DOI: 10.3969/j.issn.1673-3185.2017.06.017 **http:** // english.ship-research.com

Translated from: XIANG K B, LI W J, LAN Q H. Comparative study of rudder transmission vibration characteristics of electric and hydraulic drive[J]. Chinese Journal of Ship Research, 2017, 12(6): 114-119.

Comparative study of rudder transmission vibration characteristics of electric and hydraulic drive

XIANG Kebing[1], *LI Weijia*[1], *LAN Qiuhua*[2]

1 School of Naval Architecture & Ocean Engineering, Huazhong University of Science and Technology, Wuhan 430074, China

2 School of Energy and Power Engineering, Huazhong University of Science and Technology, Wuhan 430074, China

Abstract: [Objectives] A comparative study of the rudder transmission vibration characteristics of electric drive and traditional hydraulic drive is carried out on the basis of a scale-down rudder transmission test bed. **[Method]** First, a study is made on the rotational angular velocity and the relationship between the vibration characteristics and loading force of a rudder transmission driven by an electric servo motor. Next, the vibration characteristics of the mechanism under hydraulic drive and electric drive are compared and analyzed. **[Results]** The results indicate that the vibration intensity has a positive correlation with the rudder blade loading force and angular velocity at the zero balance position. Both the peak-to-peak values and root-mean-square values of the vibration acceleration of the electric drive are reduced by 40% compared with the hydraulic drive, meaning that the electric drive can more effectively reduce the overall vibration of the rudder transmission. **[Conclusions]** The results provide a reference for the electrification of rudder transmission.

Key words: rudder transmission; hydraulic drive; electric drive; vibration characteristics

CLC number: U664.36

0 Introduction

In order to enhance the overall combat capability, and improve the stealth performance of combat platforms such as the new generation of main combatant ships and auxiliary ships, the navies of all countries in the world have extensively used the integrated full electric propulsion systems on ships, and developed the "all electric warships" that are dynamically reconstructed.

Rudder system is an important part of a ship control system, and the fluid noise and mechanical noise caused by it are also one of the important noise sources of ships[1]. Noise suppression of rudder system itself is an effective measure to enhance the stealth performance of ships and to improve the work environment inside ships. In the traditional ship control system, the rudder controls the ship mainly through hydraulic system. Although hydraulic rudder system can provide a larger load, and achieve overload protection easily, its shortcomings are also very obvious, such as large occupied volume, inevitable leakage, and loud mechanical noise and fluid noise[2]. In recent years, with the application of integrated full electric propulsion, rudder system begins to adopt a servo motor for drive. The rapid development of AC variable frequency, modern control and other technologies has solved the problems of AC motors such as poor speed control performance and slower respond speed. Compared with hydraulic rudder, electric rudder occupies less space, and makes no fluid noise and smaller mechanical noise, which can effectively enhance the stealth performance of combat platform. At present, there are more studies on the

Received: 2017-05-02

Author(s): XIANG Kebing, male, born in 1991, master. Research interests: hydraulic and electromechanical control of ships. E-mail: 1215908069@qq.com

LI Weijia (Corresponding author), male, born in 1964, Ph.D., professor, doctoral supervisor. Research interests: underwater operation system, mechanical-electrical-hydraulic intelligent control system, and robots. E-mail:liweijia@hust.edu.cn

modal analysis and finite element simulation of hydraulic rudder and electric rudder all over the world[3-7], but most of them lack experimental research. In this paper, based on a marine scale-down rudder transmission test bed, a comparative study was conducted on the vibration acceleration characteristics of rudder transmission under hydraulic and electric drive, so as to explore the feasibility of the electrification of ship rudder system.

1 Scale-down test system for rudder transmission

The scale-down test system for rudder transmission mainly consists of four parts, including test bench, rudder blade loading system, centralized control system and data acquisition system. This device is obtained from the rudder system in a type of real ship after a scale ratio of 1∶4. After determining the performance parameters of the test system, the test bench is designed, as shown in Fig. 1. A hydraulic cylinder or electric cylinder drives the transmission rod and crank rod directly connected to it, which is the main way to provide power to drive the movement of rudder blade. In addition, two loading cylinders are also provided to load the rudder blades, and to simulate the steering process of rudder system in the case of load.

