Operation of the Thruster for Superconducting Electromagnetohydrodynamic Propu1sion Ship "YAMATO 1"*

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The Ship & Ocean Foundation set up "a research and development committee for MHD ship propulsion" in 1985 and started an extensive R& D studies, and to construct an experimental ship to demonstrate that a ship can really be propelled by MHD thrusters with all the necessary machinery and equipments on board. The experimental ship,named the YAMATO 1, was completed in the fall of 1991 and was actually propelled successfully by MHD thrusters in the summer of 1992 in KOBE harbour.

There are many complete different handlings & operational sequences required for the operation of Superconducting MHD thruster in comparison with usual one. This paper describes the manner & results of initial cooling down and exciting & demagnetization of the superconducting magnets, and compares measured data on the BOLLARD test with values calculated theoretically, and reports the agreement with them.

1. Preface

"YAMATO 1" is the first superconducting electro-magnetohydrodynamic (MHD) propulsion ship in the world. The ship was designed to be propelled by directly using electromagnetohydrodynamic force generated by sending electric current through a magnetic field cre-ated in seawater by superconducting magnets. The sea-trials were completed in the summer of 1992 success-fully in order to verify the propulsion system while being watched by many researchers in the world with keen intersest.

"YAMATO 1" is a ship built for the purpose of verifying possibilities of actualizing superconducting MHD propulsion ships. A committee named Superconducting MHD Propulsion Ship R&D Committee was organized by the Ship & Ocean Foundation in 1985 and had been engaged in develop-ment of this ship.

The superconducting MHD propulsion system requires an entirely different method of handling and operation as compared with conventional propulsion systems. The outline of "YAMATO 1" is presented in this paper. Also reported in this paper are operation of the propulsion system as well as the results obtained through bollard tests.

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2. Principle of Propulsion

The principle of MHD propulsion is to apply the Heming's left hand rule of electromagnetics to seawater directly. As shown in Fig.1, a magnetic field is created in seawater by magnets fixed on a hul1. When elec-tric current is sent to seawater at right angles to the magnetic field, and electromagnetic force (Lorentz force) acts on seawater in the direction perpendicular to both the direction of magnetic field and that of electric current. Propu1sion force is gained as a reaction force of this Lorentz force.

The Lorentz force F (N) which is the source of thrust force T is given by the following formula:

F = Jv J X B dv (N) ....(1)

where J is a current density vector of infinitesima1 volume dv and B is a magnetic flux density vector of the same.

When J and B are constant over the entire volume V (m3) of the working part where magnetic fie1d and electric current interact, Eq.

(1) can be expressed by the fol1owing formula:

$F = J \times B \times V$ (N) ....(2)

MHD propulsion systems may be classified into those of external field type and those of internal field type depending on the space where interaction occurs.

In the case of "YAMATO 1", a DC internal field type is adopted and the working part is formed in a duct passing through the hull in order to minimize the magnetic field leaking to the inside and outside of the hull as much as possible.

The Lorentz force F is a pure force generated in a part where eIectromagnetohydrodynamic force acts and the thrust force T generated by an MHD propulsion sys-tem is of a value obtained by subtracting friction forces of fluid in the duct and fluid losses at the inlets, nozzles, contracted pipes, etc. from the Lorentz force.

3. Outline of "YAMATO 1"

The principal design and specifications of "YAMA-TO 1" have already been reported in detail in the references 1)- 9). Therefore, the outline of the specifications, principal arrangement and major system diagrams are presented in this paper.

3.1 Outline of hull part and machinery part

The principal particulars are shown in Table l and the general arrangement and the outline diagram of propulsion system are shown in Figs.2 and 3 respective-ly. The outline of machinery arrangement is described hereu nder.

In the wheel house, a console is installed at the for-ward center and maneuvering equipments such as steering wheels and thruster output control levers as well as verious control and monitoring apparatus for main generators, auxiliary generator, etc. are incorporated in this console.

In the electric power panel room, two sets of electric power panels are installed. These panels are to convert AC generated by the main generators to DC and to supply to the electrodes of propulsion system.

Each one set of thruster is arranged in bulged parts on each side of the engine room under the water line.Seawater inlets are provided on the fore side of these thrusters and outlet nozzles are provided on the aft side. For astern operation, a system is provided on each side to get astern propulsion power by changing the polarity of electrodes for sending electric current through sea-water. In addition to this system, an astern operation unit of a bucket lifting and lowering type is provided at the aft side of the seawater outlet nozzles also.

