DOI: 10.3969/j.issn.1673-3185.2016.02.017 **http:** //english.ship-research.com

Translated from: ZHANG Anming, ZHANG Haipeng, CHENG Zhenghua. Shaft-ground active compensation technology of the ship shaft-rate electric field[J]. Chinese Journal of Ship Research, 2016, 11(2): 121-126.

Shaft-ground active compensation technology of the ship shaft-rate electric field

ZHANG Anming[1], *ZHANG Haipeng*[2], *CHENG Zhenghua*[3]

1 Navy military Representative Office in Dalian Shipbuilding Industry Co., Ltd., Dalian 116005, China

2 Department of Power Control, Navy Submarine Academy, Qingdao 266042, China

3 The 92730th Unit of People's Liberation Army (PLA), Sanya 572016, China

Abstract: In order to reduce marine shaft-rate electric field influence and the exposure rate of the ship, the mechanism of the electric field is analyzed in this paper, along with the principle of the active compensation system. Specifically, the electrical properties are studied based on the analysis of the mechanism of shaft-rate electric field of the ship. The ship shaft-rate electric field suppression is proposed according to the compensated negative potential. The framework and function framework of the system are designed. The weak signal monitoring and processing technology of ship shaft is investigated, and the judgment and control technology of the system is studied. The driving and power output module of the negative potential is designed, where the simulation results show that the ship shaft-rate electric field can be suppressed effectively with the proposed system, and the stealth property of the ship is simultaneously enhanced.

Key words: shaft-rate electric field; potentials compensation; electric field suppression; naval ship

CLC number: U674.7

0 Introduction

Corrosion electric field of naval ships and cathodic protection system can generate electric current in shaft. When the shaft rolls, its periodical change of impedance produces shaft-rate electric field. Shaft-rate electric field has become a prominent signal of naval ship characteristics[1]. Some countries, such as Russia, America, Britain and Canada, have made great achievements in the research of shaft-rate electric field suppression, and included the elimination of electric field of naval ship in ship building[2-4]. Attenuation law of shaft-rate electric field accords with Maxwell's electromagnetic theory, and its long propagation distance makes it easy to be detected by enemy and its characteristic signal is easy to be identified and thus applied to detect, track, position and strike the naval ships[5-7]. Therefore, the problem of suppressing shaft-rate electric field of naval ship needs urgently solving at present.

Based on the studies of equivalent electrical model and electrical properties of naval ships which are related to shaft-rate electric field, in this paper the principle of shaft-ground active compensation system is analyzed, generating module of shaft-ground active compensation system is designed and closed-loop real-time suppression system of shaft-rate electric field of naval ships is developed. What's more, the real-time suppression experiment of naval ships is stimulated in laboratory to test whether the technology can effectively suppress the intensity of shaft-rate electric field, reduce the influence of shaft-rate electric field and weaken the characteristic signal of naval ships used for remote detection so as to strengthen the stealth property of naval ships and improve their vitality.

Received: 2015 - 07 - 01

Supported by: National Natural Science Foundation of China (51377169)

Author(s): ZHANG Anming (Corresponding author), male, born in 1976, master, engineer. Research interest: electric engineering. E-mail: zhanganming@tsinghua.org.cn

ZHANG Haipeng, male, born in 1977, Ph. D., associate professor. Research interest: precision instrument and machinery. E-mail: fdrk@163.com

1 Characteristic analysis of naval ship shaft-rate electric field

Different metals composing modern naval ships demonstrate different electrode potentials in sea water, form corrosion primary battery, and generate corrosion current. In order to enhance anti-corrosion ability, naval ships usually adopt active cathodic protection system[8]. However, DC large current and corrosion current provided by active cathodic protection system are the main sources of electric field of naval ships.

To study the features of shaft-rate electric field of naval ships mainly needs to study the shafting of naval ships. Structural components of naval ships mainly include rotation shaft, back-up bearing, intermediate bearing, thrust bearing, propeller, slip ring, electric brush and marine engine system.

In the electrical analysis on shaft structure of naval ships, sea water is a significant part while the influence of marine engine is not strong. The contact resistance between slip ring on the rotation shaft and electric brush has great influence on relevant structural electrical properties of shaft-rate electric field of naval ships, and it is an important part of electrical properties of naval ships.

