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A Study on Ship Deperming Coil System Using High Temperature Superconducting Cable Technology

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Abstract: Naval ship deperming is effective to reduce the potential damage from sea mines some of which sense magnetic field of the ship, and thus, is an important treatment of naval ships in the recent world. Large electric current is required to impose the magnetic field on the ship hull, which in turn means that the deperming coil needs to be wound on ship hull when the coil is composed of conventional conductive materials, such as copper. We considered a few HTS (high temperature superconducting) coil systems to deperm naval ships because we expect the shorter deperming time and lower manual workload for ship deperming operation, compared conventional conductor coil systems. We have in the past presented a solution using a flat two-coil system arranged on seabed with tightly bound HTS conductor by analytical calculation of magnetic field on the conductor. By considering present and already developed technologies, a conductor with cylindrically wound on the core arranged as flat multi-turn coils on seabed was designed using analytical methods.

Key words: Deperming, seamine, ship, magnetic, superconducting, cable.

1. History of This Study

We propose to improve ship deperming operation using our new idea of deperming coil system which uses HTS (high temperature superconducting) cable technology. The steps to proceed with our idea are as follows. Firstly, we set a requirement for deperming coil [1] and magnetic field to deperm ships. Secondly, we have calculated the magnetic field which is generated by a few types of deperming coil. Thirdly, we calculated requirement to the cable conductor. And finally, we tried to find the best design of conductor, deperming cable system, by considering research items to be investigated for the coil type.

(1) Hypothetical requirement

We set the hypothetical requirement on deperming system as follows:

(a) Easy deperming operation with the least amount of manual operation;

(b) Effective to all types of ships, and the system's scalability to larger ships;

(c) The size of the new system (coils, cables, power supplies and support system) is no larger than that of the conventional system.

The magnetic field to deperm ships was set in our previous study [2] to 3,000 A/m by magnetic property of HY80 [3] (High Yield) and other information available in the public domain [4].

(2) Type of deperming coil

We have found that flat coils arranged on the seabed in shallow water satisfy the hypothetical requirement, which is not covered by the cable direct wound on ship hull and solenoid coil, shown in Fig. 1. The advantages of this flat coil system are that no major coils are above the water surface, and that the coil shapes are simpler consisting of long straight lines. These will avoid potential problems caused by horizontal and especially vertical bending and overly complex coil branch configuration. The disadvantages are that field is imposed perpendicular to the ship keel, which may reduce the effectiveness to deperm inside of the ship, and also that the distance of the coils from the ship is larger requiring greater electrical current through the cables than other systems.

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We calculated in the previous study [2] that two flat coils on seabed need more than 200 kA of electric current on one cable at the water depth of 12 m, as shown in Figs. 2 and 3. Model ships to deperm in our calculation were DDH (Hull classification symbol of Helicopter Destroyers) Izumo-class (248L, 38W, 7.1D, 19,500T) and SS (ibid., Submarines) with Soryu-class (84L, 9.1W, 8.5D, 2,950T) JMSDF (Japan Maritime Self-Defense Force), which will cover any of civilian ships' magnetic properties. The assumed ship shell factor: n = [Total ship weight] / [Ship hull (shell) weight] were involved in calculation, which resulted in a lower required current, but still the SS requires higher current than 200 kA.

In Fig. 3a, required current vs. first coil width 2 × Sp0 are shown. After Sp0 was fixed to 10, the required current vs. second coil space: Sp from first coil was shown in Fig. 3b, and required current was obtained to be 200 kA for DDH and SS only for n was over 3 at Sp = 10.

At the present time, many of research projects on high current HTS power transmission lines are ongoing [5, 6], still their operational currents are almost limited to approximately 10 kA. In this study, we have designed a flat multi-turn coil on seabed, in which deperming field is generated by passing electric current of 100 kA through a single cable.