On the upper deck center of the engine room, two main generators for thrusters are installed fore and aft and an anxiliary generator for general service onboard is arranged on the starboard side aft.

3.2 Outline of propulsion system

The propulsion systems are composed of superconducting magnets, persistent current switches, helium refrigerator units, seawater pipes electrodes, etc. and each one set of these systems is arranged on the port and starboard sides of the ship respectively. The super-conducting magnets are of a six-linked ring construction with six saddle type superconducting coils being arranged on a concentric circle in a helium vessel. The leakage of magnetic field around magnets are made small as much as possible by mutually combining magnetic fluxes of each coil.

The magnet I and magnet II are of the same basic specifications having the same performance and the same dimensions for mounting on the hul1, however, their detailed specifications are different to some extent due to differences in the desigh concept of respective

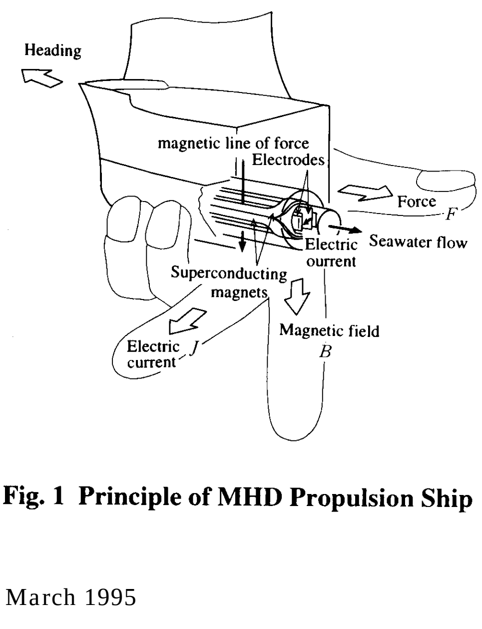

Fig. 1 Principle of MHD Propulsion Ship

Table 1 Principal Particulars of "YAMATO 1"

Particulars of "YAMATO 1"

Item		Specification
Length, overall		30.00m
Breadth, moulded		10.39m
Designed draught, moulded		1.50m
Displacement		185t
Navigation area		Smooth water area
Design speed		About 8kn
Thruster	Type	6-linked ring internal magnetic field type ×2units
	Output	Total Lorentz force About 16kN
	Electric current through seawater	About 3600kW
Onboard refrigeration system	Refrigerator	Turbo expansion Claud type×2units
	Helium compressor	Hydraulic screw type×1units
Main generator		2000kW×2units
Auxiliary generator		1800kW×1unit
Complement	Crew	3
	Others (Test personnel, etc.)	7

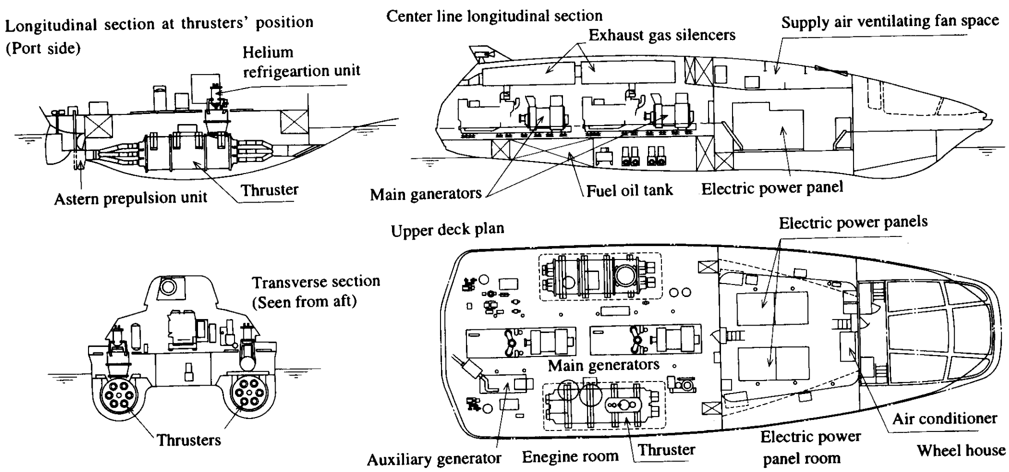

Fig. 2 General Arrangement of "YAMATO 1"

