MODELING AND FLIGHT CONTROL LAW DESIGN FOR A SEAPLANE DURING WATER SURFACE TAKEOFF

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Abstract

Dynamic model and control law of seaplane during water surface takeoff is studied in this paper. The seaplane dynamic model during takeoff is built based on the aerodynamic, hydrodynamic and propulsion system model. Based on the motion characteristics and dynamic stability requirements, a pitch rate command control augmentation system is selected as the control law structure. A turboprop seaplane is taken as an example. The simulation results indicate that the designed control law can expand the stability range and improve dynamic stability of the seaplane during takeoff.

Keywords: seaplane, hydrodynamic model, dynamic model, control law, dynamic stability boundary

1. Introduction

A seaplane refers to a fixed wing aircraft that can take off, land, and park on the water surface, combining the characteristics of general aircraft and high-speed ships. Compared with conventional land-based fixed wing aircraft, seaplanes do not require a dedicated runway and only require a large water surface to take off and landing. The construction cost of a seaplane airport is much lower than that of a land-based airport. Therefore, for countries and regions with vast water areas, seaplanes are an important means of transportation. Due to its ability to take off and landing on the water surface and low flight altitude, seaplanes still have unique advantages in carrying out tasks such as maritime patrols and rescue[1]. In addition, seaplanes can draw water during takeoff from the water surface and extinguish fires by dropping water from the air, which can play an important role in forest firefighting, especially in areas with complex terrain. [2]

During the aerial flight phase, seaplanes have no essential difference from conventional fixed wing aircraft. The main difference is reflected in the water surface taxiing, especially during takeoff.

As shown in Figure 1, the forces during the ground run of a conventional fixed wing aircraft include weight W, thrust T, lift L, drag D, landing gear ground reaction forces R_m and R_n, and tire frictions μR_m and μR_n.

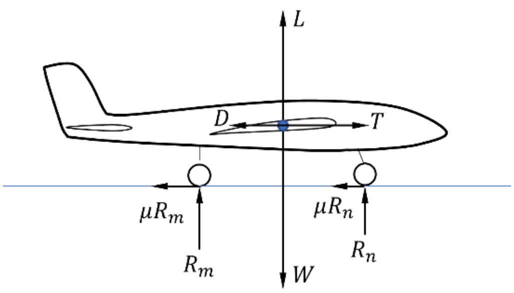

Figure 1 - Forces on fixed wing aircraft during ground run

Seaplanes are not affected by ground reaction forces and friction, but by buoyancy, hydrodynamic lift, and hydrodynamic resistance, as shown in Figure 2. The buoyancy depends on the volume of drainage; The hydrodynamic lift depends on the pitch angle, velocity, and wetted area;

Hydrodynamic resistance, as shown in Figure 3, includes wave resistance, viscous resistance, and splashing resistance [1].

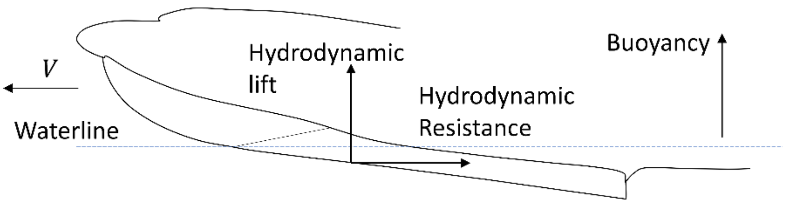

Figure 2 - Forces on seaplane during water surface taxiing

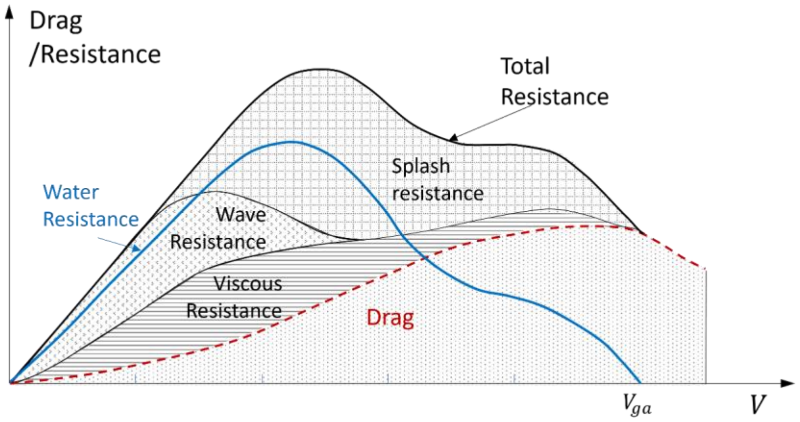

Figure 3 - Drag/Resistance during takeoff and taxiing phase of seaplane

Under the combined action of aerodynamics and hydrodynamics, seaplanes may experience periodic "pitch and heave" motions during medium to high velocity water surface taxiing. This unstable phenomenon is usually referred to as "porpoising"[1], which can cause structural damage to the aircraft and even result in fatalities. For seaplanes, the highest accident rate occurs during takeoff phase, and the most common factor causing accidents are out of control.