2. Flat Multi-turn Coil on Seabed

The size and shape of first coil on seabed were

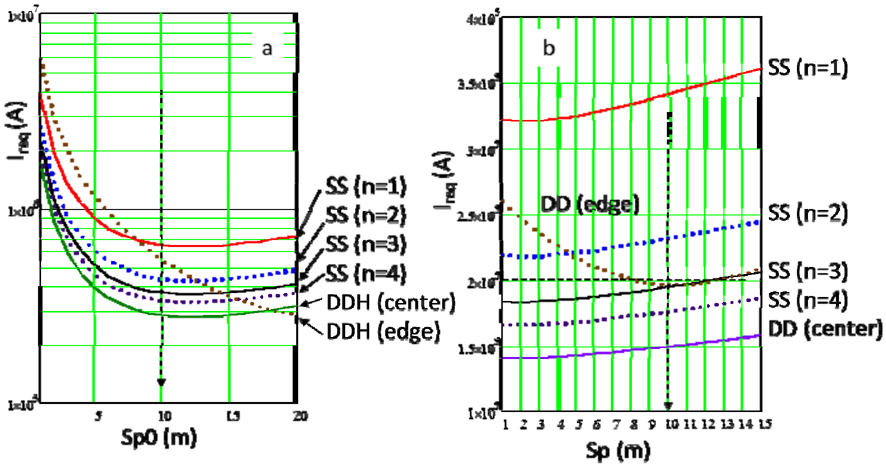

Fig. 1 Three types of ship deperming coil system.

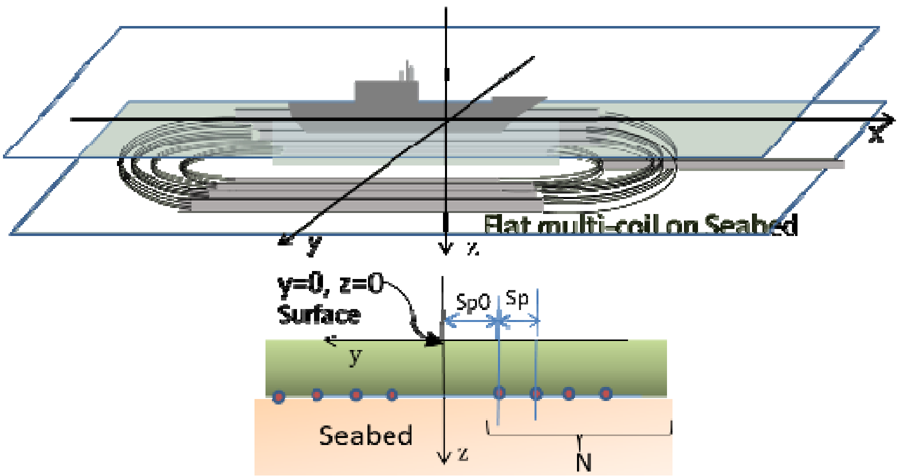

Fig. 2 Flat multi-turn coil geometry.

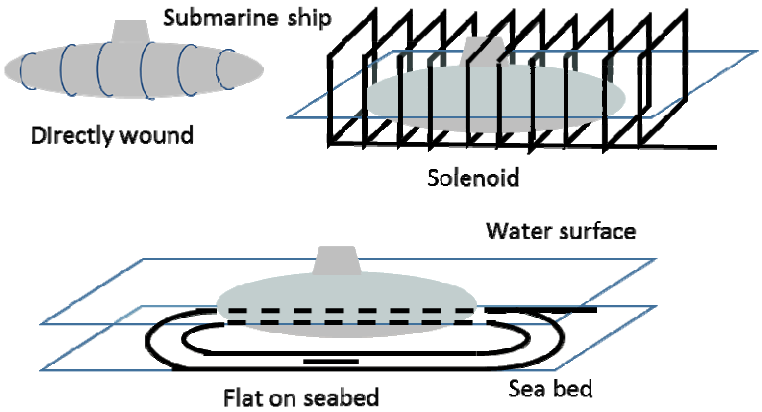

Fig. 3 Calculated required electric current vs. first coil width/2, Sp0 and second coil space from the inner coil Sp.

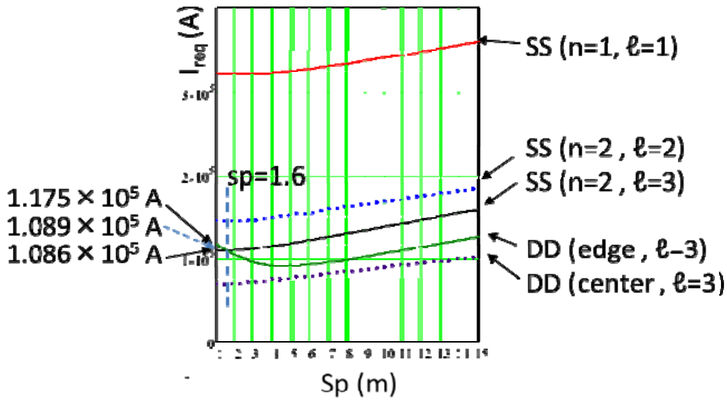

Fig. 4 Required current vs. space between the inner coil and first outer coil, depending on the outer coil number.

decided by the same process as two coils on seabed in previous study. The length of the straight part of the coil equals to ship length plus double of coil width, to avoid distortion of magnetic field at the bow and stern of the ship. The coil width was decided by magnetic field to deperm SS and DDH, since SS has high shielding factor in vertical magnetic field generated by coil.