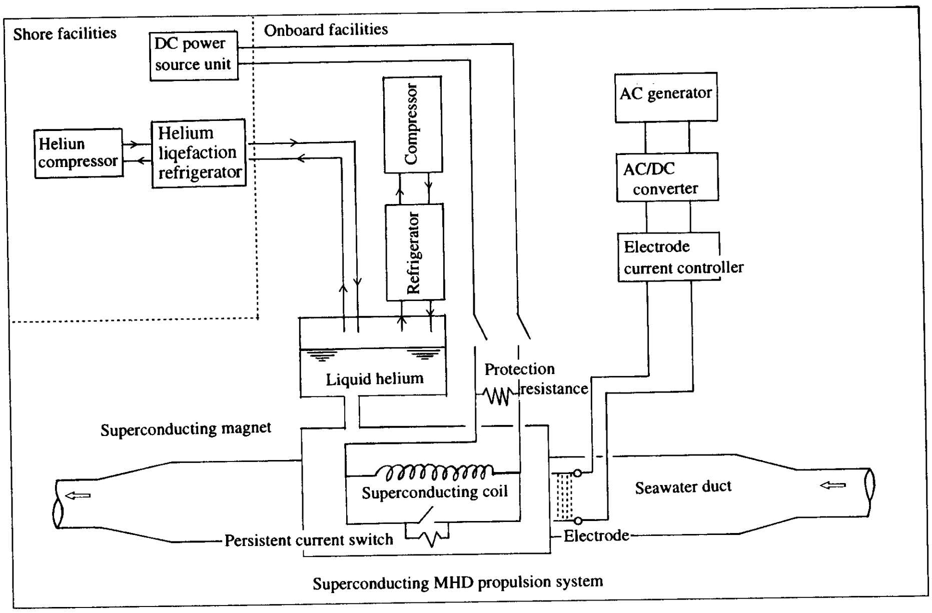

Fig. 3 Outline Diagram of Propulsion System "YAMATO 1"

manufacturer of these magnets. Details of the magnets are described hereunder using the magnet I as an example.

Table 2 shows the particulars of the six-linked ring magnet and Fig.4 shows the general assembly drawing of the six-linked ring magnet. Fig.5 shows the cross section of seawater pipe.

The seawater pipes are blow passages of seawater through the hull and are subjected to seawater pressure and electromagnetic force. Furthermore, the seawater pipes are required to be with a good insulating character against electricity in order to hold electrodes and bus bars for sending electric current. For these reasons, the seawater pipes are made of epoxy resin GFRP.

Titanium alloy is used as the base metal of the electrodes with the anode of DSA and the cathode plated with platinum. The length of electrodes is 3.4m.

3.3 Outline of shore support base

Because the superconducting magnets are to be operated in a persistent current mode during navigation, no facilities are required onboard for initial cooling of

