Status of MSBS Study at NAL

Hideo SAWADA, Takashi KOHNO, and Tetsuya KUNIMASU
National Aerospace Laboratory
7-44-1 Jindaijihigashi-machi Chofu-shi, Tokyo, Japan

Applications: Wind tunnel model suspension systems

ABSTRACT

A superconductive solenoid model core was suspended successfully in the NAL 60-cm MSBS. The cryostat containing the solenoid is 600 mm long and its diameter is 87mm and the solenoid works at 4.2K. Its material is NbTi. Duration time of the permanent current mode is about 1 hour. According to several test results, the available time for wind tunnel tests is around 30 minutes for the system. The superconducting solenoid core has the same characteristics, up to 20A in coil current, in the MSBS as the permanent magnet core does. The model position sensing system was improved to be easy to use. An auto-calibration system was built. The lighting system was improved to light up with red and green lights respectively from upper and side ways in order to avoid the interference between lateral and longitudinal position components. The 60cm MSBS was installed in a low speed wind tunnel with a closed circuit. A cylindrical model and a cone-cylinder model were suspended at various flow speeds up to 28.5m/s without any extra motion compared with flow off.

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 the magnetic field which is controlled by the coils arranged outside the test section as shown in Figure 1. Any mechanical support system is not needed in the flow field. Then the support interference problem does not exist except for very special test conditions like hypersonic flow containing ionized atoms. Besides, it is very suitable to carry out difficult tests like dynamic tests. It is also much easier to change model attitude over a wide range by an MSBS than by a mechanical support system. These features of the MSBS will improve the tunnel data productivity. Many MSBSs have been built up to the 1970s but only a few are in operation presently.

The NAL 10-cm MSBS has been developed since 1985 and the 60-cm MSBS has been developed since 1993 at the National Aerospace Laboratory (NAL).[1] The 60-cm MSBS has the largest test section in the world in the sense of the dimensions as of present. The detail of research activity relating to the 10-cm MSBS at NAL must be referred to References 1) to 4).

In order to generate a large magnetic force balancing the aerodynamic load, both a strong magnetic field and large magnetic moment of the model core are needed. The superconductive solenoid core can be mounted inside a model and can generate much larger magnetic moment than permanent magnet cores. A small superconductive solenoid model core was designed and was suspended successfully in a MSBS at Southampton University supported by NASA.[5,6] This was the only successful suspension of a superconductive solenoid until the suspension of the solenoid described in this paper. A new superconductive solenoid model core was designed at NAL and was built by a manufacturer in 1997. The core was suspended in the 60-cm MSBS successfully in 1998. As far as the authors know, there was no procedure of safety handling superconductive solenoid model cores in MSBSs. Through the experience of suspending the core in the 60-cm MSBS, a safe handling procedure was developed.

The 60-cm MSBS was installed in an old low-speed wind tunnel at NAL. The tunnel has a closed circuit and is fan-driven. The maximum flow speed is about 28.5m/s and its pressure is ambient. The MSBS has been improved to be easy for researchers to use it. The model position sensing system can be calibrated automatically with a computer. A computer controls all of the MSBS in order to avoid wrong operations. Model position and coil current data sets for 16 seconds at any time during the operation can be stored. The system is still being improved to meet to user satisfaction. Two kinds of models were suspended in the tunnel and the results were examined to determine whether or not the MSBS was acceptable for wind tunnel testing.

SYMBOLS

(x,y,z)	... coordinate system, unit : mm, See Figure 1.
(ϕ,θ,ψ)	... rolling, pitching , and yawing angles of a model, unit : degree.
H	... magnetic field intensity, (Hx,Hy,Hz).
M	.... magnetic moment (Wb.m), (Mx,My,Mz).
P[0] to P[5]	... ceiling sensing camera outputs, (counts).
P[6] to P[9]	... side sensing camera outputs, (counts).
P,Q,R,S,T	... see Eqn. (2).

Brief Description of the NAL 60-cm MSBS

The 60-cm MSBS consists of 8 electromagnets and 2 air cored coils. Four of the 8 electromagnets make a magnetic circuit with an iron ring perpendicular to the wind axis (x-axis). The other four also make a magnetic circuit with another iron ring as shown in Figure 2. Each has four pole-surfaces. The coils 1 to 4 are attached to the upstream iron ring. The coils 5 to 8 are attached to the downstream ring similarly. The coil currents can control the magnetic field surrounded by the four pole-surfaces in each ring. The four coils are always excited in pairs like a pair of coils, 1 and 3. The paired coils of (1, 3) and (5, 7) control Hz and its derivative with respect to x. Similarly, the paired coils of (2,4) and (6,8) control Hy and its derivative with respect to x. A pair of air cored coils, (0, 9) controls the derivative of Hx with respect to x. The distance between the poles of the coil pair is 640 mm. The specifications of the coils are listed in Table 1. Details of the NAL 60-cm MSBS are described in References 1 to 4 and 7.