It can be known from the in-deep analysis on the electrical properties of naval ship shafting that the periodical change of shafting resistance with the variation of rotation shaft of naval ships can result in fluctuation of electric current at different parts of circuit, in which periodical change of sea water current can radiate shaft-rate electric field. Besides, contact resistance of electric brush of naval ships causes fluctuation voltage at both ends of the brush and is closely related to current change in sea water.

2 Suppression method of shaft-rate electric field of naval ships

2.1 Proposing of shaft-ground active compensation method

Under regular ways of naval ship maintenance, the contact resistance of electric brush of naval ships is always obvious. Even if strict maintenance system is adopted, the contact resistance of electric brush of naval ships cannot be avoided and fluctuation voltage still exists at both ends of the electric brush. So in this paper, adding a shaft-ground active compensation system E_k between main shaft in circuit of naval ships and hull connecting ground is put forward, as is shown in Fig. 1. This shaft-ground active compensation potential E_k can be achieved by gradual and controllable direct electromotive force. The introduction of proper shaft-ground active compensation system can suppress the shaft-rate electric field of naval ships.

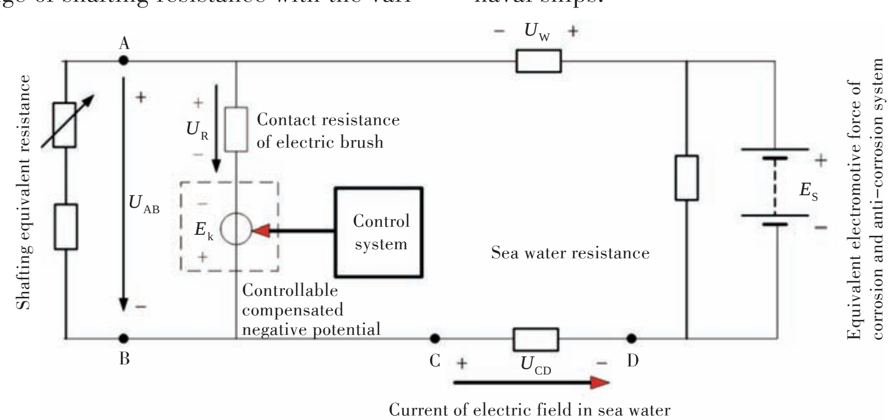
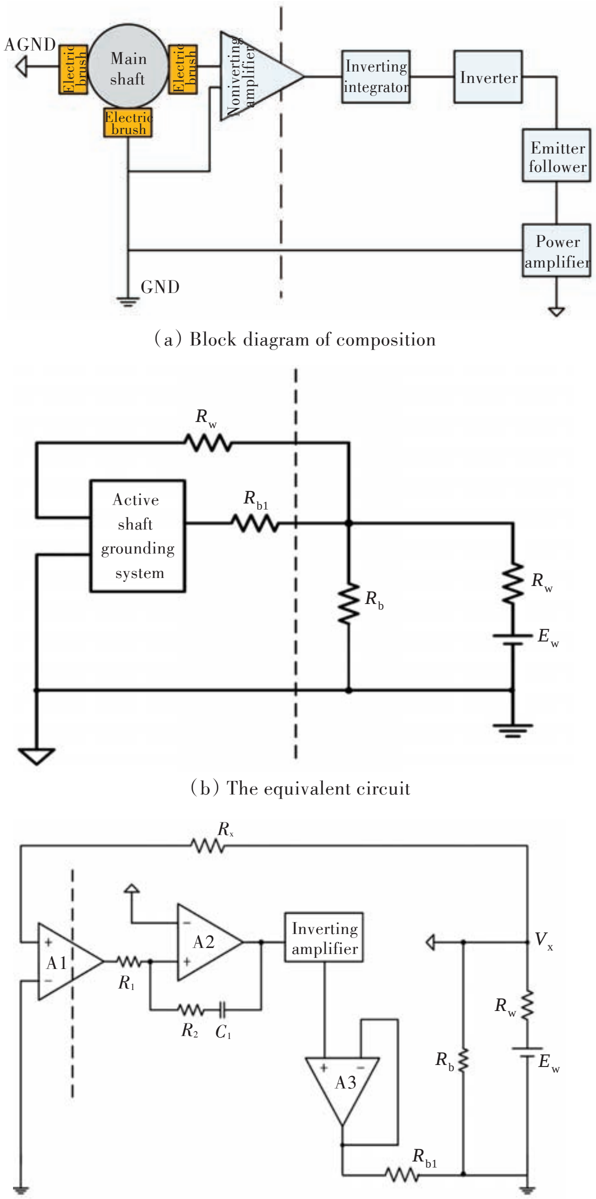


