Design and Development of a Rudder Load Simulator for the Onshore Testing of Autonomous Underwater Vehicle

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***Abstract*—Through and comprehensive tests are necessary to ensure complete stability and reliability of AUV, due to the high risk and consumption of in field testing, onshore testing technology for AUV is proposed. Rudder load simulator plays an important role in the onshore testing of AUV. In this paper, the design and development of a rudder load simulator was discussed. Rudder load calculation method during the onshore testing, system scheme, control structure, controller design and control parameters optimization are studied in detail. Several demonstration tests results demonstrated the performance of the rudder load simulator.**

Keywords—Autonomous underwater vehicles; Onshore testing; All-hardware-in-the-loop simulation; Rudder load simulator; PID parameters optimization

I. Introduction

Underwater vehicle is an important tool in the exploration, survey and investigation of the ocean and have many scientific, military, and commercial applications. Unlike human occupied vehicles (HOVs) and remotely operated vehicles (ROVs), autonomous underwater vehicles (AUVs) operate and carry out missions without manual inputs, tethers or remote control. When operates in a complex and severe underwater environment, AUV using its own power supply and make decisions according to the input from onboard sensors only. Therefore, AUV must be stable and reliable functionally, electrically and mechanically in order to accomplish missions successfully. Hence, through and comprehensive tests are necessary to ensure complete stability and reliability of AUV.

At present, most specification tests of AUV are carried out on the lake or at sea. Such field tests will take many people, many time and lot of money. Furthermore, in field testing, many specifications cannot be tested in the specify spot, and many dangers exist during the field test period. Thus, more and more researchers focusing on seeking solutions to the onshore testing of AUVs. Simulation technology is widely used in industries and academia to imitate the behavior of real-world process or systems over time. In order to test AUV effectively, efficiently and economically, an onshore testing system of AUV based on all-hardware-in-the-loop (AHIL) simulation was proposed [1].

The architecture of the onshore testing system is designed as shown in Fig. 1, which includes a real AUV and a series of subsystems. During onshore testing, the AUV operates just the same as it was cruising underwater. The onshore testing system simulate real operating environment of the AUV, such as motion simulation, real time attitude simulation, depth gauge signal simulation, DVL signal simulation, satellite positioning devices signal simulation, thruster load simulation, rudders load simulation and so on.

Rudder system plays a pivotal role in the motion and attitude control of AUV. In order to ensure that the designed rudder system can work accurately and reliably in reality, it is necessary to do load simulation experiment for the rudder system [2]. Beyond that, during the onshore testing process, motion simulation of the AUV was conducted based on AUV current moment motion information, ocean environment information, real time fins angle information and so on. Therefore, it is crucial to measure real time fins angle of the rudder system to conduct the onshore testing process. Thus, a hardware-in-the-loop simulation equipment which can reproduce desired load torque acting on the rudder system and can measure real time fins angle of the AUV is needed, namely, the rudder load simulator.

In this paper, the design and development of a rudder load simulator used for the onshore testing of AUV was presented. The rudder load simulator is actually a passive torque servo system. During the onshore testing, the rudder load simulator can emulate real time rudder load of the AUV based on calculated motion information and simulated ocean environment information. In addition, real time fins angle of the real AUV will be measured by the rudder load simulator in order to calculate the motion information of the AUV in the next time step.

In the following parts of this paper, the onshore testing system is briefly introduced; rudder load calculation method

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during the onshore testing is described; system architecture, control structure, controller design and parameters optimization of the rudder load simulator are discussed; some experimental results are presented to illustrate the specifications and performance of the rudder load simulator.