We have two permanent cylindrical magnets magnetized along their axes for the 60-cm MSBS. One is 50 mm in diameter and 300 mm long and a TOKIN K-5 type Fe-Cr-Co magnet. The other is 55 mm in diameter and 280 mm long and is an Alnico5 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 1500 W, which range from 0 to 100 A. The coils are cooled with ambient air and they can be operated for about 1 hour.

A model position sensing system for the NAL 60-cm MSBS has been developed at NAL. The principle of the system is the same for the NAL 10-cm MSBS. It is described in reference 1. Two model position sensing cameras are mounted at the side and upper side test section walls. The upper camera measures x, y coordinates and yaw angle, ψ of the model. The side camera measures z coordinate and pitch angle, θ. Each camera is connected to a computer and both measured data sets are gathered synchronously in a computer and the computer evaluates the model position with them and adjusts the coil currents. Large noise radiated from the power units affect the accuracy of the measured position significantly. All position data are modified with low pass filter of 10 Hz cut-off frequency before evaluating the model position.

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	1500 W	2 units	
model cores	50-x 300 cylindrical permanent magnet (Fe-Cr-Co)		
	55-x 280 cylindrical permanent magnet (Alnico5)		
control	5 degree of freedom except for rolling motion control		
	rolling motion : mechanical control with a fly wheel [8)]		

Table 1 Specifications of the NAL 60-cm MSBS

In order to avoid model damage and personnel accident during initial suspension, the 60-cm MSBS has a model holding system. The system was designed to hold the model horizontally at the center of the test section as shown in Figures 2 and 5. The arm part of the system can be moved out from the test section completely after releasing the model. After moving out of the test section, the open space on the test section wall for motion can be closed with a removable window by hand. In order to confirm that the model is in balance, the model holding system is equipped with a balance. If the output from the balance becomes very small in its magnitude, it suggests that the model has been in near balance condition. The balance is accurate enough to monitor a model balance condition. Details of the model holding system and the monitoring system are in Reference 7.

A Superconductive Solenoid Core

A superconductive solenoid model core, shown schematically in Figure 3, was designed and built in 1997 by NAL and a manufacturing company. The cryostat is 600 mm long and 87mm in diameter. The solenoid is 300 mm long and 72 mm in outer diameter and 43mm in inner diameter and works in liquid helium at 4.2 K. The superconductive material is NbTi. The maximum magnetic moment is above 0.0057 Wb_m. Duration time of the permanent current mode is about 1 hour. The maximum storage of liquid helium is about 1 liter. Details are in Table 2.

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 continuously at the present time. During the gas exhausting, aerodynamic forces cannot be measured because the flow around the model is disturbed by the exhausted gas jet. The mass of the cryostat is about 7.4 kg.

The magnetic moment, *Mx*, was measured with the 60-cm MSBS magnetic field and it is 0.0023Wbm when the solenoid is excited at 20A. The cryostat was inserted into a thin cylinder of 91mm in its outer diameter to protect the cryostat shell from the model holding system. The mass of the whole model including the model mass is 8.7kg and the inertia moment about the gravity center is about 0.233kgm^2, which was evaluated by oscillation tests. Because the MSBS does not have rolling motion control capability as of present, a small thin plate of lead was attached inside the cylindrical model so that the helium gas exhaust pipe exit may be upwards in balance. The control constants were estimated with the constants of a permanent magnet model core.

	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/cm^2	Actual:45.1 kA/cm^2
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 2 Superconductive solenoid model core specifications for the 60-cm MSBS

Handling and Operating Test Results of the Superconductive Solenoid Model Core.

It is necessary to estimate the procedure in detail for testing a model with the superconductive solenoid model core in the MSBS because only one example of suspending a small superconductive solenoid core in the small MSBS[5)] was reported. After several tests, a testing procedure was built temporarily, which is subdivided into 62 steps. Fundamental sequential steps are listed in Table 3.