To improve the stability and safety of seaplane during takeoff, this paper will build the longitudinal dynamics model and design appropriate control laws.

2. Dynamic Model of Seaplane during Takeoff

As shown in Figure 4, the dynamic model of seaplane during water surface taxiing consists of aerodynamic model, thrust model, hydrodynamic model, and equation of motion. Where, aerodynamic forces depend on the aircraft's flight parameters and control surface deflections, thrust depends on engine throttle and flight parameters, and hydrodynamic forces depend on motion parameters.

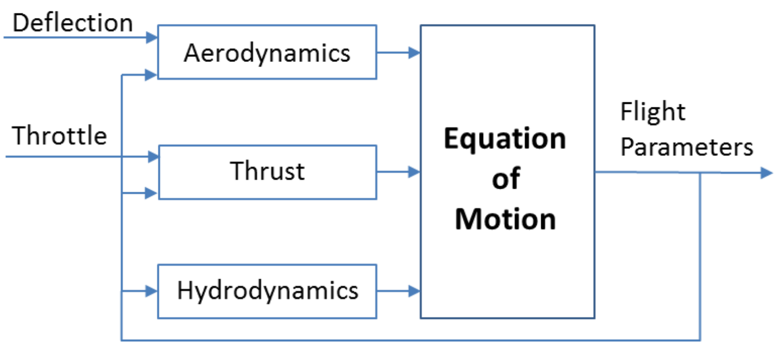

Figure 4 - Dynamic model of seaplane during water surface taxiing

2.1 Aerodynamic Model

For longitudinal, the lift, drag, and pitch moment coefficients can be obtained based on the linearized aerodynamic model [3]:

$$C_L = C_{L0} + C_{L\alpha}\alpha + C_{Lq}\bar{q} + C_{L\dot{\alpha}}\dot{\alpha} + C_{L\delta e}\delta_e \tag{1}$$

$$C_D = C_{D0} + C_{D\alpha}\alpha + C_{Dq}\bar{q} + C_{D\dot{\alpha}}\dot{\alpha} + C_{D\delta e}\delta_e \tag{2}$$

$$C_m = C_{m0} + C_{m\alpha}\alpha + C_{mq}\bar{q} + C_{m\dot{\alpha}}\dot{\alpha} + C_{m\delta e}\delta_e \tag{3}$$

Where, C_{L0}, C_{D0}, C_{m0} are the coefficients of lift, drag, and pitch moment with 0 angle of attack (AOA) and elevator deflection; $C_{L\alpha}, C_{D\alpha}, C_{m\alpha}$ are the derivatives of lift, drag, and pitch moment coefficients with respect to the AOA α; $C_{L\delta e}, C_{D\delta e}, C_{m\delta e}$ are the derivatives of lift, drag, and pitch moment coefficients with respect to elevator deflection δ_e; C_{Lq}, C_{Dq}, C_{mq} are the derivatives of lift, drag, and pitch moment coefficients with respect to $\bar{q}$

$$\bar{q} = \frac{q\bar{c}}{2V} \tag{4}$$

and $C_{L\dot{\alpha}}, C_{D\dot{\alpha}}, C_{m\dot{\alpha}}$ are the derivatives of lift, drag, and pitch moment coefficients with respect to $\bar{\dot{\alpha}}$.

$$\bar{\dot{\alpha}} = \frac{\dot{\alpha}\bar{c}}{2V} \tag{5}$$

2.2 Thrust Model

Seaplanes mainly perform tasks such as search, rescue, and firefighting. These tasks do not require high altitude and velocity but require long endurance. In addition, the water resistance is high during water surface taxiing. Therefore, seaplanes are usually equipped with turboprop powerplants.

The power available of turboprop powerplant

$$P_a = \eta_p P \tag{6}$$

Where, P is the power of the engine, η_p is the efficiency of propeller.

For a given altitude, power available doesn't vary with velocity, the thrust available

$$T_a = \frac{P_a}{V} \tag{7}$$

2.3 Hydrodynamic Model

According to the two-dimensional slicing method [4], the total hydrodynamic force is equal to the integral of the forces acting on the slice along the fuselage [5].