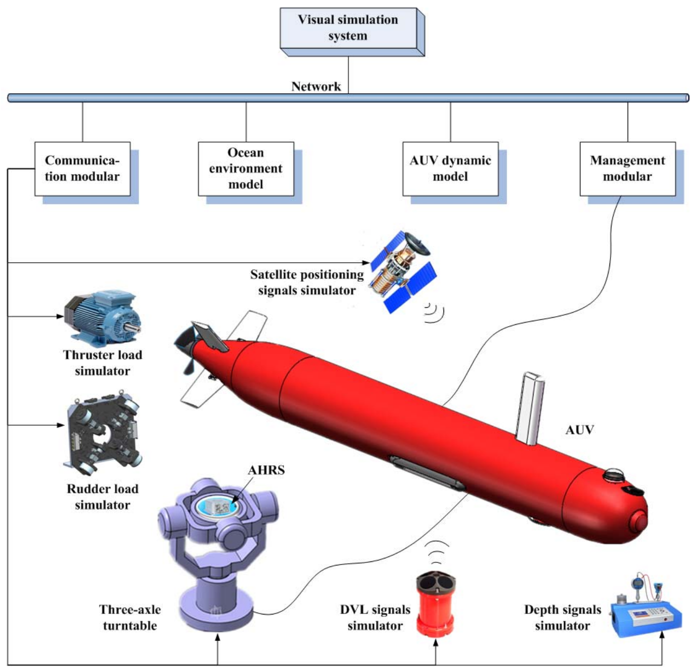

Fig. 1. Architecture of the onshore testing system for AUV

II. Rudder Load Calculation During the Onshore Testing of AUV

A. The Onshore Testing Process of AUV

As illustrated in Fig.1, the onshore testing system include a real AUV and a series of subsystems. When the onshore testing of AUV starts, the motion state of the AUV, ocean environment information, and other initial conditions and parameters will be initialized based on the setting situation. The AUV operates to execute its mission, thruster and rudder system act according to instructions of the controller. Then, motion information of the next time step can be calculated based on AUV dynamic model, thruster information, fins angle, ocean environment information and other information.

After obtained the motion information such as linear velocities, angular velocities, attitude angles, depth and horizontal position, the simulate of real operating environment of the AUV begins.

Three-axle turntable operates according to the calculated angular velocities and attitude angles, rotate the AHRS of the AUV to simulate the change of attitude. Real time thruster load and rudder load will be calculated based on thruster load model and rudder load model, load torques will be applied to AUV thruster and rudder system by thruster load simulator and rudder load simulator respectively. Hydraulic pressure corresponding to current depth will be generated by depth signal simulator and applied to the depth gauge of AUV. Acoustic beams contain current linear velocity information will be generated by DVL signals simulator. Electromagnetic signals identical to the signals of satellite positioning systems will be generated by satellite positioning signals simulator.

At the same time, the AUV operates in the simulated environment, acquire information from onboard sensors and equipments, and make control instructions according to its control algorithms. Then, actuators such as thruster and rudder system act according to those instructions, and the next simulation process begins.

B. Rudder Load Calculation

When moving underwater, there is relative movement between the fins of AUV and water body. For the convenience of discussion, it can be assumed that the AUV is stationary, and there are relative sea current flow around. Fig. 2 is a sketch top view of the fin of AUV. As shown in Fig.2, if the relative sea current is not parallel to the longitudinal section of the fin (that is to say $\alpha \neq 0$), the hydrodynamic force acting on the two side of the fin will out of balance, and there will be load torque acts on rudderpost of the AUV, that is the rudder load.

Define M_{r} represents the load torque acts on the rudderpost of AUV, according to the illustration of Fig. 2, M_{r} can be calculated by:

$$M_{\mathrm{r}} = P_N (x_P - a) \tag{1}$$

where:

P_N : vertical component of the hydrodynamic force acting on the fin.

x_P : distance between the front end of the fin and center of the hydrodynamic force acting on the fin.

a : distance between the front end of the fin and the rudderpost.

The center of the hydrodynamic force acting on the fin is determined by the shape of the fin and the direction of the relative sea current. In engineering practice, x_P can be calculated by:

$$x_P = C_{\mathrm{p}}(\alpha) * b \tag{2}$$

where:

C_{p} : pressure center coefficient of the fin.

b : chord length of longitudinal section of the fin.

α : included angle between direction of the relative sea current and the longitudinal section of the fin.

The pressure center coefficient C_{p} is a variable of α , the relationship between C_{p} and α is determined by the shape of the fin.