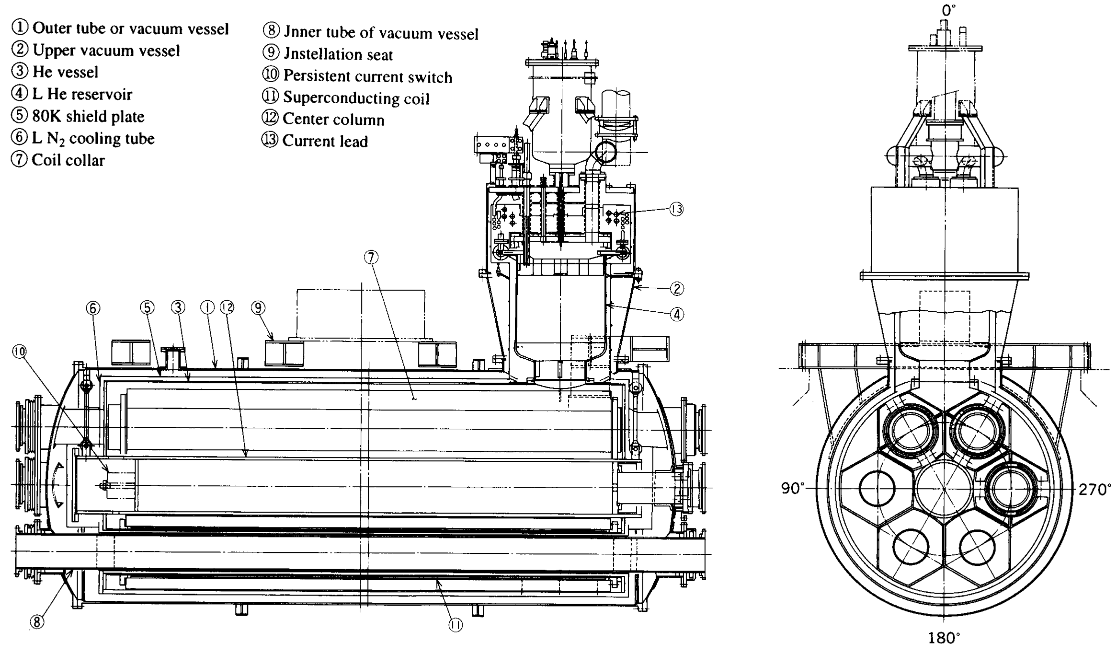

Fig. 4 General Assembly of 6-linked Ring Magnet

the superconducting MHD propulsion system from room temperature to the liquid helium temperature and for magnetization and demagnetization. Therefore, these facilities are installed ashore and it has been planned to reduce the weight of "YAMATO 1" and to simplify the propu1sion system onboard.

The general arrangement of shore support base is shown in Fig.6 and the particulars of major facilities on shore are shown in Table 3.

Table 2 Particulars of 6-linked Ring Magnet

Item		Specification
Type		6-linked ring internal magnetic field type superconducting electromagnet
Superconducting coil		Dipole coil 6
Performance	Magnetic flux density at duct center	4T at 3770A
	Inductance	3.0H
	Electromagnetic energy	21.3MJ
Dimensions	Inside diameter at ambient temperature	260mm
	P.C.D of Bore at ambient temperature	1050mm
	Outer diameter of vacuum vessel	1850mm
	Overall length of vacuum vessel	5400mm
Cryostat	Type of insulation	L N_2 and vacuum shield
	Coil cooling	L He immersion
	Material	Stainless steel (L He vessel) Al alloy (vacuum vessel)
Accessories		Coil control panel (including quenching detection and control system) Protection resistor (0.6Ω) Persistent current switch Power lead Protection lead

4. Cooling method and cooling result of propulsion system

Unit coils were cooled for magnetization tests by submerging in L N2 and then submerging in L He. However, the 6-linked ring magnets are of a complicated construction, therefore, they were cooled by G He from room temperature to about 20K. In this method of cooling, air in the He vessel for the propulsion system was replaced with G He at first. Upon confirming that dew point became lower than -45oC and O2 content

