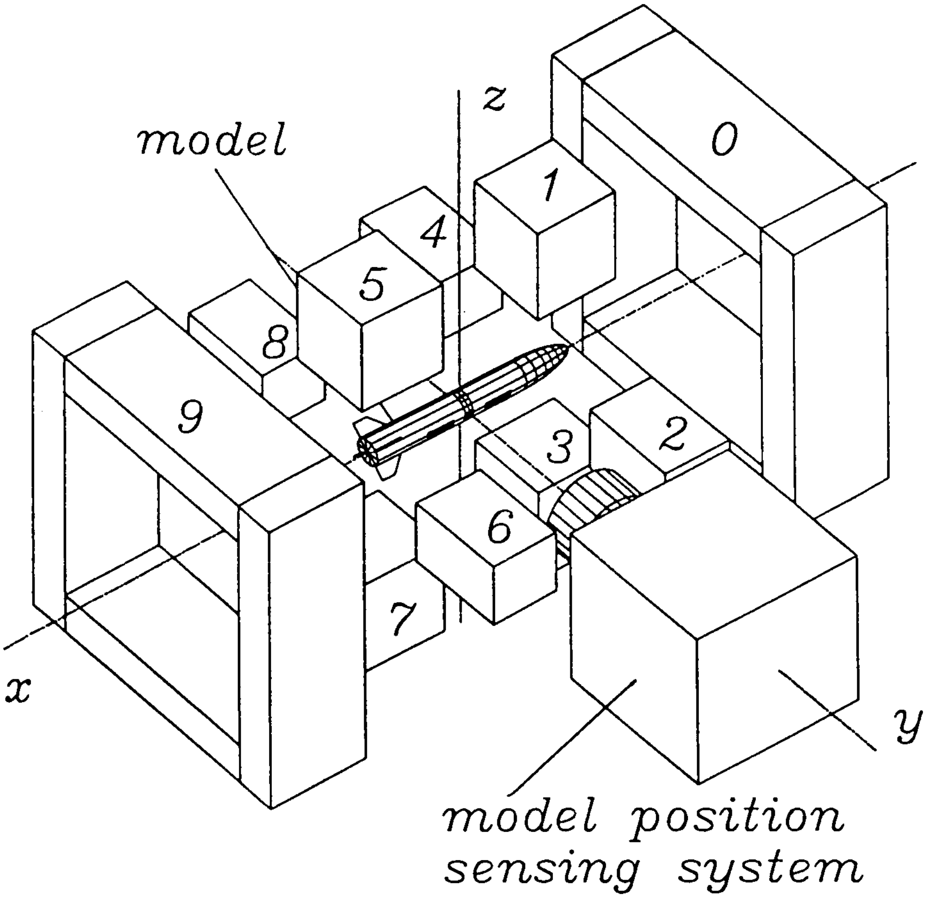

Figure 1 Coil Arrangement of the NAL 60-cm MSBS

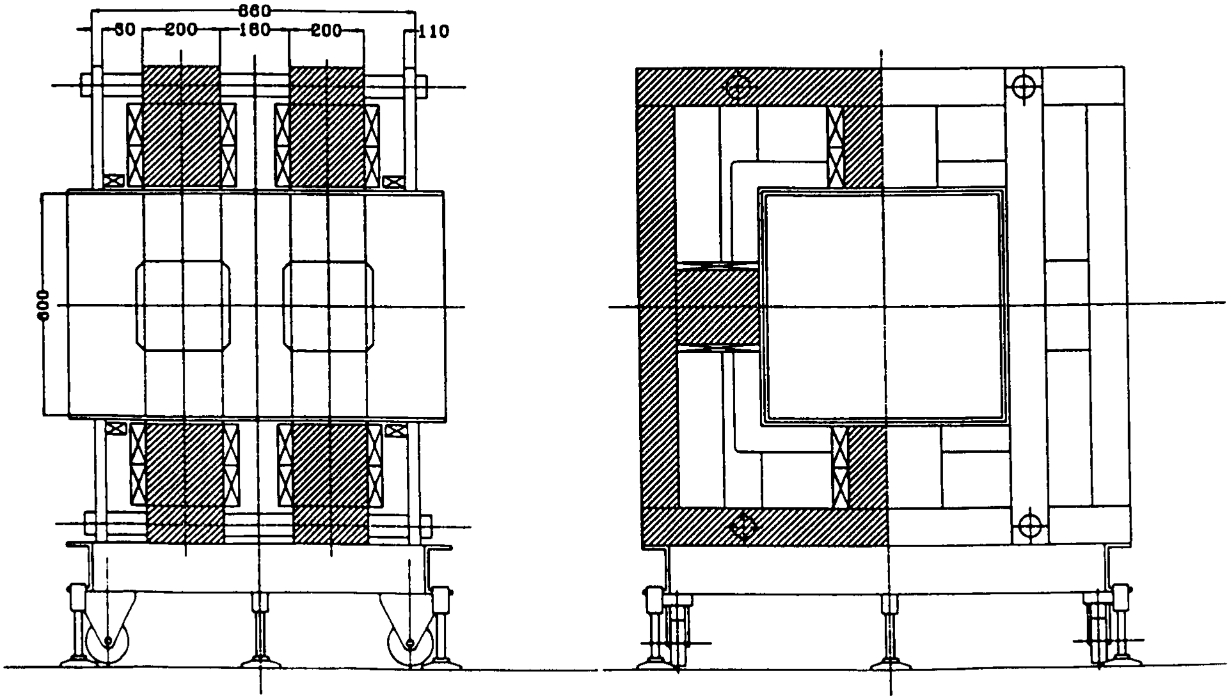

Figure 2 The 60-cm MSBS

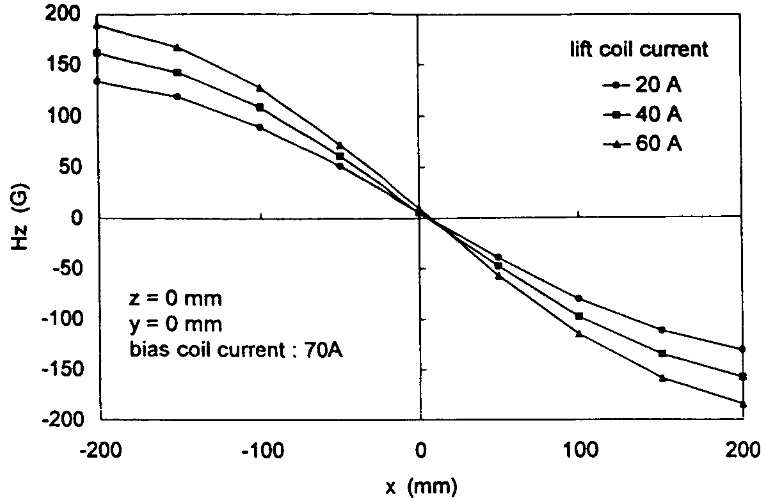

Figure 3 *Hz* Measured in the 60-cm MSBS

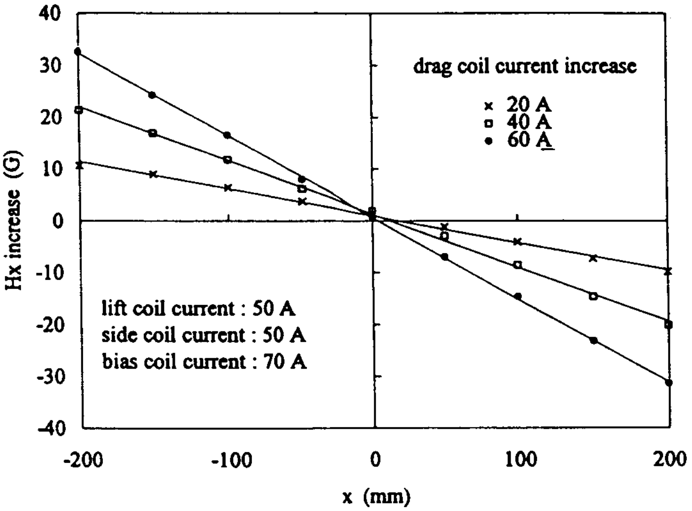