The coil temperature history is shown in Figure 7, which was monitored at the model suspension test in the 60-cm MSBS. The solenoid was excited at 20A. Parts of the temperature history during the model suspension are not depicted because the cables are disconnected during that time. At the first test in the figure, it took one hour and 43 minutes to cool down the solenoid and it took 16 minutes to build the permanent current mode to 20A and to disconnect all cables. Then the model was suspended in the MSBS for about 30 minutes. After holding the model by the holding system, we waited for quench phenomenon. When the quench happened, the solenoid temperature rose up suddenly as shown in the figure. Once quench happens, we must wait for an hour to achieve uniform temperature in the solenoid. In order to proceed to the next test, the solenoid was cooled again. It took about one and a half-hour to cool it and store liquid helium inside the cryostat. After exciting the solenoid, the model was tested in the MSBS again. The model was held by the holding system at 10 minutes before expected quench time. Then the power unit sank the current passing through the solenoid safely. The cryostat was stood on a base to pour liquid helium into it. The solenoid was cooled soon again because heat was not generated by quench. The third test was also carried out safely as shown in this figure. If quench is avoided, model suspension tests of about 20 minutes duration could be carried out every 150 minutes. It took 30 minutes to cool down the solenoid with this procedure. It also took about 1 hour to store enough liquid helium inside the cryostat. The one-hour of the storing time was decided through several cool down test experiences. Then, there is some room to make the time shorter. The whole procedure listed in the Table 3 for suspending and holding and de-energizing the superconductive solenoid model core safely was confirmed by several tests.

---

1. get the 60-cm MSBS ready to suspend a model,
2. stand the cryostat vertically on a base,
3. connect coil temperature and liquid helium monitoring cables,
4. disconnect the short bar on the solenoid ends,
5. start measuring the coil temperatures and liquid helium level,
6. start transferring liquid helium into the cryostat,
7. wait until conditions are satisfied completely,
8. finish transfer of liquid helium, (See Figure 4.),
9. disconnect coil temperature and liquid helium monitoring cables,
10. insert the cryostat into a model,
11. connect coil temperature and liquid helium monitoring cables again,
12. connect coil exciting cables,
13. mount the model on the model holding system,
14. hold the model strongly, (See Figure 5.)
15. switch on a power unit for the solenoid,
16. build permanent coil current mode,
17. switch off the power unit,
18. short the solenoid ends with the short bar,
19. disconnect the coil exciting cables and monitoring cables,
20. start operation of the 60-cm MSBS, (See Figure 6.)
21. hold the model by the holding system before 10 minutes of quench phenomenon,
22. stop operation of the MSBS,
23. connect the monitoring cables,
24. decide whether or not to continue sinking current procedure by the monitored coil temperatures,
25. connect the coil exciting cables,
26. switch on the power unit,
27. disconnect the short bar,
28. sink the coil current completely,
29. switch off the power unit,
30. disconnect all cables,
31. release the model from the model holding system,
32. pull out the cryostat from the model,
33. stand the cryostat on a base,
34. connect the monitoring cables,
35. transfer liquid helium into the cryostat again if it needed,

---

Table 3 Handling procedure for the superconductive solenoid model core at the NAL 60-cm MSBS

The model with the superconductive solenoid model core was suspended successively in the NAL 60-cm MSBS as shown in Figure 8. The 20A current passed through the solenoid at the test. It was not necessary to tune up the control performance with the reduced control constants from theperma- nent magnet cores. The responses of model position change were acceptable as shown in Figure 9. Large differences in response and suspension performance did not appear between a permanent magnet core and the superconductive solenoid core at the time. In Figure 6, strings are shown in the figure, which have no tension and do not affect the suspension at all. The strings were attached to the model in order to avoid accidental drop directly against the test section wall. A picture of the suspended superconductive solenoid model core model without any strings is shown in Figure 8. The cryostat was out of order after the test and the coil temperature could not cool down with liquid helium. According to the manufacturing company's repair report, the cause was that the solenoid suspension rods inside the cryostat were broken which caused the thermal insulation performance to degrade significantly. It was repaired. The success of suspending the super conductive solenoid model core suggests the possibility of realizing larger sized MSBS by using the superconductivity technology. We are proceeding to design a 2m MSBS for a low speed wind tunnel.

Improved Model Position Sensing System

The model position sensing system at the NAL 60-cm MSBS was significantly improved in accuracy two years ago by adding another sensing camera in upper side of the model. However, the two cameras were connected to computers, respectively. One computer, which received the measured model position by the upper camera, controlled the lateral model motion. Similarly, the other computer, which gathered the model longitudinal model position with the side camera, controlled the longitudinal model motion. Only the x coordinate was corrected by measured model yaw angle. Practically, a model is lighted with four optical fiber illumination systems. The two systems light the model from the upper side and the other two systems light from the side. Then a part of the model surface is lit up more strongly than the other lighted parts from both ways. In order to avoid interference between the lateral and longitudinal measured data sets, the upper side model is lit up with red light with color filter sheets on the upper window and the side surface of the model is lit up with green light with a color filter sheet on the side window.