Fig.1 Schematic diagram of shaft system with compensation circuit

2.2 Principle analysis on shaft-ground active compensation system

Shaft-rate electric field of fishing boat JC is taken as an example. The change of contact resistance between its shaft and bearing causes the change of voltage, producing electric field that changes periodically (i.e. , R_b is a variable resistance). If equal potential between main shaft and hull is guaranteed when the main shaft is rolling, the fluctuation of shaft-ground voltage can be ensured to be zero, thus the shaft-rate electric field can be reduced. Under the guidance of this idea, shaft-ground active compensation system is proposed and Fig. 2 is the principle schematic diagram of this system, where R_x is resistance of circuit; R_{b1} is contact resistance of electric brush or slip ring; R_b is the resistance between bearing and gear; R_w is the resistance from propeller to hull; E_w is potential difference of corrosion or anti-corrosion between hull and propeller.



(a) Block diagram of composition

(b) The equivalent circuit

(c) Circuit diagram of refine system

Fig.2 Schematic diagram of compensation circuit

According to the law of Kirchhoff, the shaft-ground voltage V_x can be zero as long as E_w is approximate to $I_w R_w$ and $I_w = I_1 + I_2$, where I_1 is electric current generated by electrochemical corrosion or anti-corrosion and I_2 is output electric current of compensation system. In the light of Thevenin's theorem, there is:

$$I_1 = \frac{E_w}{R_w + \dfrac{R_b R_{b1}}{R_b + R_{b1}}} \tag{1}$$

$$I_2 = \frac{E_k R_b}{R_{b1}(R_w + R_b) + R_b R_w} \tag{2}$$

$$E_k = kV_x \tag{3}$$

Then

$$\begin{cases} I_w = \dfrac{E_w(R_{b1} + R_b) + kV_x R_b}{R_{b1}R_w + R_w R_b + R_b R_{b1}} \\ V_x = E_w - R_w I_w \end{cases} \tag{4}$$

From Eq. (4), it can be seen that V_x and I_w have connection. Substituting the expression of I_w into $V_x = E_w - R_w I_w$, there is:

$$V_x = \frac{E_w R_b R_{b1}}{R_{b1}R_w + (1+k)R_w R_b + R_b R_{b1}} \tag{5}$$

From Eq. (5), it can be seen that with the increase of compensation gain k, V_x decreases gradually. In order to make V_x be zero, $k \to \infty$. To research the value of k corresponding to V_x approximate to zero, parameters provided by Russian literature are used for simulate calculation. The calculation conditions are: $E_w = 0.7\ \text{V}$, $R_w = 0.07\ \Omega$, and $R_b = 0.03\ \Omega$. Supposing that $R_{b1} = 0.01\ \Omega$, the change of V_x with the change of k is shown in Fig. 3 (in vertical coordinate, 1 μV is 0 dB). Fig. 3 shows that if V_x is controlled within 100 μV, k should be above 1 700.

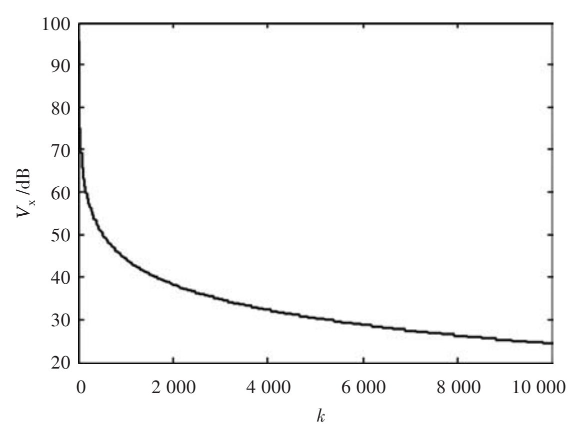


Fig.3 Relation curve of the shaft-ground votage and the gain

3 Design of shaft-ground active compensation

3.1 Control framework

Designing actual shaft-rate electric field suppression system according to the theory of shaft-ground active compensation system needs to take the followings into consideration on the basis of control system composition principle (Fig. 2):

1) Reliable control system is needed for controller so that the controller can adjust shaft-ground active composition system E_k timely, and fits the change of electric brush voltage U_R automatically.