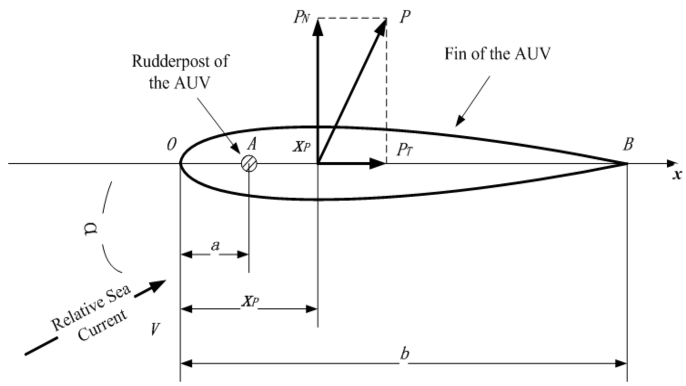

Fig. 2. Sketch top view of the fin of AUV

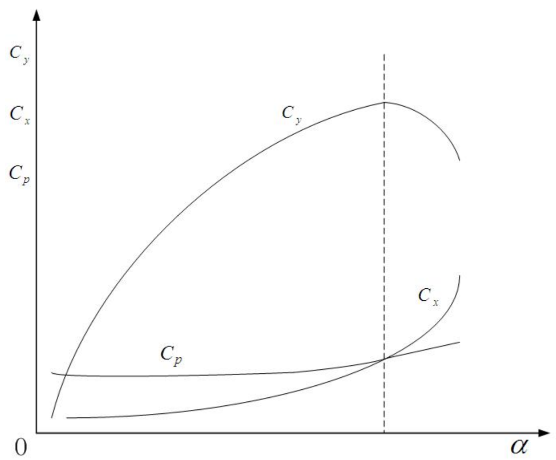

Fig. 3. Illustration of the variation relationship between non-dimensional coefficients of the fin

The vertical component of the hydrodynamic force acting on the fin P_N is determined by:

$$P_N = \frac{1}{2} C_N \rho V^2 A_R \tag{3}$$

where:

ρ : density of water bodies surrounding the AUV.

V : inflow velocity of the relative sea current.

A_R : area of the fin.

C_N : normal force coefficient of the fin.

The normal force coefficient C_N is one of the non-dimensional coefficients to describe the characteristic of the fin. The relationship between the normal force coefficient C_N and another two coefficients is:

$$C_N = C_y \cos\alpha + C_x \sin\alpha \tag{4}$$

where:

C_y : lift coefficient of the fin.

C_x : drag coefficient of the fin.

For a certain fin, the relationship between the pressure center coefficient C_P , the lift coefficient C_y , the drag coefficient C_x and the included angle α is determined. A brief illustration of the variation relationship between C_P, C_y, C_x and α is shown in Fig. 3.

III. System Design of the Rudder Load Simulator

A. System Scheme of the Rudder Load Simulator

The onshore testing system introduced in this paper is designed for the onshore testing of a portable AUV, named Explorer-100 [3,4]. As shown in Fig. 4, the Explorer-100 AUV is equipped with an X-shaped fins to control yaw and pitch. The rudder system of the Explorer-100 AUV uses four digital torque servos as rudder motor, the maximum output torque of the digital torque servo is 2.84N.m, maximum rudder angle of the Explorer-100 AUV is 30degree.

In order to achieve high performance, loading device of the rudder load simulator should be selected according to the actual situation. Generally speaking, there are four kinds of loading devices, namely, mechanical torsion bar loading devices, pneumatic loading devices, electro-hydraulic loading devices and electric loading devices [5,6]. Comparing with other loading devices, electrical loading devices have advantages such as good control performance, better small signal response, more steadiness, less noise and small volume [7], and are widely used in high accuracy loading situation.