The two cameras are driven synchronously with one signal and the measured data sets are gathered into one computer at the same time. Then interference among the five model position components is corrected with following linear equations:

$$\begin{pmatrix} x \\ y \\ z \\ \theta \\ \psi \end{pmatrix} = \begin{pmatrix} +0.0680 & -0.0011 & +0.0001 & -0.0174 & -0.0009 \\ +0.0001 & -0.0646 & +0.0009 & +0.0009 & +0.0048 \\ -0.0001 & +0.0046 & +0.0527 & -0.0001 & +0.0002 \\ -0.0000 & -0.0000 & -0.0010 & +0.0349 & +0.0026 \\ +0.0000 & +0.0005 & +0.0004 & -0.0005 & -0.0367 \end{pmatrix} \begin{pmatrix} T \\ R \\ P \\ Q \\ S \end{pmatrix} + \begin{pmatrix} +39.59 \\ -76.80 \\ +70.88 \\ -1.05 \\ +0.68 \end{pmatrix} \quad \ldots(1)$$

where

$$T = \frac{(P[0] + P[1])}{2}$$
$$R = \frac{(P[2] + P[3] + P[4] + P[5])}{4} \quad \ldots (2)$$
$$P = \frac{(P[6] + P[7] + P[8] + P[9])}{4}$$
$$Q = \frac{(P[6] + P[7] - P[8] - P[9])}{4}$$
$$S = \frac{(P[2] + P[3] - P[4] - P[5])}{4}$$

The 60-cm MSBS was equipped with the 60-cm low-speed wind tunnel this spring. Aerodynamic tests will be carried out with various models in near future. The model position sensing system must be calibrated much more easily and often for each tested model. Then, an automatic calibration system was built as shown in Figure 10. A specially made calibration model, which has the same shape and surface condition as the aerodynamic test model, is positioned by a computer and its position measured automatically. The model is in very similar condition at the calibration test as the aerodynamic test model is suspended inside the test section. The calibration coefficient matrix and offsets are evaluated easily with the gathered data sets by the same computer on the spot. The simple relations between model position, T to S in Eqn. (2) and sensing camera outputs are depicted on the monitor of the computer during the calibration test. Then, if unexpected relations are observed, the test can be stopped anytime and the system can be adjusted again. The calibration coefficients and offsets used in the MSBS control program can also be changed with the new obtained coefficients and offsets on the spot. y and Ψ calibration test results are shown in Figures 11 and 12. As shown in Figure 12, the interference still remains larger than 2 degrees in Ψ. Another computer is placed by the control computer, which gathers the all measured model position data sets and a part of coil current data at the same speed as the control computer. When a special key is hit, the model position and coil currents are stored as a file on hard disk for about 16 seconds after the time.

Installation of the 60-cm MSBS at the 60-cm low speed wind tunnel

The NAL 60-cm MSBS was built in 1990 and operated successfully in 1993. The MSBS has been improved in its control and in its sensing system. But it has not been installed at a low speed wind tunnel because a low-speed wind tunnel with a 60cm x 60cm test section was not available. A very old wooden wind tunnel was proposed to use for the MSBS in 1998. Then the MSBS was moved to the tunnel in the spring. The tunnel had been used for boundary layer research and was modified to have a long test section of 2m. The long test section consists of two parts of 1m long. The main parts except its contraction and test section were made of wood. It is good for MSBS. Besides, the iron contraction is 1m upstream far from its downstream test section inlet. The MSBS replaced the downstream test section and is far from the iron contraction by 1m as shown in Figure 13. The upstream test section was made of aluminum alloy in its frame parts and transparent material in the other parts. The test section of the MSBS was made of wood and 1.2m long. A 15cm x 15cm sensing window is in a side and ceiling walls of the test section, respectively. A replaceable 15cm x 47cm window is in the other side wall for a model holding system going out of the test section. A new collector was designed and installed to meet the new situation of this tunnel. The fan system was designed to be good up to 1500rpm but was limited up to 1000rpm because of fan belt oscillation trouble presently. Then the highest speed is 28.5m/s, which was measured 1m upstream from the MSBS test section inlet. A flow quality data set is not available yet.

The possible model incidence ranges up to 12.5 degrees because the drag coil current reaches around 65A at this model attitude without flow. In order to increase the maximum incidence beyond this value, drag coil current must be increased. The model, at the incidence of 12.5 degrees, is shown in Figure 14. A cylindrical model was tested at the incidence of 4 degree in the flow of 28m/s as shown in Figure 15. The model stayed at a position during the test without any additional motion.

One of the purposes of equipping the tunnel with the MSBS is to estimate the model support system interference in a new airship development project at NAL. The drag of airships consists of the friction drag and pressure drag. The two kinds of drags which are significantly affected are the boundary layer transition and flow separation. The flow is very complicated around the connecting sections between the model support and model itself. There is concern whether or not the simple subtraction method of evaluating the interference could be still available in this sensitive case. It is easy to estimate the model drag interference free case if the drag is measured with the MSBS.