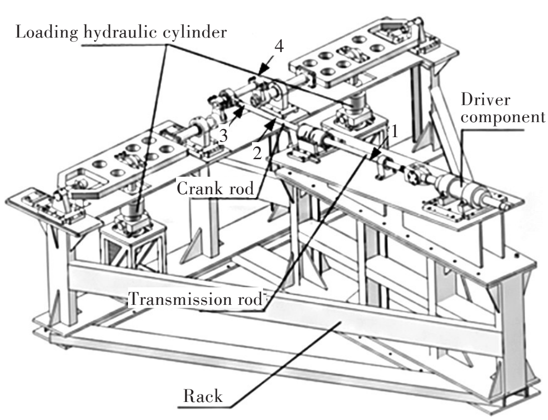


Fig.1 Test bench structure

The loading system is mainly used to exert a certain load pressure on the rudder blades in the operation of rudder transmission, and to simulate the external force in the working process of rudder system. During the steering of actual ship, as the rudder angle changes, the force exerted on the rudder is rather complicated. To facilitate study, the magnitude of applied force is approximated as linearly changing with rudder angle. A passive loading system of hydraulic spring consisting of a pre-charged pressure accumulator and a loading hydraulic cylinder is used, the maximum loading capacity of which is 50 kN and the response of which is faster. And there is no vibration noise during working.

The centralized control system has two control modes, including hydraulic servo drive control and electric servo drive control. The former adopts electro-hydraulic position servo control mode[8], and feeds back the current position of rudder angle by analog signals. It drives the hydraulic cylinder to make fast, accurate and smooth follow actions through electro-hydraulic servo valve, and the hydraulic servo control schematic is shown in Fig. 2. The latter uses digital AC servo drive control method based on CANopen local communication[9]. The host computer sends the digital control instruction of the target position to servo driver through CANopen communication, and the servo driver drives the servo motor to rotate. It drives the rudder blades to make fast, accurate and smooth follow actions through the ball screw and electric cylinder. The electric servo control schematic is shown in Fig. 3.

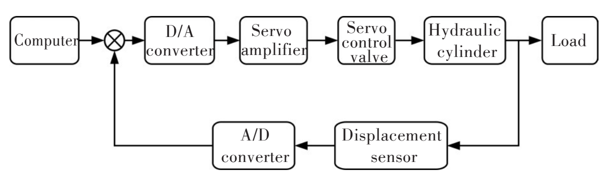


Fig.2 Hydraulic servo control schematic

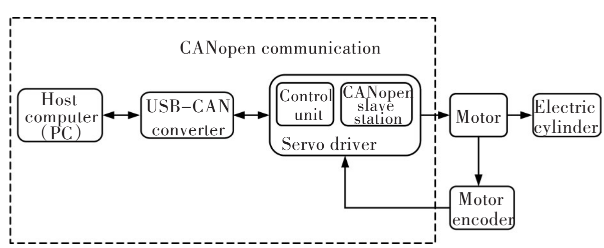


Fig.3 Electro servo control schematic

The measuring system measures the vibration generated by transmission rod on which the electric cylinder directly acts and the vibration transmitting from the transmission rod to the crank rod through guiding device. In order to conduct comparative study on the transmission and amplification of vibration acceleration at the outlet of driving cylinder and the vibration acceleration during the process of driving rudder blades through the space slider mechanism under two drive modes[10-11], the arrangement of acceleration sensors is shown in Fig. 1. The 1-4 in the figure represent Nos. 1-4 sensors. Among them, Sensor 1 is arranged close to the outlet of hydraulic cylinder or electric cylinder at the transmission rod, Sensor 2 is arranged at the crank rod close to the guiding device, Sensor 3 is arranged far away from the guiding device at the crank rod, and Sensor 4 is arranged at the crank. Sensor 1 measures the vibrations at the drive end, and the other three sensors measure the vibrations at the transmission end. As the most typical one in the three sensors, Sensor 2 is selected for research.