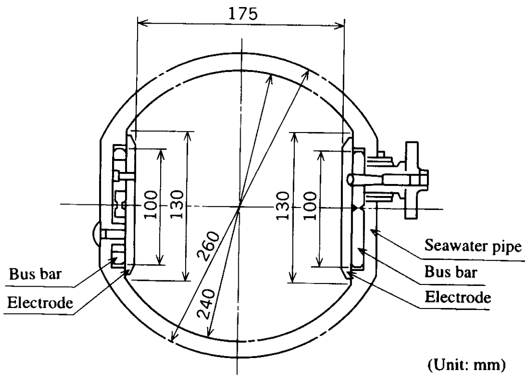

Fig. 5 Cross Section of Seawater Pipe

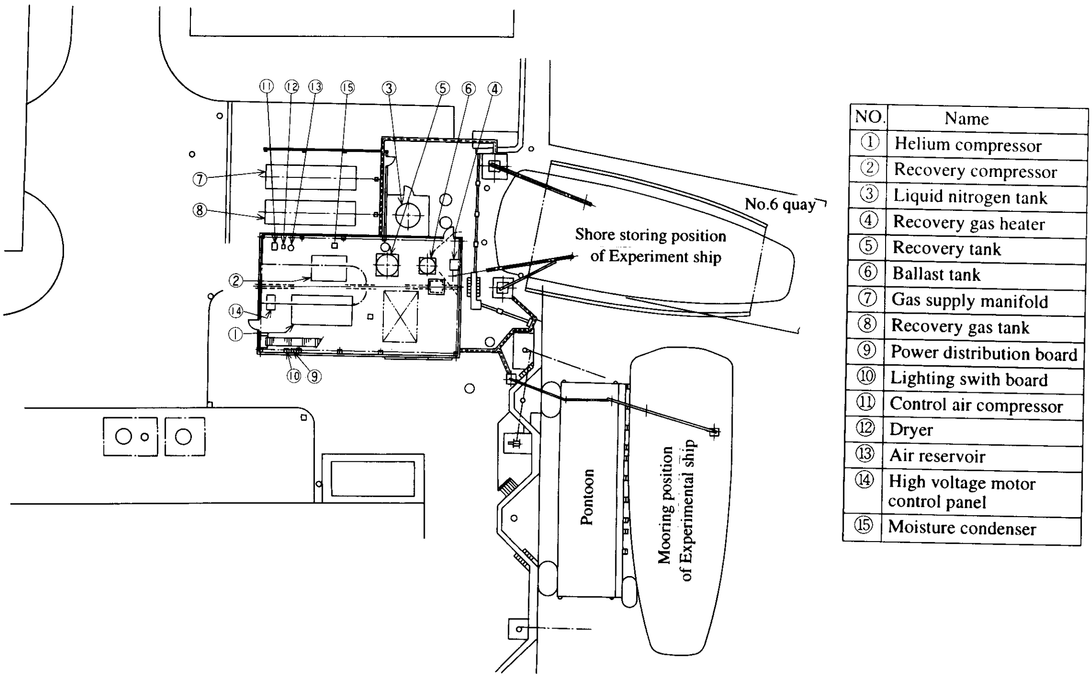

Fig. 6 General Arrangement of Shore Support Base

reached below 50ppm, G He was then refined further to have a dew point of lower than -80t and an O_2 content of lppm through a G He refiner. Cooling of the magnets was then started. Prior to start cooling, the procedure for cooling was determined by making cooling simulation calculations and thermal stress analyses.

The cooling G He supply pipe is designed to blow out G He against an end plate fitted at the aft bottom part of the He vessel and G He used for cooling of coils, etc. is returned to the refrigerator by being sucked from the upper part of the L He reservoir. This G He supply pipe is designed to be commonly used also as the discharge pipe when discharging L He.

The magnets are to be cooled by circulating cooling G He, however, in order not to damage the propulsion system by thermal stresses caused by excessive temperature differences (in particular, temperature difference in the He vessel between the inner tube which cools down slowly and the outer tube which cools down fast),the temperature of supply cooling G He was gradually lowered step by step so that the temperature differences did not exceed 40K by monitoring temperatures of coils and various parts of the He vessel.

Table 3 Particulars of Major Facilities in Shore Support Base

Name of equipment	Number of units	Capacity and type
Helium compressor	1	1,950 Nm³/h 16 atm
Helium liquefier	1	300 W, 100ℓ/h
Helium recovery compressor	1	70 Nm³/h 150 kgf/cm²
Gas Bag	1	70m³ ~ 150 kgf/cm²
Liquid nitrogen tank	1	20m³ vertical type
Cooling water supply unit	1	125 tons of refrigeration
DC power source panel	2	4,800 A. 10V

Cooling was continued until the representative temperature of coils reached about 20K and then the super-conducting coils were cooled to about 4K by filling L He to the full level. L He filling was done by connecting L He Dewar to the L He filling port of the large He refrigerator on shore.

The results of initial cooling tests are shown in Fig.7 and the result of L He filling is shown in Fig.8.

5. Procedure and results of magnetization and demagnetization of propulsion system

The electric circuit diagram of the 6-linked ring magnets is shown in Fig.9. In the figure, P-1 - P6 are coils. The persistent current switch (PCS) is of a thermal type and turns to the OFF position when sending current to the PCS heater and to the ON position when stop sending current to the PCS heater and cooled to the L He temperature.