A cone-cylinder model was tested at 0 incidence at speeds up to 28m/s in the tunnel as shown in Figure 16. The drag coil current was measured with respect to the flow speed. The result shows the averaged drag current changes in proportion with its dynamic pressure as shown in Figure 17. The measured model position shows that the model stayed at the same position during the test. However, this figure shows only the trends of the obtained data set but is not a valid aerodynamic data set at all because the flow has not been calibrated yet. Besides, the model surface was poor because the model was wrapped with a sheet of white paper. The figure shows only the availability of the 60-cm MSBS. A 6:1 ellipsoid model will be tested in the wind tunnel this fall. The model surface will be painted in white and will be aerodynamically smooth. Several tests conducted during this spring and fall show the MSBS works well in flow at the speeds up to 28m/s in the tunnel. The tunnel will be improved in its maximum speed next year.

Concluding Remarks

The superconductive solenoid model core designed and built by NAL and a manufacturing company was suspended successfully for about 30 minutes at the NAL 60-cm MSBS. The handling procedure of testing the solenoid model core was examined and confirmed as safe. The control performance of the core looks like those of the permanent magnet cores.

The control system of the MSBS was improved to be one computer control with two synchronously driven cameras of the model position sensing system. The position sensing system can be calibrated automatically with a control computer and the obtained calibration coefficients can be available quickly on the spot. The lighting system was also improved to light up with red and green lights respectively from upper and side ways in order to avoid the interference between lateral and longitudinal position components.

The 60-cm MSBS was installed in a low speed wind tunnel, of which flow speed is up to 28.5m/s and pressure is ambient. A cylindrical model and a cone-cylinder model were tested in the wind tunnel at various speeds including the maximum one. No motion was observed during the tests. Although several aerodynamic data sets were obtained, they are not valuable, except to demonstrate the availability of the MSBS, because the model surfaces were poor and any flow quality data sets are not available. After calibrating the flow and finishing model surface smoothly, valuable data sets will be obtained.

REFERENCES

1. H.Sawada, H.Kanda, and H.Suenaga : "the 10cm x 10cm Magnetic Suspension and Balance System at the National Aerospace Laboratory." AIAA 91-0397, 1991
2. H.Sawada and H.Suenaga : "Status of MSBS Study at NAL", NASA CP 3247, 1994, pp. 275-289
3. H.Sawada and H.Suenaga : "Magnetic Suspension and Balance Systems at NAL." Pacific International Conference on Aerospace Science and Technology, Conference Proceedings Vol. 2, 1993, pp. 1014-1021
4. H.Sawada, H.Suenaga and T.Kohno : "Status of MSBS Study at NAL in 1995." NASA CP 3336, 1996, pp. 505-519
5. C.P.Britcher : "Progress Toward Magnetic Suspension and Balance Systems for Large Wind Tunnels." Journal of Aircraft, Vol. 22, No. 4, April, 1995 pp. 264-269
6. J.Eskins : "Further Investigation into Calibration Techniques for a Magnetic Suspension and Balance System." NASA CR-178056, 1986
7. H.Sawada, T.Kohno and T.Kunimasu: "Superconductive Solenoid for the NAL 60cm MSBS" NASA CP-1998-207654, 1998, pp. 425-439
8. T.Kohno, H.Sawada and T.Kunimasu: "Roll Motion Restraint System for NAL 0.6m MSBS" NASA CP-1998-207654, 1998, pp. 141-150