Figure 4 *Hx* Measured in the 60-cm MSBS

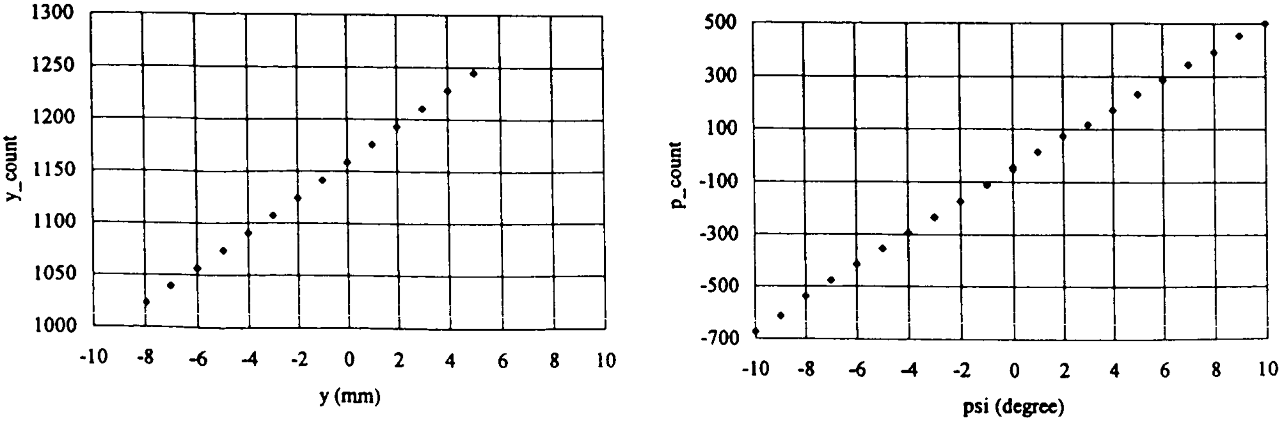

Figure 5 Calibration Test Results of the Improved Model Position Sensing System

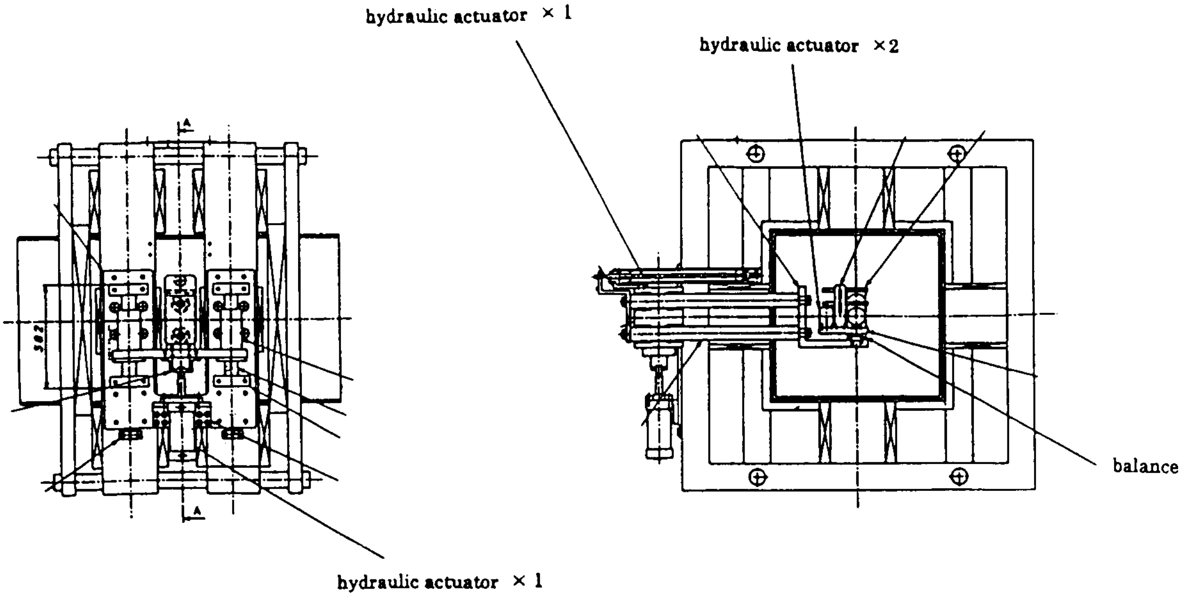

Figure 6 Model Holding System