For magnetization, the PCS is to be set at the OFF position. Electric current is to be raised by handling the DC power source panel and the PCS is to be switched to the ON position when the current has reached the

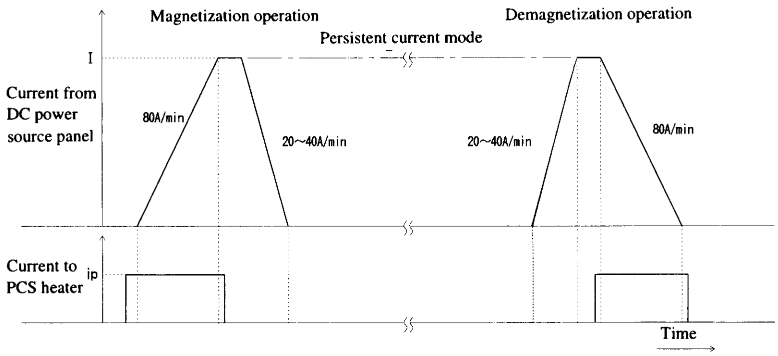

Fig. 10 Magnetization/Demagnetization Current Patern

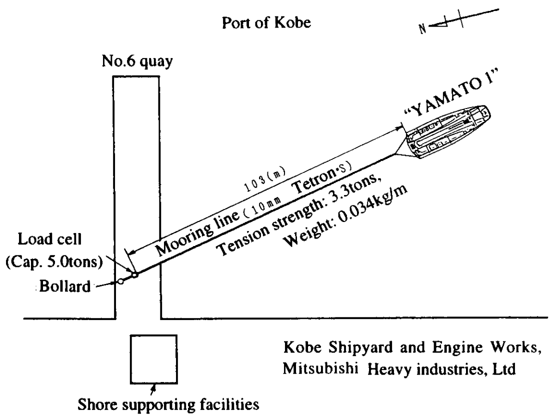

Fig. 11 Amangement of Bollard Test

reached a predetermined value, the PCS is to be switched to the OFF position and the current is to be lowered to O A.

The current patterns for magnetization and demagnetization are shown in Fig.10.

6. Thrust performance (Bollard test results)

6.1 Procedure for bollard test

As shown in Fig.1 1, the experimental ship with the superconducting magnets in a magnetized condition was moored to a quay by mooring lines fitted with ten-sion meters. Under this condition, electric current was sent between the electrodes and the generated pull force and pressure in the thruster duct were measured.

6.2 Calculation method for estimating thrust force

This ship is of superconducting MHD propulsion of an internal magnetic field type with a king of water jet propulsion system.

Thrust force T (N) generated by water jet is expressed by the fo11owing formula in general:

$T=pQ(Un-U_{\infty})$ ....(3)

where T: thrust force (N)

p: Seawater density (kg/m^3)

Q: Flow in duct (m^3/s)

Un: Jet stream velocity from nozzle (m/s)

U_{∞}: Ship speed (m/s)

In the case of this ship, the propulsion system is composed of two ducts passing through the hu1l fore and aft with water flow being ejected into water at the stern. Therefore, in estimating the actual thrust force,the effects of pressures at the inlet and outlet of these ducts were taken into account additiona1ly and the fo1-1owing formula was usedl0):

$Td=p.Q(Un-Ui)+Pn.An-pi.Ai$.....................(3a)

where Td: Actual thrust force (N)

Vi: Inlet flow velocity (m/s)

Pn, Pi: Nozzle outlet pressure and inlet pressure respecti vely (N/m^2)

An, Ai: Nozzle outlet area and inlet area respectively (m2)

By applying the Bernoullis' equation to each part of the duct system from the inlet to the nozzle outlet, the fol1owing formula can be obtained:

$1/2.Ui^2\ 1/p+gH$

$=1/2.Un^2 + 1/p.Pn+f.1/2.Ui^2$ ....(4)

where H (m) is a head given to sea Water at the workjng part, g is the acceleration of gravity, and f is the total loss factor in the duct including the inlet and nozzle.

The Bernou1lis' equation applied over the range between an infinitely forward point and the inlet becomes the fo11owing formula:

$1/2.U_{\infty}{}^2 +1/p.P_{\infty} = 1/2.Ui^2 +1/p.Pi$

.............................(5)

From Eq.s (4) and (5), the fol1owing formula is obtained:

$gH = -1/2.U_{\infty}{}^2 +1/2.(x^2 +D.Ui^2 +1/p.Pa$

.................................(6)

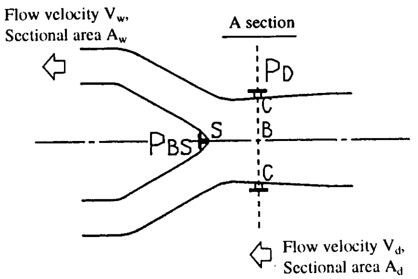

Fig. 12 Pressure Measuring Positions in 6 Branch Pipes

	1 T	2 T
Lorentz force	+	×
Bollerd pull force	○	**o**
Thrust force (calculated from pressure in the duct)	□	■
Thrust force (estimated by calculation)	—·—	- - - - -