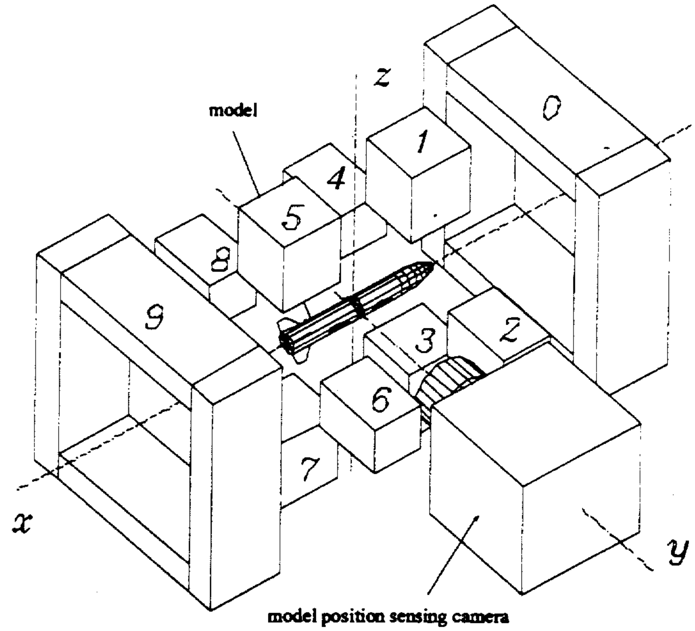

Figure 1 Coordinate system at the NAL 60-cm MSBS

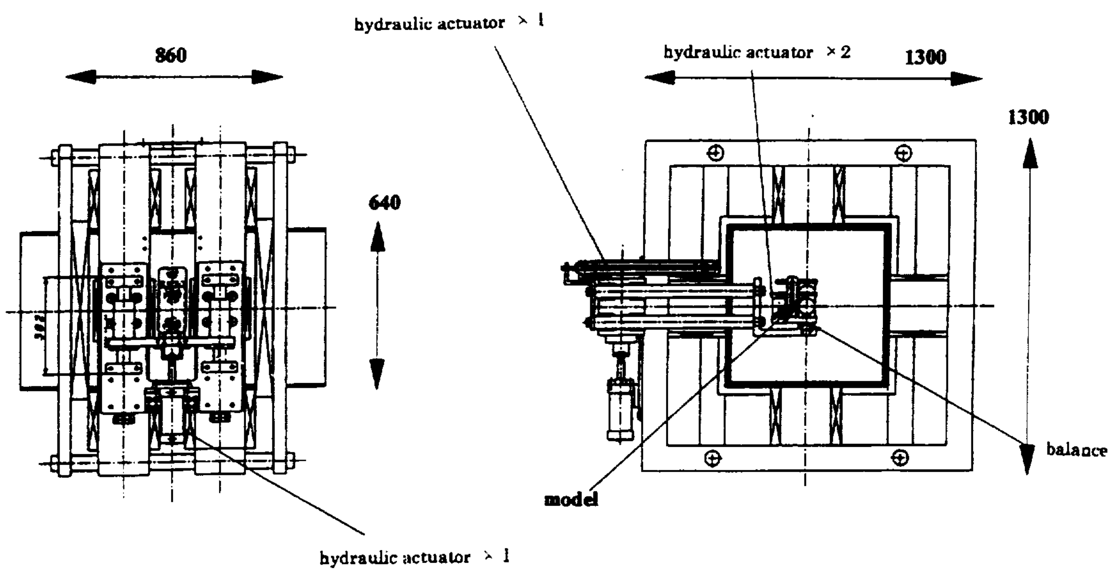

Figure 2 The NAL 60-cm MSBS and the model holding system

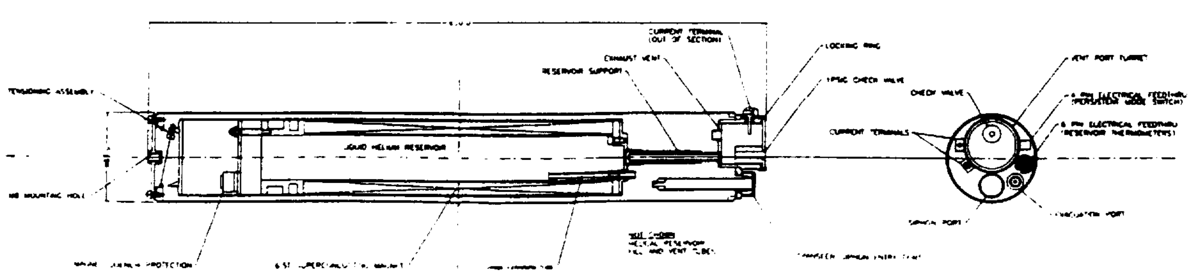

Figure 3 The NAL superconductive solenoid model core

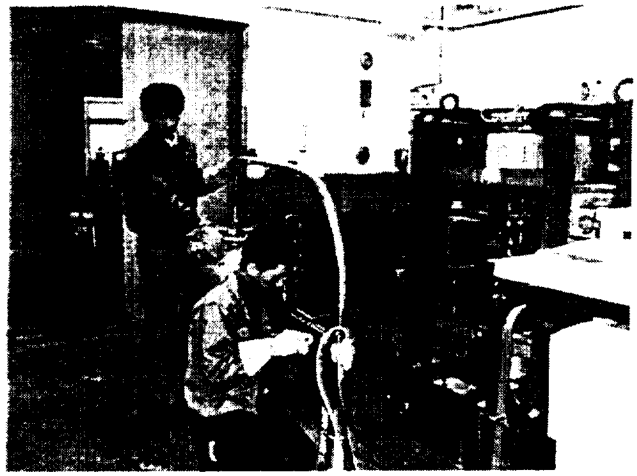

Figure 4 The NAL superconductive solenoid model core on a base