2) In order to make shaft-ground active compensation system fit the change of electric brush voltage automatically, sensor needs to monitor a certain phys-

ical quantity that can reflect the change of electric brush voltage. This system monitors the voltage between rotation shaft and hull of naval ships, and because electrical equipment shell is usually taken as potential reference point (namely earthing point) of circuit, voltage between rotation shaft and hull of naval ships is often called briefly as shaft-ground voltage.

Shaft-ground voltage is usually at around millivolt level, so high-accuracy monitoring circuit needs to be selected.

3) As for routine organization, because shaft-rate electric field suppression system needs an inverse electrodynamic potential provided by shaft-ground active compensation system E_k, inverted controllable direct-current power supply is taken as implementing module to achieve the self-adaptive adjustment of shaft-ground active compensation system.

3.2 Function framework

The achievement of shaft-rate electric field suppression system of naval ships based on shaft-ground active compensation system needs the combination of specific shafting structure.

According to function, this shaft-rate electric field suppression system can be divided into several function modules, including voltage monitor, signal conditioning, judgment, control, drive, power output, etc. It is worth noting that due to the high integrity and strong functions of many current circuit modules, structural modules in this system may not be one-to-one correspondence with function modules. Sometimes, one circuit structure module can achieve two or more function modules simultaneously.

The input interface of this shaft-rate electric field suppression system is the fluctuation voltage between rotation shaft and hull of naval ships. Moreover, voltage signal is weak and fluctuation is even smaller. Thus, only the sensor sensitive to minor voltage fluctuation can meet the demand.

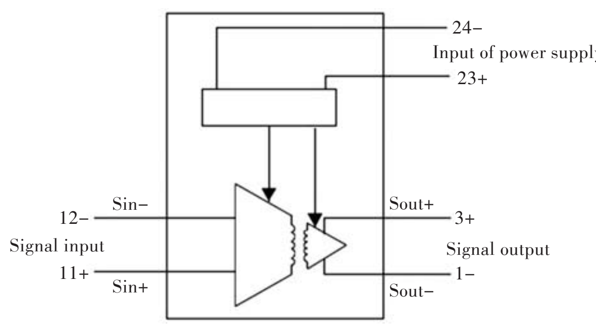
The output interface of shaft-ground active compensation system should be designed as a controllable direct-current power supply module.

4 Shaft-rate electric field suppression technology based on shaft-ground active compensation system

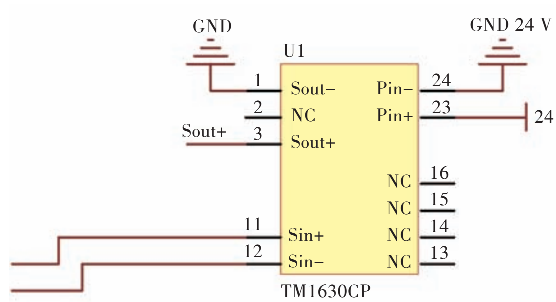
4.1 Monitor and adjustment of shaft-ground weak signals of naval ships

At present, isolation transmitter of TMxxxxCP series shown in Fig. 4(a) is the weak signal monitoring device with good performance. Its front end uses active isolation module with millivolt-level positive-negative bipolar signal input, and its back end uses active isolation module with positive-negative bipolar signal output.

Core parts of shaft-ground weak signal monitor and adjustment components of shaft-rate electric field suppression system adopt TM1630CP chips (Fig. 4(b)) which together with peripheral ancillary circuit can achieve monitor and adjustment of weak signal.



(a) Schematic diagram



(b) Circuit module of isolation transmitter

Fig.4 Weak signal monitoring and control module

4.2 Judgment and control of shaft-rate electric field suppression system

Fig. 5 is the circuit of logical judgment and signal control that aims to achieve shaft-rate electric suppression system.

In the figure, Sout+ is the shaft-ground voltage between main shaft and hull, and the signal comes from monitor and adjustment modules of shaft-ground weak signal. When Sout+ voltage increases, electric current in circuit decreases with the increase of resistance in loop. To ensure the sea water current is constant, V_{sc} output signal needs to be controlled through logical judgment. Shaft-ground active compensation system value is driven to increase in reversed direction. On one hand, it can bring down the voltage Sout+ at both ends of bearing to the equilibrium position. On the other hand, the branch current of slip ring is enlarged, and decreased electric current by the increase of resistance in loop is compensated, so as to maintain constant current in sea water. On the contrary, when this Sout+ voltage decreases, circuit drives shaft-ground active compensation system according to reversed logic to control V_{sc} output signal and maintain the constant current in sea water.