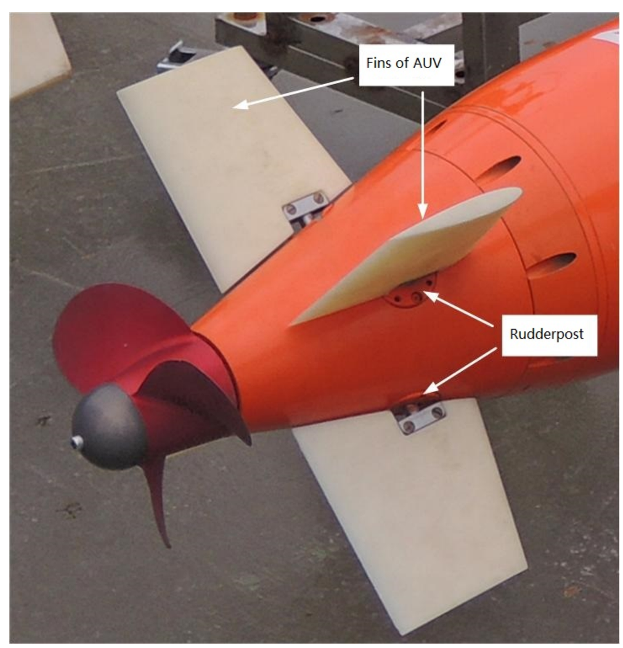

Fig. 4. Rudder system of the Explorer-100 AUV

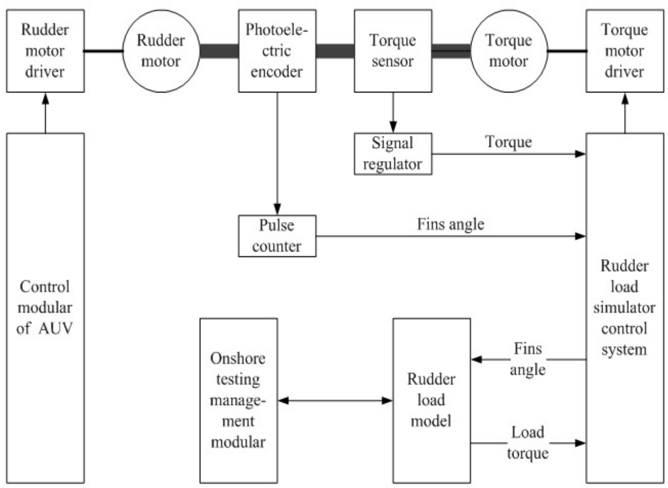

Fig. 5. Architecture of the rudder load simulator

The rudder load simulator described in this paper uses a torque motor as loading device, thus the loading device of the rudder load simulator is actually a passive torque servo system. Architecture of the rudder load simulator is shown in Fig. 5, which consists of a torque motor and a torque motor driver, a torque sensor and a signal regulator, a photoelectric encoder and a pulse counter, a rudder load simulator control system and some mechanical devices. When operating, the torque motor provide rudder load torque exert to the rudder motor of the AUV. The torque sensor measure real time load torque exert on the rudder motor, the photoelectric encoder measure real time fins angle of the AUV.

B. Control Structure Design

In order to get credible onshore testing results, loading accuracy of the rudder load simulator must be controlled within a proper range. Otherwise, such all-hardware-in-loop simulation will has little reference value. It is not an easy task to achieve high precision loading performance because loading device of the rudder load simulator is connected with the rudderpost rigidly and the motion of the rudder motor interferences the loading process heavily [5].

The core factor influencing the loading precision of passive torque servo system is the position un-synchronization between the loading device and the rudder motor. Due to the rigid connection between rudder motor and loading device, from the perspective of loading system, the motion of rudder motor leads to strong disturbance, which was defined as surplus torque [8]. In order to suppress surplus torque in loading system, a large number of studies have been performed and massive results have been obtained. Generally speaking, existing surplus torque suppress methods can be divided into parameter optimization method, feed-forward compensation method, robust control method and speed or position synchronization method .

Different surplus torque suppress methods suit for different specific applications. Parameter optimization method reduce the intensity of surplus torque through the optimization of system parameters, this kind of approach has simple structure, but the ability to suppress surplus torque is limited. Feed-forward compensation method consider the loading system as a linear system with known disturbance, and uses some feed-forward units to offset the disturbance. Robust control method think the loading system has unknown exogenous disturbance, and designs robust controller for the loading system. Speed or position synchronization method committed to control the loading device moving synchronously with the rudder motor in speed or position. This kind of method has clear physical meaning and remarkable effect on torque elimination, and is especially suit for electric loading system.

The control diagram of the rudder load simulator is shown in Fig. 6, which consist of current control loop, speed control loop and load torque control loop. Current control loop is the bottom control loop of the loading system, responsible for keeping the current of the torque motor within a proper range. Speed control loop is designed for surplus torque suppress purpose. Based on the idea of speed synchronization, speed control loop control the speed of the torque motor and keep it synchronized with the speed of the rudder motor.