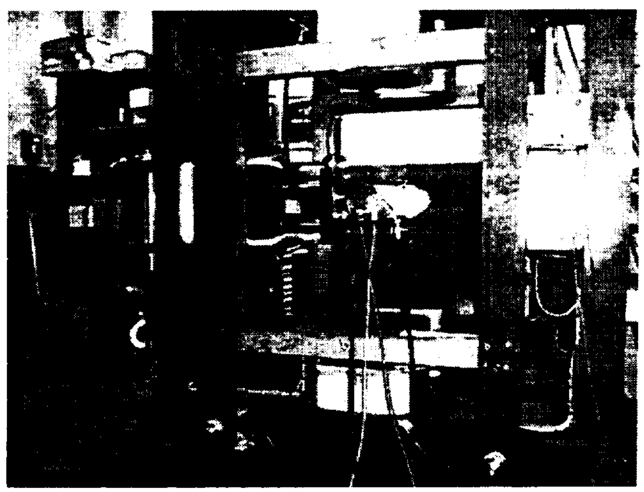

Figure 5 The NAL superconductive solenoid model core in the model holding system

Figure 6 The NAL superconductive solenoid model core suspended in the 60-cm MSBS

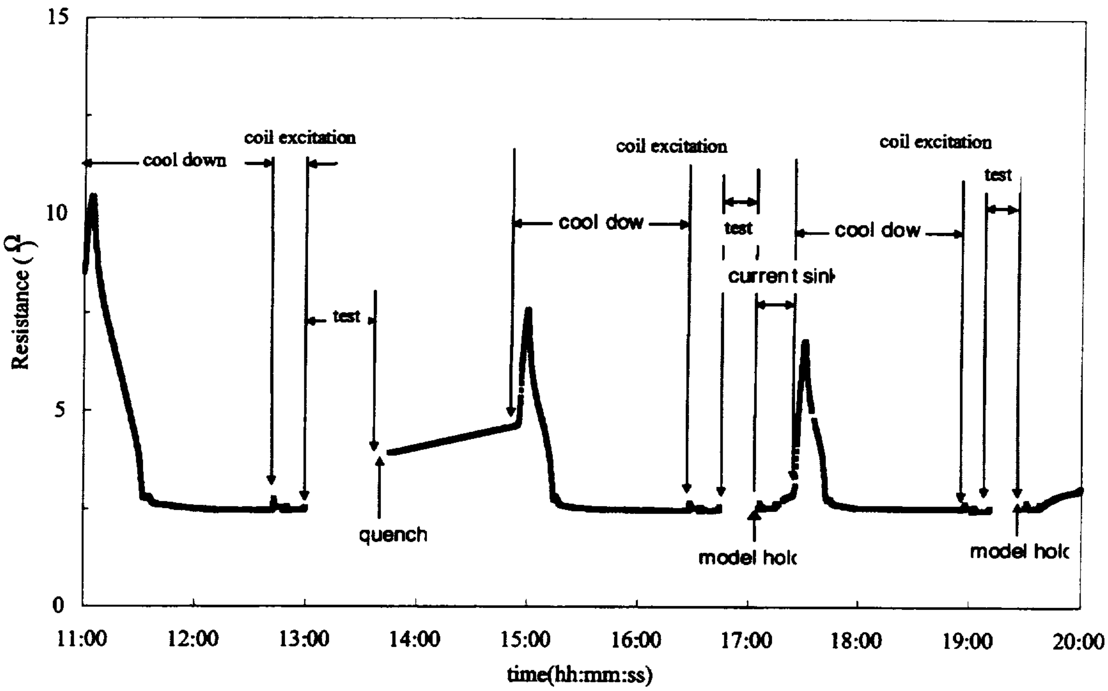

Figure 7. Time history of the superconductive solenoid temperature at the NAL 60-cm MSBS