The data acquisition system uses the TMR200 measuring instrument from TML Company, Japan. Acceleration sensor uses 352C33 sensor, with sensitivity of 100 mV/g, measurement range of ±50 g, and frequency working range of 0.5–10 kHz, which can meet the measurement requirements under various cases in this test.

2 Research on vibration characteristics of electric drive

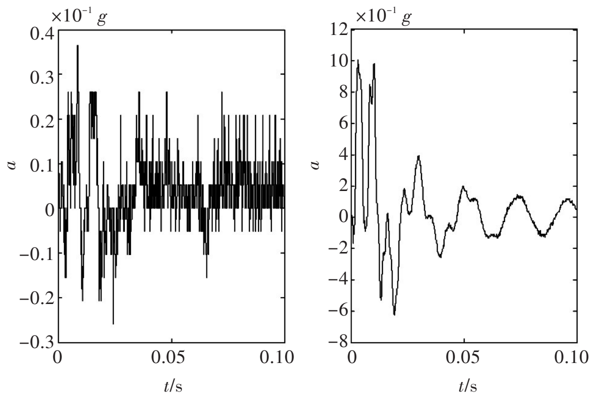
During steering, there are many factors that influence the vibration noise generated by rudder system, the greatest of which is the force exerted on rudder during rudder swinging and the rudder swinging speed. Meanwhile, the force exerted on rudder blades is not only related to rudder angle, but also closely related to ship speed. In order to study the vibration characteristics of rudder transmission in the process of operation under electric drive and control the rudder transmission to do the typical sinusoidal motion, vibration tests are carried out under the following two cases. Their acceleration data are measured, and the vibration characteristics are analyzed.

1) Vibration test of rudder blade under constant-slope loading force and different rotational angular velocities.

2) Vibration test of rudder blade under constant rotational angular velocity and loading force of different slopes.

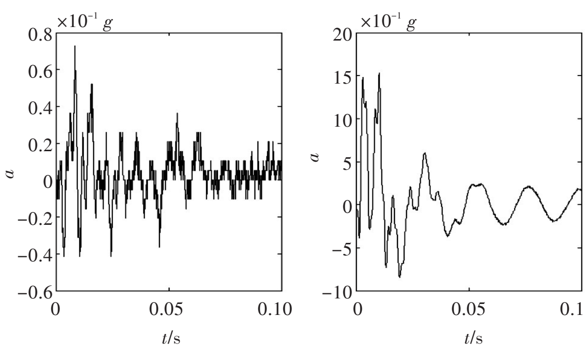
In the two cases, the case of constant-slope loading force is approximate to the force case of rudder blades under constant speed, and the case of constant rotational angular velocity is approximate to the one of different velocities under one rudder swinging speed. Considering that the normal rudder swinging range of rudder system is ±20°, this test mainly studies the vibration acceleration characteristics of the system whose rudder angle is within 20°.

In the typical case where the loading force is 60% of the maximum loading force, by controlling the sine signal value of host computer, the rotational angular velocities of rudder blades at the zero balance position are selected as 1, 2, 3, 4 and 5 (°)/s respectively. Vibration test is conducted, and vibration acceleration curves of Sensor 1 and Sensor 2 during the movement are obtained, as shown in Fig. 4–Fig. 8.



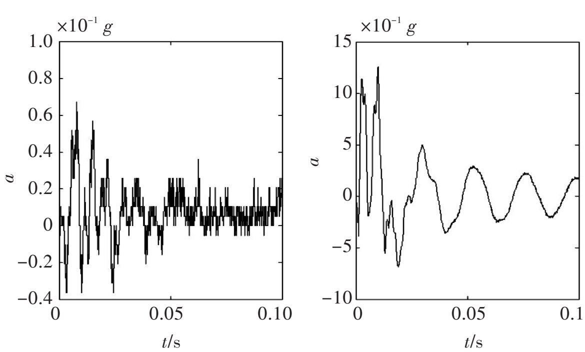
(a) Transmission rod (b) Left end of crank rod