The torque control loop is responsible for the regulation of the output load torque, ensure its consistency with the calculated rudder load. Due to its straightforward algorithm, fine robustness and high reliability [9], a proportion–integration-differentiation (PID) controller is used in the torque control loop. The performance of the PID controllers are greatly affected by the tuning of parameters [10]. To achieve better control performance, a great deal of attention is given to the parameters tuning of PID controller, approaches such as simultaneous perturbation stochastic approximation [11], modified simple particle swarm optimization [12], cultural based ant colony algorithm [13], adaptive genetic algorithm [14], particle swarm optimization [15] have been used for PID controller parameters optimization. In the implementation of the rudder load simulator, an genetic algorithm based approach is utilized to optimize the PID parameters [16].

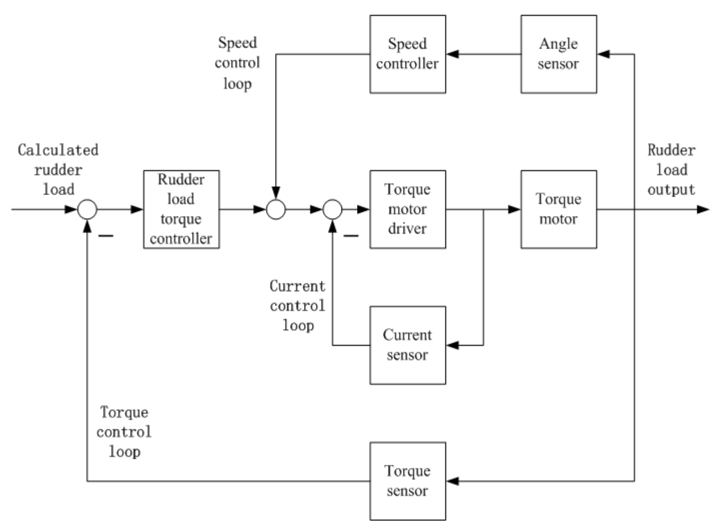

Fig. 6. Control diagram of the rudder load simulator

IV. Implementation and System Performance

The whole rudder load simulator for the onshore testing of Explorer-100 AUV is illustrated in Fig. 7. As mentioned above, the Explorer-100 AUV is equipped with an X-shaped fins, and there is four rudder motors in its rudder system, each rudder motor control the motion of one of the X-shaped fins. To cooperate with rudder system of the Explorer-100 AUV, the loading system of the rudder load simulator consists four sets of loading devices. All loading devices are mounted on a vertical metal base and arranged in X-shape.

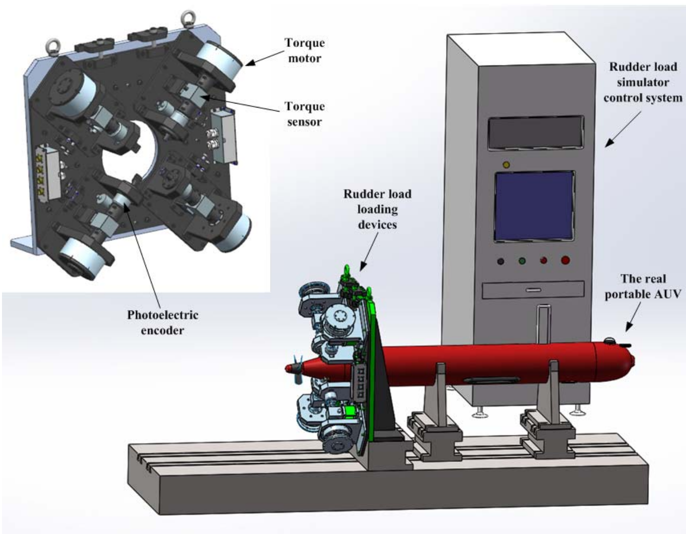

Fig. 7. Mechanical structure of the rudder load simulator

In order to verify the performance of the rudder load simulator, several demonstration tests were conducted. Fig. 8 shows the simulated rudder load outputs when there is a step change calculated load (maximum 0.3N.m), Fig. 9 and Fig. 10 show the simulated load when there is a trapezoidal wave change calculated load.