Multi-turn coils are arranged outside the first coil with the same distance: Sp, from each other. Fig. 4 shows the required current vs. Sp, for SS and DDH with n and ℓ, which is the number of coils outside the first coil. DDH has a width of 38 m which is greater than the water depth, then magnetic field at the center and the edge of the ship was calculated separately. Calculated results show the required current: I_{req} at 109 kA with Sp0 = 10, Sp = 1.6 and ℓ = 3 for DDH center and edge and for SS with n = 2. Including the assumption of n = 2 for SS, which means that the half of the total ship weight is loaded to the shell made by HY80, 100 kA cable is a realistic target of this study.

Obtained I_{req} of flat two coils and flat multi-turn coil on seabed are shown on Table 1 with the sizes of the coil and total length of the cable.

3. Conductors of the Cable

In order to conduct electric current of 109 kA through a single cable, and to extend total length of the coils to 3,841 m as shown in Table1, a cable with conventional conductor with a cross sectional area of 100 mm^2 and maximum current of 355 A needs 23.0 MW of power supply. Zero electric resistivity of HTS conductor is attractive for this application, and many of developed technologies concerning power transmission line projects can be referenced. After the discovery of HTS phenomenon in 1986, BSCCO (Bismuth Strontium

Table 1 Calculated required current and coil parameters.

I_{req} (kA)	Sp0 (m)	Sp (m)	ℓ	Total length of cable (m)	n (shell loading factor)	Remark
200	10	10	1	1,420	1 for DDH, 3, 4 for SS	Two coils
109	10	1.6	3	3,841	1 for DDH, 2 for SS	Multi coils

Calcium Copper Oxide) and ReBCO (Rare-earth Barium Copper Oxide) were found to show the HTS properties by cooling with liquid nitrogen. Liquid nitrogen is a coolant with higher thermal capacity and boiling point than liquid helium and hydrogen which were then commonly used for superconducting systems, and it is the reason why the extensive development of ReBCO and BSCCO for many applications was conducted. Electric power transmission cable is one of these applications, and a piece of 240 m cable line made of BSCCO was developed and tested in a civilian power network system [5]. Although the use of BSCCO has been successfully implemented in the processes of commercial line production, the degradation of critical current under magnetic field is a problem. This means zero electric resistivity is restricted by the surrounding magnetic field, which is generated originally by electric current itself. ReBCO, on the contrary, has better critical current dependence on magnetic field, and test pieces of ReBCO tape with high critical current in magnetic field have been reported.

In our study, magnetic field generated by electric current is calculated analytically, and the limit of superconducting current under magnetic field is found by using reported data of ReBCO tapes. The consistency of current and magnetic field certifies the conductor's design. We calculated and reported one case of this conductor for 200 kA by closely bound ReBCO tape stack, which was based on the report of TSTC [7] (Twisted and Stacked-Tape Conductor). The designed conductor has symmetrical structure in its cross section and magnetic field inside was expected to be low. However, square cross section of each tape stack with short clearance between each tape stack will degrade the symmetry and in turn lower the critical currents.

Acommonly designed cable by HTS tapes is to wind each tape one after another on circumference of the cylindrical core. The effect of this is that the major component of magnetic field generated by each tape will be parallel to the surface of the core. As a result, magnetic field is parallel to the tape surface. Because of the crystal structure of ReBCO on tape, this parallel field enables less degradation of critical current dependence on magnetic field. The operational current of each tape element to make 100 kA cable and maximum magnetic field on the tape vs. number of the layer were shown in Fig. 5a with the image of cross section of the cable in Fig. 5b.

We calculated the magnetic field by the following cross sectional structure. The number of the tape element in one layer is to cover 90% of the core surface, and the space between each layer is to be 0.0005 m considering the thickness of the tape element. The electric current is concentrated at the center of the tape element and the same current is conducted on each tape element.

For the conductor to pass 100 kA of total current, one case is to have the core radius $r_0 = 0.03$ m, number of tapes in each layer $n_j = 42$, when number of layer $n_l = 28$, required current on each tape $I_r = 85$ A and maximum field on each tape $H_e = 0.376$ T. Another case is to have $r_0 = 0.07$, $n_j = 98$, when $n_l = 10$, then $I_r = 102$ A and maximum field $H_e = 0.207$ T.