Fig.4 Vibration acceleration curves when angular velocity of rudder blade is 1 (°) / s



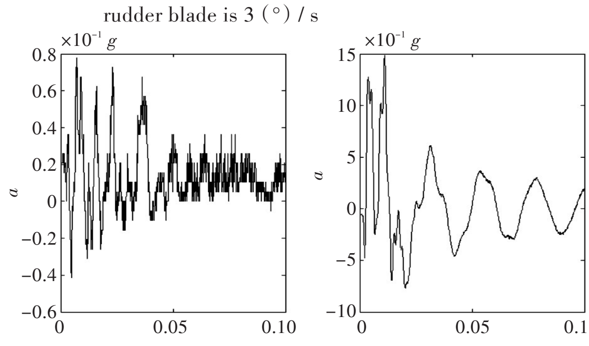
(a) Transmission rod (b) Left end of crank rod

Fig.5 Vibration acceleration curves when angular velocity of rudder blade is 2 (°) / s



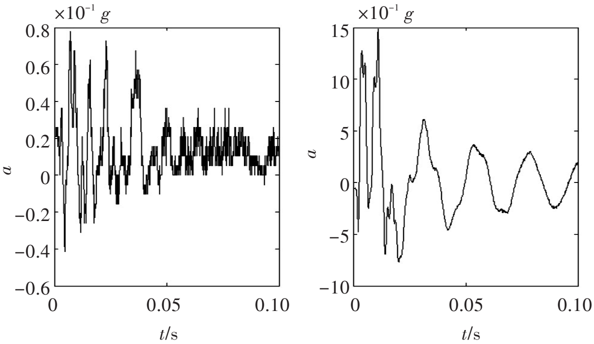
(a) Transmission rod (b) Left end of crank rod

Fig.6 Vibration acceleration curves when angular velocity of rudder blade is 3 (°) / s



(a) Transmission rod (b) Left end of crank rod

Fig.7 Vibration acceleration curves when angular velocity of rudder blade is 4 (°) / s



(a) Transmission rod (b) Left end of crank rod

Fig.8 Vibration acceleration curves when angular velocity of rudder blade is 5 (°) / s

It can be seen from the figures that both the peak-to-peak and root-mean-square values of the vibration acceleration at the transmission rod are relatively small, while those at crank rod are larger, indicating that the control effect of electric cylinder is better and the operation is more stable.

Meanwhile, the loading force is adjusted to 40% and 80% of the maximum loading force for vibration test of constant-slope loading force. Vibration accelerations at Sensor 1 and Sensor 2 are measured during the movement. After the pretreatment of data analysis software, the results of three groups of loading force tests are imported into Matlab. Through calculation, the peak-to-peak and root-mean-square values (unit: 0.1 g) in the cases of constant-slope loading force and constant rotational angular velocity are obtained, as shown in Table 1 and Table 2.

Table 1 Peak-to-peak acceleration values in different conditions

Maximum loading force /%	Rotational angular velocity/((°)·s^{-1})									
	1		2		3		4		5	
	Sensor 1	Sensor 2	Sensor 1	Sensor 2	Sensor 1	Sensor 2	Sensor 1	Sensor 2	Sensor 1	Sensor 2
40	0.622 8	14.876 4	0.752 6	18.747 3	1.089 9	23.579 6	1.323 5	26.438 5	1.505 1	27.475 8
60	0.696 9	14.825 8	1.141 8	23.048 3	1.323 5	22.871 2	1.349 4	24.844 6	1.764 6	27.728 8
80	1.167 8	20.012 3	1.203 8	22.618 2	1.686 8	38.405 4	1.583 0	34.559 8	1.816 5	41.466 7