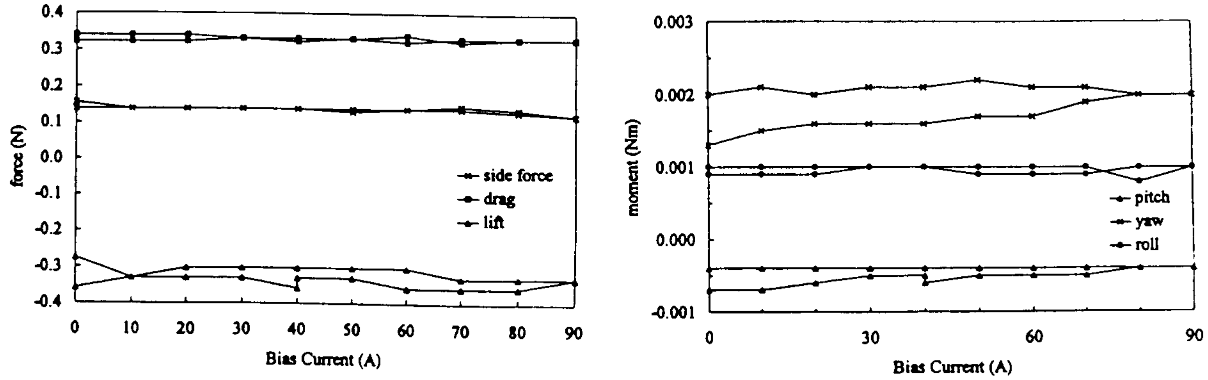

Figure 7 Model Holding System Effect on the Balance Output

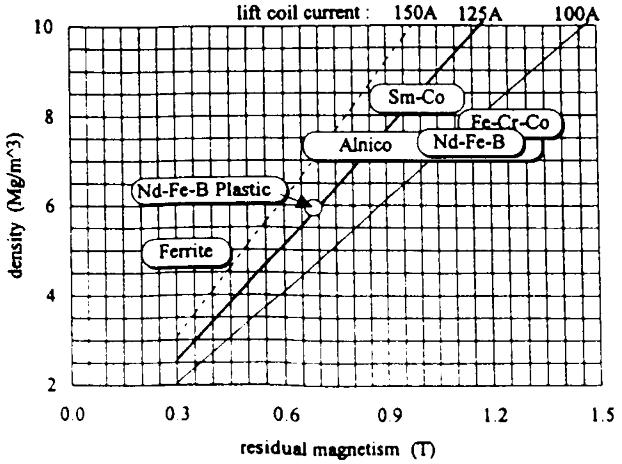

Figure 8 Performance of The Permanent Magnet Core for the 60 cm MSBS

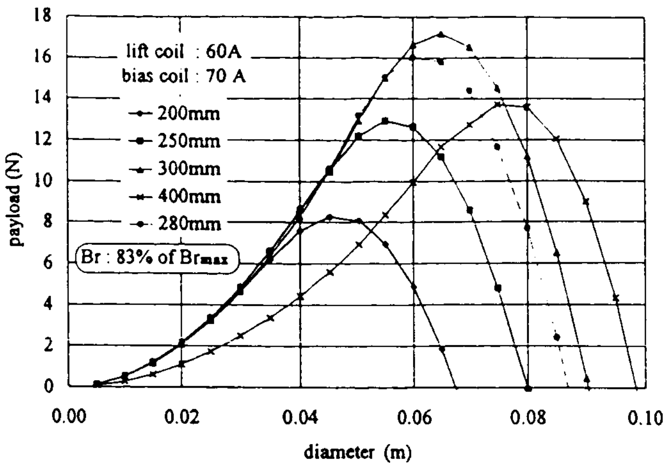