Reported critical current degradation I_c/I_{c0} (I_{c0}:I_c at 77 K, 0 T) by magnetic fields H [6-10] is shown in Fig. 6. Considering ReBCO IBAD-PLD (Ion Beam Assisted Deposition-Pulsed Laser Deposition) tape at 77 K, which may have I_{c0} = 240 A/4 mm-w [11], I_c degradation factor is 0.56 for ReBCO IBAD-PLD at 77 K, at 0.376 T of H_e. This means I_r is 63% of

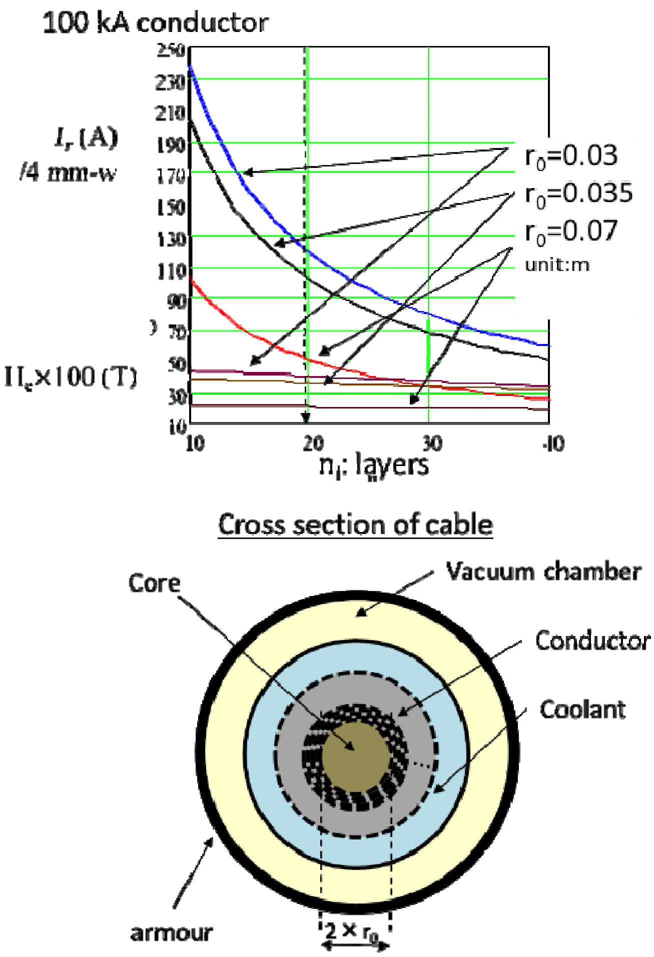

Fig. 5 (a) Operational current and maximum field on each tape element; (b) Image of cable cross section.

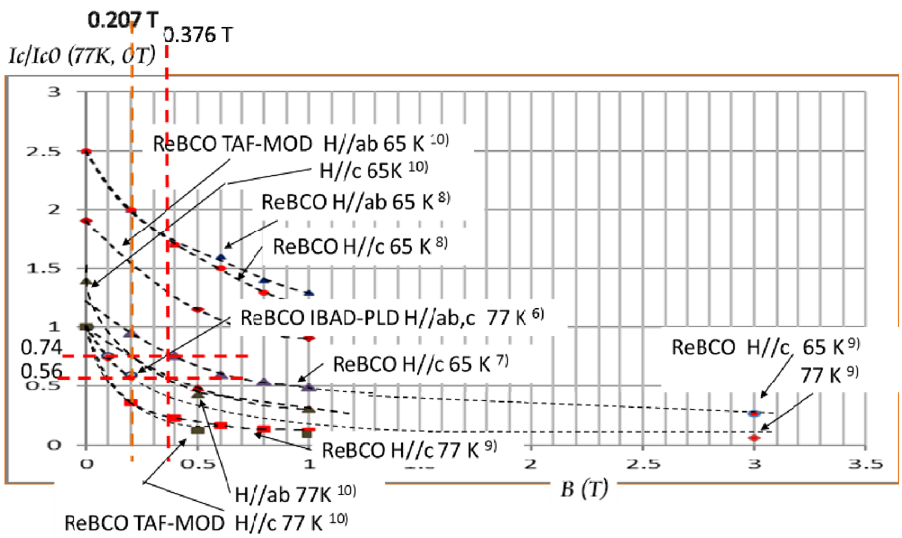

Fig. 6 Critical current vs. magnetic field for ReBCO cited from reports.

I_c (=134.4 A/4 mm-w), and this operational current is expected to be successful. Another case of r_0 = 0.07, degradation factor by H_e is 0.74, and I_r is 57.4% of I_c (= 178 A/4 mm-w).