DAC and FB_AD signal interfaces are connected with Digital Signal Processing (DSP) system. When the influence of bearing resistance change on shaft-rate electric field is eliminated to a very low degree, the change rule of sea water resistance between propeller blade and the electrode can be estimated using advanced algorithm by DSP system. The DAC interface is connected with control circuit for communication.

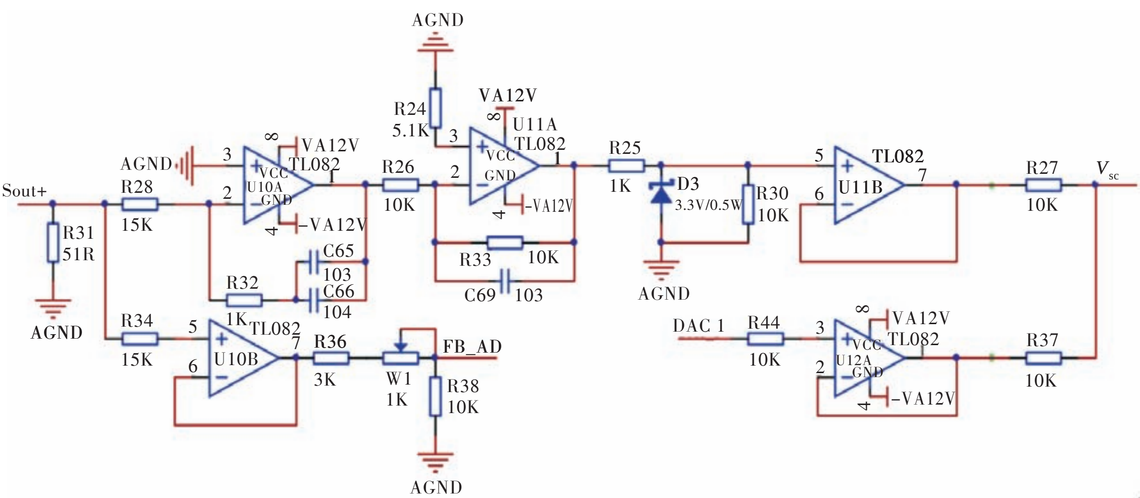


Fig.5 System logic judgment and signal control module

4.3 Drive and power output of shaft-ground active compensation system module

Shaft-rate electric field suppression system of naval ships, as the controllable power supply of shaft-ground active compensation system, has the characteristics of low voltage, large current and high speed of load response. Factorized Power Architecture (FPA) and integrated power V·I chip proposed by Vicor company can meet the demand of this system. As shown in Fig. 6, Voltage Transformation Module (VTM) is a basic element of FPA and Pre-Regulator Module (PRM) can transform unsteady voltage input into steady voltage output. It uses the control framework of buck and boost voltage stabilizer to provide accurate and steadily ascending and descending adjustment of voltage.

The combination of PRM and VTM can provide DC-DC converter which is isolable and has steady voltage output. PRM only has the function of stabilizing voltage, and VTM has functions of transforming and isolating voltage.

As for drive and power source modules of this system, controllable power supply composed of PRM_P045F048 and VTM48EF012T130A00, with high efficiency, low voltage, large current and fast speed of load response, is selected to produce