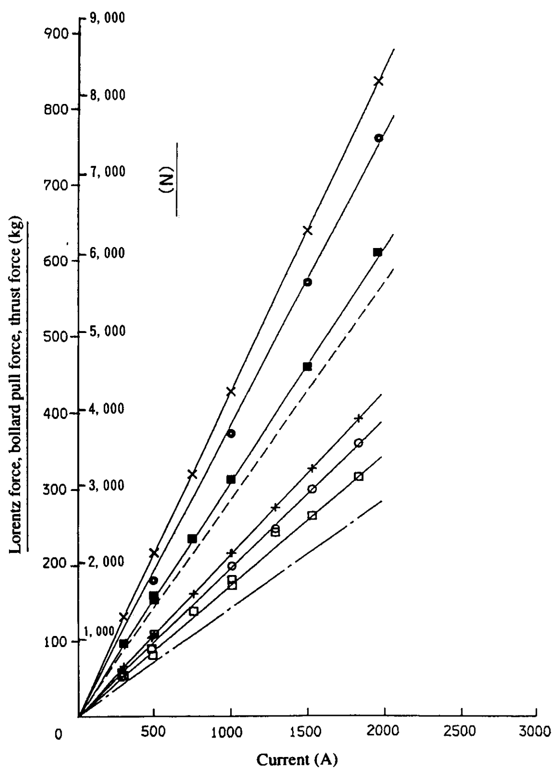

Fig. 13 Results of Bollard Pull Force Measurement

	Marks			Linearly approximated gradient		
	1 T	2 T	1 & 2 T	1 T	2 T	1 & 2 T
F	—○—	- -△- -	—·—	0.9108	0.8961	0.8994

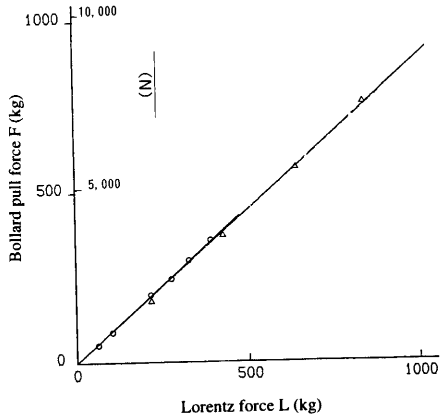

Fig. 14 Bollard Test Results (Lorentz Force vs. Bollard Pull Force)

where x: the ratio of flow velocity at the nozzle outlet against that at the inlet

P_a:P_n-P_∞

P_∞: Pressure at an infinitely foreward point (N/m2)

It has been found from the test results that interference between ship speed and jet stream velocity can be neglected and that the following formula holds:

$Pa \fallingdotseq \rho \cdot K_2 \cdot 1/2 \cdot U_n^2$ ············(7)

From Eq.s (6) and (7), the following formula is obtained:

$1/2 \cdot U_i^2 = (gH + 1/2 \cdot U_\infty^2) \div \{(1+K_2)x^2+f\}$ ············(8)

Likewise, the following formula is obtained by substituing Eq. (8) into Eq(5):

$1/\rho \cdot P_i = -(gH + 1/2 \cdot U_\infty^2) \div \{(1+K_2) \cdot x^2+f\} + 1/2 \cdot U_\infty^2 + 1/\rho \cdot P_\infty$ ············(9)

On the other hand, the head H given to seawater at the working part is expressed by the following formula:

$H = F/\rho \cdot g \cdot A_\omega = J_s \cdot B \cdot b/\rho \cdot g \cdot A_\omega$ ············(10)

where Aw: Sectional area of working part (m2)

Js: Electric current to electrode (A)

B: Magnetic flux density at working part (T)

b: Distance between electrode (m)

Consumed power at the working part is given by the following formula:

$W = J_s \cdot E$

$= J_s \cdot \{B \cdot U_\omega \cdot b + b \cdot J_s/\sigma \cdot a \cdot l\}$ ············(11)

where W: Consumed electric power

E: Voltage between electrodes (V)

	Marks			Linearly approximated gradient		
	1 T	2 T	1 & 2 T	1 T	2 T	I & 2 T
T_{EXP}	—⊖—	- - △ - -	— - —	0.8298	0.7272	0.7527
T_{CAL}	- - - - - - - - - - - - - - - -			0.6697	0.6698	0.6698

