An improved linear quadratic regulator of shipborne Stewart platform for wave compensation

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***Abstract*—Ocean-operating ships in rough sea conditions are highly susceptible to wave disturbance. A shipborne Stewart platform with a gangway offers an effective means to enhance the safety of operator and extend the duration of operation. However, the Stewart platform faces time-varying disturbance from ship motions, while the gangway endures off-center loads. These problems make it difficult to design the controller and confirm its parameters of the shipborne Stewart platform. Therefore, an improved linear quadratic regulator with a linear extended state observer is proposed. Specifically, the inverse kinematic model of the Stewart platform's chain limbs and the hybrid Jacobi matrix are developed. The proposed controller is then developed in joint-space, and its stability is verified using Lyapunov theory. On this basis, simulations of random motion signals are carried out in the roll, pitch, and heave directions. Simulation results confirm that the proposed scheme effectively addresses the previous challenges in the adjustment of parameters without overshooting and oscillation and demonstrates excellent performance in anti-disturbance and decoupling.**

I. INTRODUCTION

Due to increased environmental awareness and rising energy demands, marine resources have emerged as a major focus for global extraction [1]. However, offshore operations are vulnerable to ship motions in roll, pitch, yaw, surge, sway, and heave position caused by waves [2], which seriously limits the window period for resource extraction and the accessibility of equipment maintenance [3]. Over the past half-century, researchers have extensively investigated wave compensation devices and proposed many innovative mechanical structures and control methods [4-6]. The existing wave compensation systems are mainly composed of active and passive heave compensation [7-9] and are classified into single degree of freedom (DOF) and multi-DOF compensation [10-12] based on the dimension. With the development of marine technology, shipborne equipment demands higher precision for wave compensation. The shipborne Stewart platform equipped with a gangway is the main wave compensation device due to its full-dimensional compensation capability. However, the base platform experiences nonlinear random ship motion, while the top platform is influenced by the substantial eccentric loads from the gangway [13]. Thereby, resulting in a more complex dynamics model for the shipborne Stewart platform and increasing the difficulty in calibrating parameters of controller.

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In recent years, many scholars have begun to study suitable controllers for the shipborne Stewart platform. Cai et al. designed a velocity feedforward compensator coupled with a command filtered sliding mode backstepping controller to counteract ship motion disturbance [14]. Wei et al. introduced a fuzzy controller based on inverse kinematics to address the motion redundancy issues in the Stewart and gangway hybrid systems [15]. Chen et al. developed a complete dynamics model that includes actuator inertia and utilized a sliding mode controller to demonstrate the system decoupling capabilities [13]. Liu et al. designed a task-space controller using the beetle antennae search methods to mitigate coupling errors [16].

The shipborne Stewart platform often operates in complex sea conditions, facing time-varying ship motion disturbance and strong coupling between each chain limb of the Stewart structure [17]. Consequently, the existing control strategies face the common challenge of determining the parameters of the controller and adapting to the complex dynamics of the shipborne Stewart platform. The linear quadratic regulator (LQR) offers strong dynamic tracking capability and simple parameter adjustment without overshooting and oscillation. However, it has not been widely applied to the shipborne Stewart platform for poor anti-disturbance. To tackle these above challenges, this paper proposes an improved linear quadratic regulator (ILQR) with a linear extended state observer (LESO). The proposed control scheme addresses previous challenges in channel parameter adjustment without overshooting and oscillation, with strong anti-disturbance and effective decoupling performance.

The rest of the paper is organized as follows: Section II establishes the inverse kinematic model and hybrid Jacobi matrix. Section III designs the ILQR controller and uses the Lyapunov theory to prove stability. Section IV gives the simulation results to illustrate the performance of the proposed controller. Section V presents the conclusions of this work. The main research object of this paper is depicted in Fig. 1.

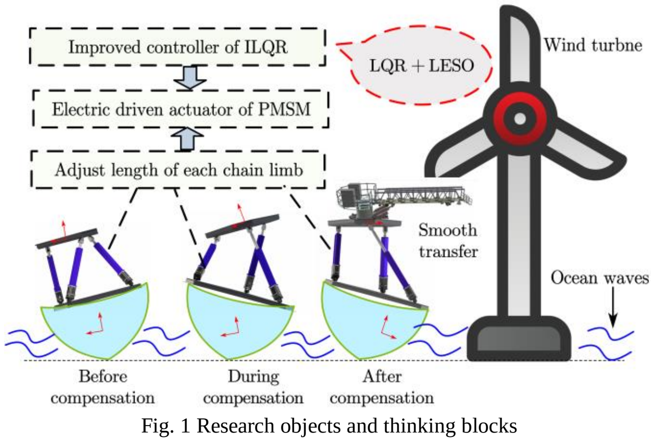

Fig. 1 Research objects and thinking blocks