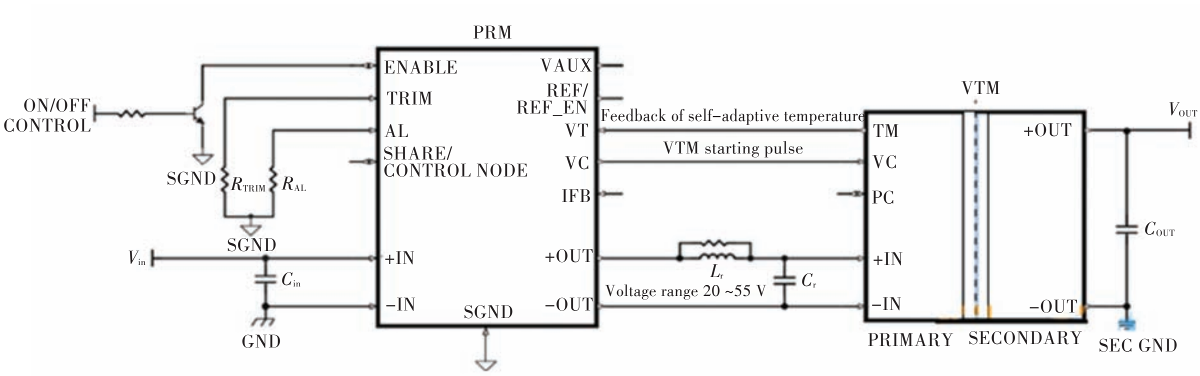


Fig.6 Drive core components and power output

shaft-ground active compensation system in the electric field suppression system.

5 Simulation test of shaft-rate electric field suppression

5.1 Test devices

Scale model of a naval ship is adopted for the test, as shown in Fig. 7. This scale model simulates the parts of real ships that have the closest relation with shaft-rate electric field. Bearing, electric brush, slip ring and shafting are all scaled down. Propeller is taken place by copper-made metal sheet and a metal container containing sea water is placed on the propeller end and the sea water contacts with the propeller.

Fig.7 Scale model of ship shaft system

Electric field measuring electrodes are Ag/AgCl electrodes, and they are respectively fixed at two sides of a 2 m stick, namely that the distance between measuring electrodes is 2 m. Weight is added on both sides of the stick to make the stick sink into water and keep even. Meanwhile, the electrodes are kept 1 m away from water, measuring electrodes are 3 m away from propeller and reference electrode is 1 m away from two measuring electrodes.

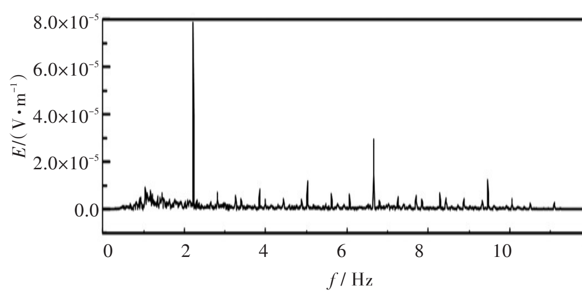
Measurement devices of electric field are composed of signal adjustment circuit, power amplifier and USB-6216 capture card. Signal adjustment circuit includes wave filter circuit and voltage amplifier circuit, in which wave filter circuit is a band-pass filter is composed by the cascade of two-order low-pass filter and six-order high-pass filter. The range of pass band is 1-7 Hz, and amplifier circuit can magnify signal within this range by about 5 000 times. USB-6216 capture card can conduct A/D transformation on output signal of signal adjustment circuit, and then transfer the transformed digital signal to computer. The computer controls data collection and storage through software.

5.2 Experimental method

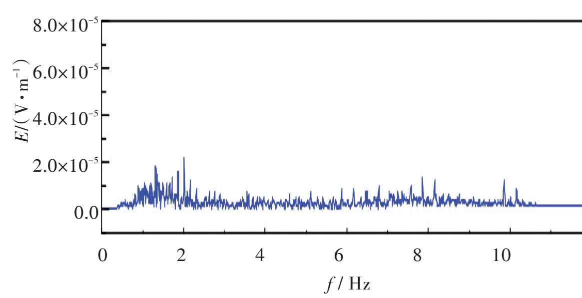
In the experiment, small motor is used to drive the propeller, and rotate speed is kept at around 150 r/min. First, the shaft-rate electric field signal is measured before shaft-rate electric active compensation system is started. About 10 min later, shaft-rate electric active compensation system is started and monitoring of the shaft-rate electric field signal is continued.

5.3 Data analysis

Spectral analysis of the test data is conducted. Measured data within a certain time before and after the start of shaft-ground active compensation system are selected for analysis, whose frequency domain distribution is shown in Fig. 8. Fig. 8(a) is frequency domain distribution of measured data before shaft-rate electric suppression circuit starts and Fig. 8(b) is frequency domain distribution of measured data after shaft-rate electric suppression circuit started.



(a) Before the start of suppression circuit



(b) After the start of suppression circuit

Fig.8 Frequency distribution of measurement data

Comprehensive data analysis on time and frequency domains shows that before shaft-ground active compensation system starts, the average intensity of alternating electric field with a frequency of 1-7 Hz is around 2.86×10^{-4} V/m. After shaft-ground active compensation system starts, the intensity of alternating electric field in this frequency domain decreases obviously, with an average of about 0.72×10^{-4} V/m.