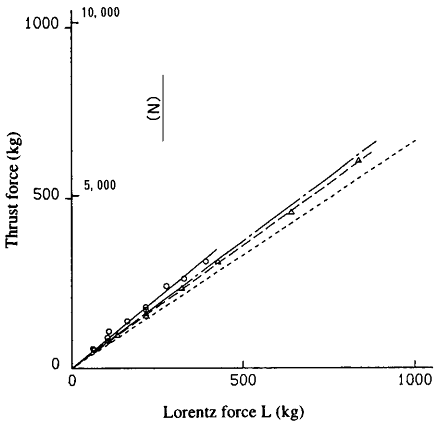

Fig. 15 Bollard Test Results (Lorentz Force vs. Thrust Force)

a, 1: Width and length of electrodes, respectively (m) Uw: How velocity at working part (m/sec)

As for the method to obtain thrust force from the results of pressure measurements, Vd is to be calculated using the following formula, then Ui, Un, etc. are to be calculated and the actual thrust force is to be calculated by the Eq. (3a) using the measured values of Pi and Pn:

$v_d = a * \sqrt{2g(p_{Bs} - P_d}$ ....(12)

where PBs and PD are static pressure (N/m2) at the position shown in Fig. 12 and a is 0.8432 obtained from the result of model tests.

With respect to the method to estimate thrust force by calculation, when the consumed power is given, UOO =0 in the case of bollard tests, therefore, Ui, Js H, etc.can be obtained from Eq.s (8), (9), (10), (11), etc. and the actual thrust force can be calculated using Eq. (3a).In this series of calculation, Un is calculated from An.Un=Ad.Vd usin9 the value of Vd calculated by Eq.(12) with measured values of Pss and PD at bo1lard tests, then K2 is obtained from Eq. (7) using this value of Un and the Pressure Pa measured at the nozzle part.

6.3 Results of bollard tests

Fig.13 shows the results of bollard pull force mea-surements and the results of calculation for the Lorentz force and thrust force. lt can be seen from the figure that bollard pu1l force and thrust force increase proportionally to increase of electrode current. Bollard pu11
force increases more than duct generated thrust force,however, this is the same phenomenon at found in the case of ordinary ships with screw propellers in moored conditions also and is due to pressure distribution around the hull which is different from that in navigat-ing conditions.

Figs.14 and 15 show the results of bollard pull force measurements and those of thrust force calculations against Lorentz force respectively.

For thrust forces. TExp obtained from the results of measuring pressures in the ducts and TcAL estimated by calculation are listed together, however, the latter shows somewhat lower values than the former. For the convenience of arrangement, etc., pressure measuring points in the ducts for thrust force calculation were positioned a little inside of the inlets and nozzles.Furthermore, there were some grids installed at the inlet. Considering that the pressures were measured at such positions and that these grids should have some effects on thrust force generated, it is presumed that the thrust force actally generated in the ducts is smaller than TExp and it may be stated that the results of mea-surement well agreed with the results of theoretical ca1-culation.

7. Closing remarks

R&D on superconducting M HD propulsion ships were started from basic investigation since the Ship & Ocean Foundation (formerly the Japan Shipbuilding Industry Foundation) set up the Superconducting MHD Propulsion Ship R&D Committee (Chairman: Mr. Y.Sasakawa) in 1985 and basic experiments, model tests,etc. were continued. On the basis of the results obtained through these efforts, "YAMATO 1" was built and var-ious tests including cooling tests, magnetizatioNdemag-netization tests, bollard tests and sea trial were comp1et-ed as planned successfully while being watched with keen interest by those persons concerned.

In order to make superconducting ships practically available, it is necessary to develop higher magnetic field larger size superconducting magnets and to study to improve electricconductivity of seawater from the viewpoint of increasing thrust force and improving propulsion efficiency. Furthermore, it is necessary to study systems which make special shore support bases unnecessary by installing initial cooling facilities and magnetization/demagnetization facilities also onboard.It is highly expected that these facilities will be devel-oped before long and such ships will be actually built for commercial service.

In closing this paper, the authors wish to express their gratitude to those concerned with the aforemen-tioned committee including Messrs. Motora and Imaichi for their valuable advice in many years.

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