4. Discussion

Deperming is to control microscopic magnetic domain in ferromagnetic materials, in this study this is steel. Magnetic field on steel is to move domain wall and final orientation of microscopic magnetization becomes random in space and the total magnetization leads to zero. In the deperming process, one phenomenon that cannot be ignored is so called de-magnetization, which is the reverse magnetic field in the material caused by the external volumetric magnetic field. This effect was calculated on the spheroidal shell model of ship, and required deperming field was introduced. However, for real ships, composed of material and shapes that are complex, and while the deperming coil is larger than ship size, imposing magnetic field on ship is not uniform. Physical scale model experiments should be conducted to validate effectiveness of flat coil deperming proposed in this study.

In order to compose a high electric current cable, where the conductor is an assembly of HTS tape elements, we calculated two patterns of cable conductor, one is a bounded tape stack, the other is tapes on cylindrical core. In both cases, electric current is assumed to run at the center of the tape, and magnetic shielding effect on tape element was not included. In commercial BSCCO tape, thin line elements are in the sheath of conventional conductor and superconducting shielding current may be neglected. However, for ReBCO tape, this effect may be not negligible because of its single-crystal structure that covers the tape surface. The electric current spread over the tape and effect of the boundary should be included in the calculation and the results are to be validated by experiments on real tape elements for the cable conductor.

For the deperming of ship, electric current of the coil is to be changed from positive maximum to negative maximum and successively in this cycle, the maximum intensity is decreased gradually to zero. Although zero-electric resistivity of HTS conductor causes almost zero voltage to conduct the current, this time dependent electric current generates voltage through inductance of the coil, and may cause power for power supply. However, this wattage of the power supply can be limited by proper control of the current time change. The inductance of the coil is proportional to the square of coil turns (n_{turn}), which can be reduced by parallel connection of the tape elements, still this will increase the required current of power supply. The connection of the tapes, whether parallel or serial, is to be designed considering above matters.

Even the results of our study are from optimistic calculation, total length of the tape element is to be 3,841 m, and in case r_0 is 0.07 m, 98 × 10 elements are to be required. Experiments with a few hundred meters of ReBCO test cable for 3 kA of current are reported and production technologies for the high quality and long tape element seem to be already present. Considering the fabrication technologies of a cable conductor, requiring precise control of tape element winding for the long cables, better cable design should be obtained.

5. Conclusions

We propose a new deperming system which is available to large combatant ships and submarines. Our deperming coil image is to be set on seabed in shallow water, with multi-turn coils of 100 kA cable line. Reported HTS tape element was used to design the conductor of the line by analytical methods. In order to proceed further in this study, shape and boundary of tape will be included in the calculation, and physical scale model experiments should be conducted to confirm the calculations.

References

[1] Hirota, M. 2015. "Potential Application of High-Critical-Temperature Superconducting Cable Technology to Naval Ship Deperming System." *MARELEC,* Philadelphia.

[2] Hirota, M. 2017. "High Temperature Superconducting Cable Application to Ship Magnetic Deperming." *UDT,* Bremen.

[3] Holmes, J. J. 2008. *Reduction of a Ship's Magnetic Field Signatures.* Morgan & Claypool Publishers.

[4] www.mod.go.jp/msdf/formal/gallery/ships/dd/.

[5] Ohya, W. et al. 2013. "SEI Technical Review." In Japanese, (182): 39.

[6] "NEDO Project Report." No. 20130000000857, Ⅲ-2.2.44, in Japanese.

[7] Minervini, J. V., Takayasu, M., and Bromberg, L. 2010. "Recent Developments in High Temperature Superconductors (HTS) for Fusion Magnets." In *Proceedings of the VLT Conference Call*.

[8] Hazelton, D. W. 2013. "HTS Conductor Forum—Representative Manufacturer's Point of View." 3A-SS-01 EUCAS-2013, Genova, Italy.

[9] Daibo, M., Fujita, S., and Igarashi, M. 2014. Recent Progress in R&D of REBCO Coated Conductors and Coils at Fujikura, the 2014 Kyoto Workshop on HTS Magnet Technology for High Energy Physics—The 2nd Workshop on Accelerator Magnet in HTS (WAMHTS-2) at Kyoto University, Japan.

[10] Inoue, M. et al. 2011. "Current Transport Properties of RE123 Coated Conductor." Annual Report at High Field Lab. For Sup. Mat., Inst. For Mat. Res., Tohoku Univ., 32-4.

[11] Yoshida, M., and Nagata, M., et al. 2013. "The World Largest 5 kA_{rms} • Extremely-Low-Loss High-Tc Yttrium-based Superconducting Power Cable." *Fujikura Tech. Rev.* 2 (125): 37-43.