The distribution of frequency domain in Fig. 8(a) shows that before shaft-rate electric field suppression circuit starts, alternating component with obvious frequency of 2.2 Hz is contained in measured data of electric field and it is easy to calculate the corresponding rotate speed is 132 r/min. However, we expect the rotate speed to be 150 r/min when the motor starts. Because of the influences including manufacture error of ship model, non-zero motor torque, friction of the system and errors of voltage driven by motor, frequency component (2.2 Hz) measured data of electric field are considered to be identified to actual rotate speed of motor. Besides, an alternating component with an obvious frequency of 6.6 Hz exists in the measured data of electric field, and this frequency is the frequency multiplication of the fundamental frequency of 2.2 Hz, which also proves that radiation electric field of naval ships has close relation with shaft-rate.

The distribution of frequency domain in Fig. 8(b) shows that after shaft-rate electric field suppression circuit starts, the original obvious frequency of 2.2 Hz from measured data and its frequency multiplication disappear. The frequencies have similar energy and no obvious frequency exists. This means that after suppression circuit starts, measured radiation electric field is mainly environmental electric field with dispersed frequencies and shaft-rate electric field is almost eliminated.

6 Conclusions

In the light of the studies on shaft-rate electric field mechanism and its electrical equivalent model, this paper puts forward a shaft-rate electric field suppression technology based on shaft-ground active compensation system. The working principle of shaft-ground active compensation system is analyzed and systematic signal processing module, logical control module and power-drive module are designed. Scale model of naval ship is adopted to simulate the electric field suppression test. The test shows that this shaft-ground active compensation system can suppress more than 75% shaft-rate electric field of naval ships, which is an effective shaft-rate electric field suppression technology.

References

[1] LIN C S, GONG S G. Ship physical field [M]. Beijing: Weapon Industry Press, 2007 (in Chinese).

[2] ZHANG Haipeng , CHEN Xingang , AO Chenyang, et. al. Research on the cancellation method of compensated negative potential for ship shaft-rate electric field [J]. Power Electronics, 2015, 49(2):24-27(in Chinese).

[3] LI J. Investigation on electric field stealth technology of warships [D]. Wuhan: Naval University of Engineering, 2010 (in Chinese).

[4] DYMARKOWSKI K, UCZCIWEK J. Ships detection based on measurement of electric field in disturbance existing region [C]//Proceeding of the Conference on UDT. London, UK, 2000.

[5] ZHANG Haipeng, CHEN Xingang, AO Chenyang, et. al. An analysis on electrical properties of ship structure based on the mechanism of shaft-rate electric field [J]. ElectricaI Automation, 2015, 37(2): 24-26(in Chinese).

[6] SUN Ming. Investigation on induced electric field and extremely low frequency electric field of ships[D]. Wuhan: Naval University of Engineering, 2003 (in Chinese).

[7] ZHOU S H, SUN Y L, LIU Y Z. Non-acoustic characteristics study and the application technology of targets in water [C]//Paper collection of characteristics study on targets in water. Dalian, 2002 (in Chinese).

[8] GONG Shenguang, LU Xincheng. Pilot study of electric field characteristics of warship [J]. Journal of Naval University of Engineering, 2008, 20(2): 1-4, 26 (in Chinese).

舰船轴频电场的轴地有源补偿技术

张安明[1], 张海鹏[2], 程峥华[3]

1 海军驻大连船舶重工集团有限公司军事代表室,辽宁 大连 116005

2 海军潜艇学院 动力操纵系,山东 青岛 266042

3 中国人民解放军92730部队,海南 三亚 572016

摘 要: 为了有效减少舰船轴频电场的影响,降低舰船的暴露率,在分析轴频电场产生机理和相关电学特性的基础上,提出舰船轴频电场的轴地有源补偿方法,分析轴地有源补偿系统的原理,设计系统的控制框架和功能框架。研究舰船轴地微弱信号监测与调理技术以及电场抑制系统的判断与控制技术,设计轴地有源补偿系统的驱动和功率输出模块,开展轴频电场抑制效果的模拟测试。试验结果表明:除去环境电场的影响,该系统对轴频电场的抑制能力超过75%,可以有效降低舰船轴频电场对舰船隐蔽性的影响。

关键词: 轴频电场; 电势补偿; 电场抑制; 舰船