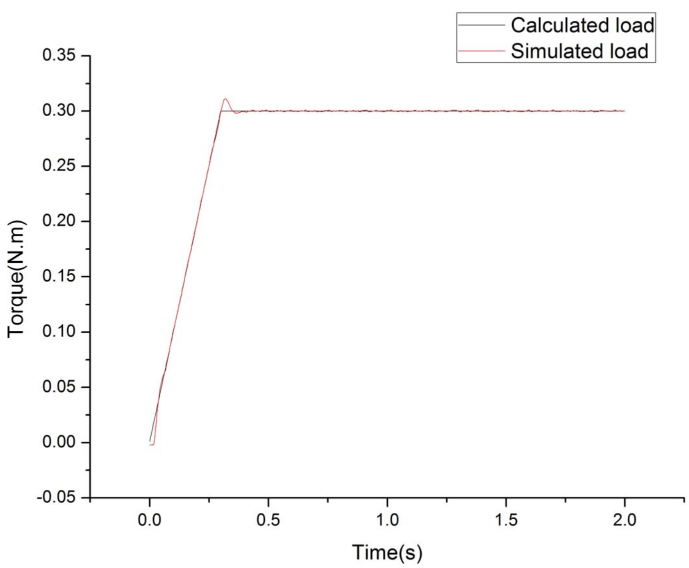

Fig. 8. simulated load with a step change calculated load (max 0.3N.m)

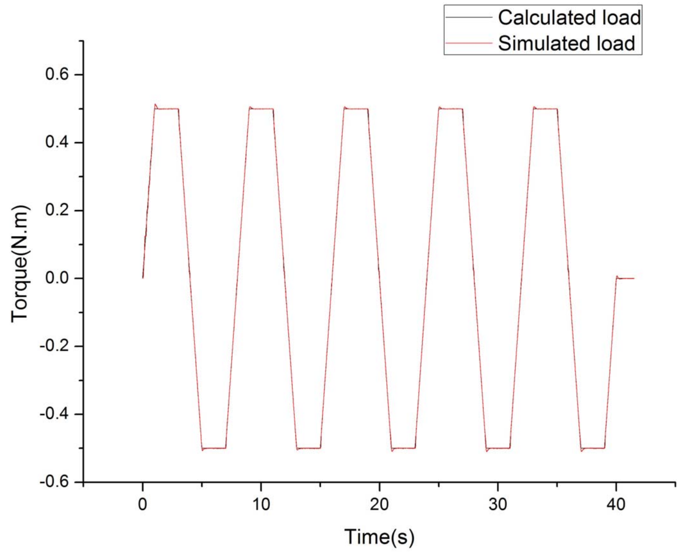

Fig. 9. simulated load with a trapezoidal change calculated load (max 0.5N.m)

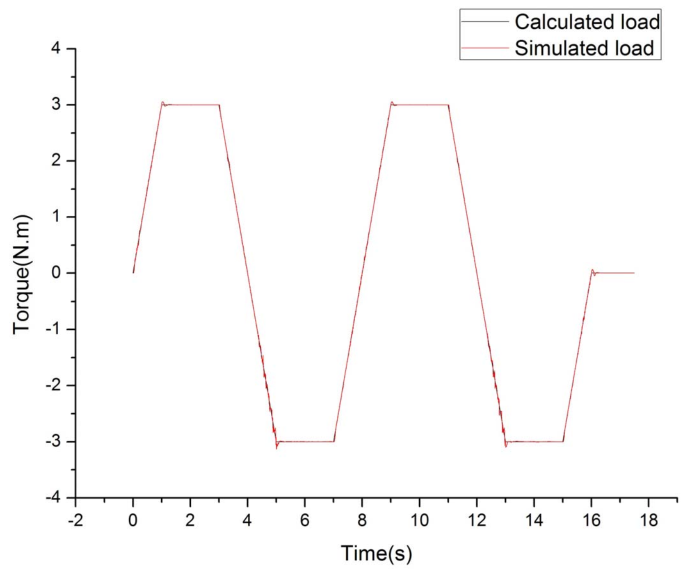

Fig. 10. simulated load with a trapezoidal change calculated load (max 3N.m)

V. Conclusion

This paper discussed the design and development of a rudder load simulator used for the onshore testing of the Explorer-100 AUV. The onshore testing system of the AUV is briefly introduced; rudder load calculation method during the onshore testing is described; system scheme, control structure, controller design and PID controller parameters optimization of the rudder load simulator are studied in detail. Several demonstration tests results demonstrated the performance of the rudder load simulator.

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