Figure 9 Alnico Magnet Performance at the 60-cm MSBS

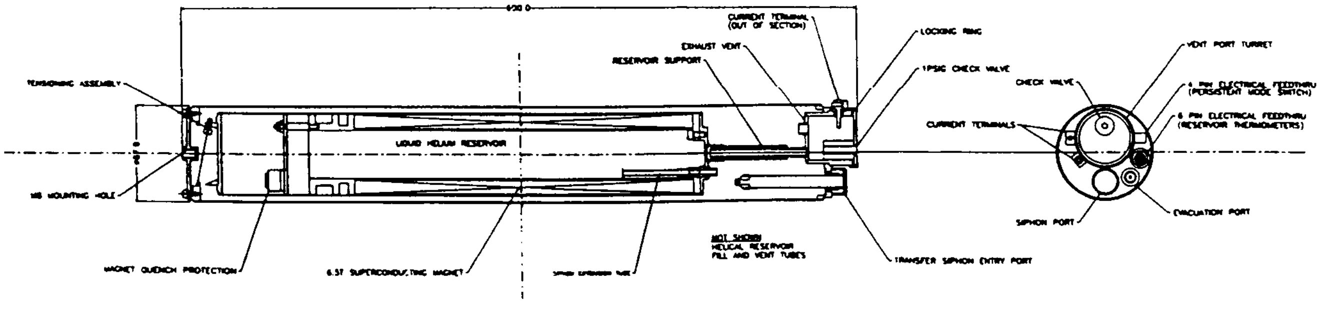

Figure 10 The Superconductive Solenoid Core for the 60-cm MSBS

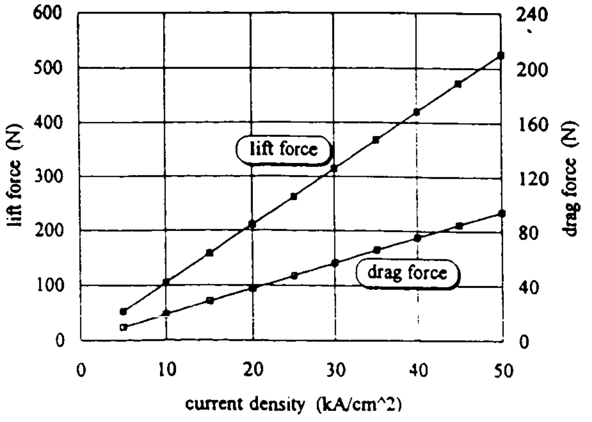

Figure 11 The Evaluated Magnetic Force Acting on the Superconductive Solenoid