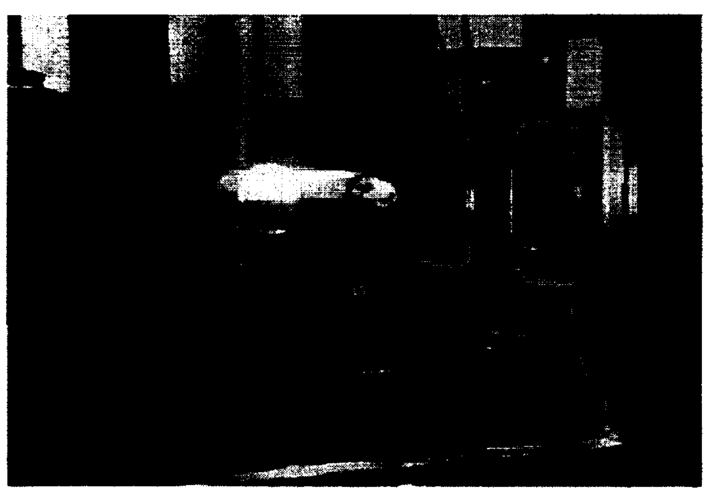

Figure 8. A superconducting solenoid model core suspended in the 60-cm MSBS

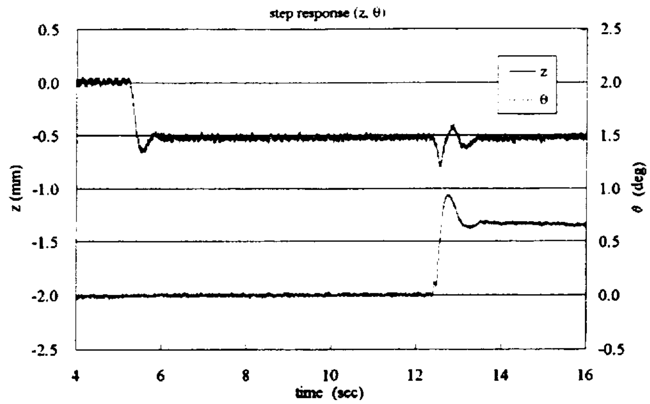

Figure 9. Step response of a superconductive solenoid model core at the NAL 60-cm MSBS

Figure 10. Auto-calibration system

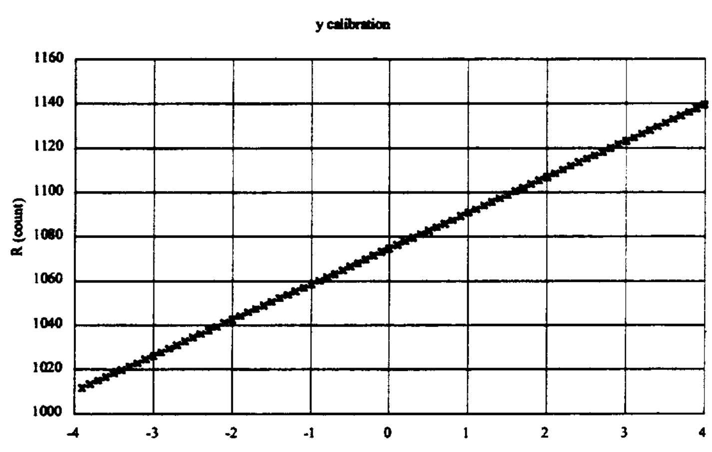

Figure 11 y calibration test results

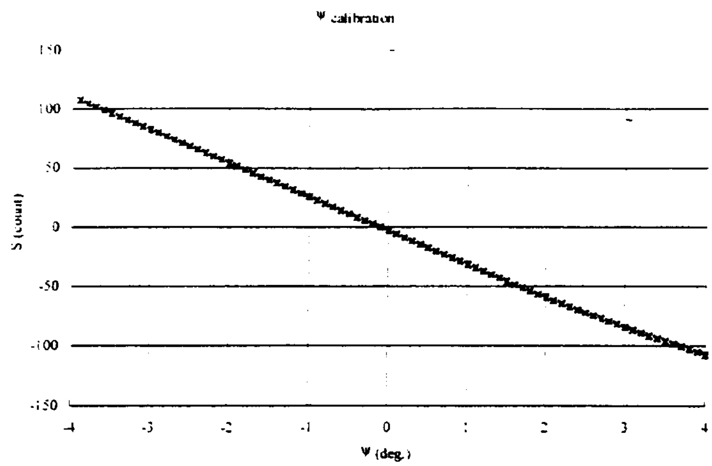

Figure 12 ψ calibration test results

Figure 13. The 60-cm MSBS installed in the 60-cm-low-speed-wind-tunnel
(A new collector is removed.)

Figure 14 A cylindrical model at the incidence of 12.5 degree

Figure 15 A cylindrical model at 4 degree incidence in the flow of 28m/s

Figure 16 A cone-cylinder model at zero incidence in the flow of 28m/s

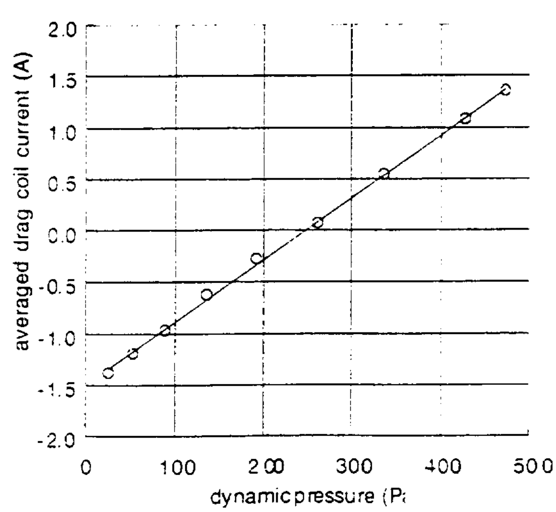

Figure 17 Relation between uniform flow dynamic pressure and drag coil current for the cone-cylinder model