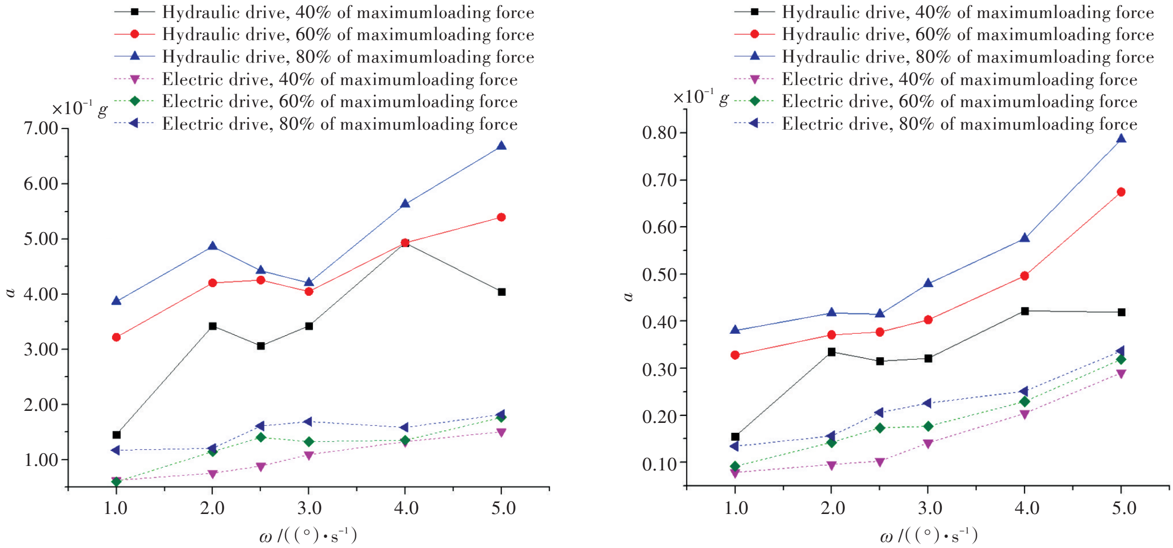
Table 2 Root-mean-square acceleration values in different conditions

Maximum loading force /%	Rotational angular velocity/((°)·s^{-1})									
	1		2		3		4		5	
	Sensor 1	Sensor 2	Sensor 1	Sensor 2	Sensor 1	Sensor 2	Sensor 1	Sensor 2	Sensor 1	Sensor 2
40	0.078 7	2.383 2	0.095 6	3.143 6	0.141 4	3.830 3	0.204 1	4.309 1	0.290 5	4.518 2
60	0.091 5	2.353 2	0.142 5	3.587 1	0.176 6	3.705 4	0.229 4	4.081 8	0.318 9	4.555 6
80	0.134 4	2.964 0	0.156 4	3.501 4	0.226 0	5.052 6	0.251 1	5.050 4	0.337 0	5.710 6

Based on the analysis of the test results measured in cases of different loading forces and different maximum rotational angular velocities of the rudder transmission under electric drive, and figures of peak-to-peak values and root-mean-square values drawn in the above, it can be known that the higher the loading force is when the rudder blade travels to the maximum angle, the larger the rotational angular velocity of rudder angle at the zero position is, and the higher the vibration intensity generated by the drive system is. In addition, during the axial transmission process of vibration from the transmission rod to the crank rod, the vibration intensity increases rapidly. This is mainly because there is a gap at the hinge joint of revolute and crank rod in the guiding device, and the vibration is amplified when passing through the gap.

3 Comparison of vibration characteristics under different drive modes

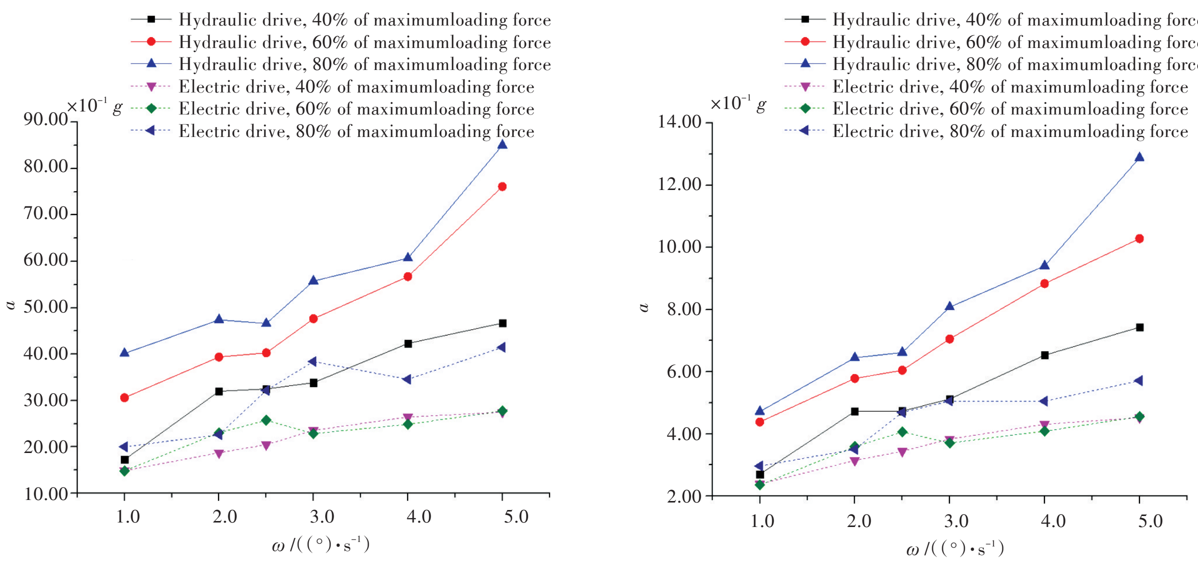
In order to carry out comparative study on mechanical noise generated by the rudder system in the two ways of hydraulic drive and electric drive, a series of sinusoidal motion tests are performed on the rudder transmission. In order to obtain the control stability of system under hydraulic drive mode, the design is optimized based on Reference [11] to make the vibration generated by system the minimum under the control strategy of linear acceleration. The rudder blade loading system is adjusted to make the loading force be 40%, 60% and 80% of the maximum loading force, and make the rotational angular velocities of rudder blades respectively be 1, 2, 2.5, 3, 4 and 5 (°)/s when they pass the zero position of rudder angle. The vibration accelerations at Sensor 1 and Sensor 2 are measured after vibration test, and the peak-to-peak values and root-mean-square values of each group of acceleration data are calculated through Matlab. And the changing trend schematics of calculation results in different cases under two drive modes are plotted, as shown in Fig. 9 and Fig. 10.



(a) Variation of peak-to-peak values of acceleration

(b) Variation of root-mean-square values of acceleration

Fig.9 Peak-to-peak and root-mean-square values of vibration acceleration of the transmission rod under two drive modes



(a) Variation of peak-to-peak values of acceleration

(b) Variation of root-mean-square values of acceleration

Fig.10 Peak-to-peak and root-mean-square values of vibration acceleration of the left end crank rod under two drive modes

By comparing the variations of peak-to-peak values and root-mean-square values of vibration acceleration at the transmission rod and the left end of crank rod when the rudder transmission is in two control modes of hydraulic servo drive and electric servo drive, the following conclusions can be acquired:

1) Under two drive modes, the vibration generated by rudder transmission drive system enhances with the increase of the rotational angular velocity of rudder blade at zero balance position and with the increase of loading force of rudder blade at the position where the angle is the maximum.

2) With the gradual increase of rotational angular velocities of rudder transmission at the zero balance position and loading force of rudder blade, the intensity of vibration under hydraulic drive mode increases faster, especially at the rotational angular velocities of 4 and 5 (°)/s. The intensity of vibration under electric drive mode increases smaller.

3) When the rudder transmission is in the case of small load and slow rotational angular velocity, the differences of the peak-to-peak values and root-mean-square values of vibration acceleration generated by two drive modes are small, both of which are less than 10%. In the cases of larger load and higher rotational angular velocity, the peak-to-peak values and root-mean-square values generated by electric servo drive decrease significantly compared with those generated by hydraulic servo drive, with a decrease of about 40%.

4) From the perspective of the vibration intensity and system stability of rudder transmission, the electric servo drive mode is superior to hydraulic servo drive mode.

4 Conclusions

Through the vibration characteristics test of rudder transmission in two cases of different loading forces and different rotational angular velocities at the zero balance position, the vibration acceleration characteristics of transmission itself under electric drive are firstly studied. The test shows that the vibration intensity caused by the drive system has a positive correlation with the rudder blade loading force and rotational angular velocity at the zero balance position, and the vibration intensity gradually increases in the transmission process. Afterwards, a comparative study is performed on the vibration accelerations produced under hydraulic drive and electric drive. From the test, it can be seen that both the peak-to-peak values and root-mean-square values of the vibration acceleration of rudder under electric drive are reduced by 40% compared with those under hydraulic drive. The electric drive mode has better performance in mechanical vibration noise and system operating stability, so it is feasible to replace hydraulic rudder by electric rudder in terms of performance index.

References

[1] HE S Q. Noise analysis and control scheme of ship machinery equipment[J]. Science and Technology & Innovation, 2015(12): 115 (in Chinese).

[2] MA X R. Fluid noise control of ship hydraulic rudder system [D]. Harbin: Harbin Engineering University, 2010 (in Chinese).

[3] LIN C G, ZOU M S, JIAO H F, et al. Identification of non-stationary excitation and analysis of transient radiation noise on steering engine[J]. Journal of Ship Mechanics, 2016, 20(6): 758-767.

[4] MENG B M, LV Y Q, REN G C. Analysis of the reliability of anti-resonance for ball screw based on the finite element method[J]. Modular Machine Tool & Automatic Manufacturing Technique, 2011(2): 10-12, 16 (in Chinese).

[5] WANG T, WANG K H, XIE K H. An analytical solution to longitudinal vibration of a pile of arbitrary segments with variable modulus[J]. Acta Mechanica Solida Sinica, 2001, 14(1): 67-73.

[6] ZHAO W J. Analysis of static and dynamic characteristic of ball screw feeding system based on ANSYS[J]. Journal of Mechanical Transmission, 2010, 34(5): 68-70 (in Chinese).

[7] WEN B C, LIU S Y, HE Q. Theory and dynamic design method of vibration machinery[M]. Beijing: China Machine Press, 2002 (in Chinese).

[8] XIAN L B. Research on valve-controlled cylinder electro-hydraulic position control system [D]. Wuhan: Huazhong University of Science and Technology, 2007 (in Chinese).

[9] LIU Y Q, HOU W P, GAO J L. The software realization of motion control system low level driver based on CANopen protocol[J]. Equipment for Electronic Products Manufacturing, 2014, 43(12): 31-34 (in Chinese).

[10] FUNABASHI H, OGAWA K, HORIE M, et al. A dynamic analysis of the plane crank-and-rocker mechanisms with clearances[J]. Bulletin of JSME, 1980, 23(177): 446-452.

[11] HUANG Y N, XIE G, LI W J, et al. Research on the impact vibration and optimal control of a mechanism for steering gear with clearance[J]. Journal of Wuhan University of Technology (Transportation Science & Engineering),2017,41(1): 132-135,140 (in Chinese).

舵传动装置的液压与电气驱动振动特性对比研究

向科兵[1]，李维嘉[1]，兰秋华[2]

1 华中科技大学 船舶与海洋工程学院，湖北 武汉 430074

2 华中科技大学 能源与动力工程学院，湖北 武汉 430074

摘　要：[**目的**] 针对传统的液压驱动的舵传动装置，基于缩比舵传动装置试验台，开展电气驱动方式振动特性研究。[**方法**] 首先研究舵传动装置在电气驱动下机构本身振动特性与负载力及转动角速度的关系，然后对液压、电气两种驱动方式下机构的振动特性进行对比分析。[**结果**] 试验表明，传动装置产生的振动强度与舵叶加载力、舵角零点位置角速度呈正相关，电气驱动方式产生的振动加速度峰峰值和均方根值与液压驱动相比均降低了40%，有效降低了传动装置的整体振动，[**结论**] 对舵传动装置电气化具有参考价值。

关键词：舵传动装置；液压驱动；电气驱动；振动特性