Hydrodynamic force

$$N_w = \int_{l_k} \left(f_s + f_{cfd} \right) dx_b \tag{8}$$

Buoyancy

$$F_b = \int_{l_w} f_b dx_b \tag{9}$$

Hydrodynamic pitching moment

$$M_{wd} = \int_{l_k} \left(f_s + f_{cfd} \right) x_b \cdot dx_b + \int_{l_k} f_b \cos\theta x_b \cdot dx_b \tag{10}$$

Where, f_b is the slice buoyancy, f_{cfd} is the slice crossflow resistance, and f_s is the slice hydrodynamic force.

By projecting the hydrodynamic force and buoyancy onto the body axis system, the forces generated by water along the x and z axis can be obtained.

$$\begin{aligned} F_{wx} &= -R_s \cdot \cos\theta - D_F + F_b \cdot \sin\theta \\ F_{wz} &= -R_z \cdot \sin\theta - N_w - F_b \cdot \cos\theta \end{aligned} \tag{11}$$

where, R_s is the splashing resistance, D_F is the frictional resistance, and θ is the pitch angle.

2.4 Dynamic Model of Seaplane during Water Surface Taxiing

By combining the forces and equation of motion, a longitudinal 3DOF dynamic model of a seaplane can be obtained [5].

$$\begin{cases} mqw + m\dot{u} = F_x \\ -mqu + m\dot{w} = F_z \\ \dot{q} = M / I_y \\ \dot{\theta} = q \\ \dot{x}_e = u\cos\theta + w\sin\theta \\ \dot{z}_e = -u\sin\theta + w\cos\theta \end{cases} \tag{12}$$

Where, F_x and F_z are the components of the total external force acting on the aircraft in the body axis system; M is the total pitch moment; m is the mass of the aircraft, I_y is the pitch inertia mass; q is the pitch rate; u and w are the forward and vertical velocity; x_e and z_e are the displacements of the aircraft along the Ox_b and Oz_b axes.

Based on the small disturbance theory, a linearized state space equation can be obtained:

$$\begin{bmatrix} \dot{u} \\ \dot{w} \\ \dot{q} \\ \dot{\theta} \\ \dot{z}_e \end{bmatrix} = \boldsymbol{A}_1^{-1}\boldsymbol{A}_2 \begin{bmatrix} u \\ w \\ q \\ \theta \\ z_e \end{bmatrix} + \boldsymbol{A}_1^{-1}\boldsymbol{B}_1 \begin{bmatrix} \delta_e \\ \delta_t \end{bmatrix} \tag{13}$$

where,

$$A_1 = \begin{bmatrix} m - a_{17} & -a_{18} & -a_{19} & 0 & 0 \\ -a_{27} & m - a_{28} & -a_{29} & 0 & 0 \\ -a_{37} & -a_{38} & I_y - a_{39} & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}, \quad B = \begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \\ b_{31} & b_{32} \\ 0 & 0 \\ 0 & 0 \end{bmatrix}$$

$$A_2 = \begin{bmatrix} a_{14} & a_{15} & a_{11} - m\omega_0 & a_{13} - \mathrm{mgcos}\theta_0 & a_{12} \\ a_{24} & a_{25} & a_{26} - mu_0 & a_{23} - \mathrm{mgsin}\theta_0 & a_{22} \\ a_{34} & a_{35} & a_{36} & a_{33} & a_{32} \\ 0 & 0 & 1 & 0 & 0 \\ -\sin\theta_0 & -\cos\theta_0 & 0 & -u_0\cos\theta_0 - \sin\theta_0 & 0 \end{bmatrix}$$

$$a_{ij} = \frac{F_i}{x_j}, \; b_{ik} = \frac{F_i}{u_k}$$

$$\boldsymbol{F} = \left[F_x, \, F_z, \, M\right]$$

$$\boldsymbol{x} = \left[x_e, \, z_e, \, \theta, \, u, \, w, q, \, du, dw, dq\right]^T$$

where, du and dw are the axial and normal accelerations under the body axis system, and dq is the pitch acceleration.

3. Dynamic stability and Control Law Design of Seaplane during Water Surface Takeoff

3.1 Dynamic Stability

The takeoff of a seaplane, as shown in Figure 8, staring from a stationary state, passes through the navigation, transition, taxiing and takeoff phases, and leaves the water surface when it reaches the get away velocity V_{ga}, and ending by climbing to an altitude of 10.7 meters (35 feet) above the water surface[7].

During the navigation phase, the weight of the aircraft is mainly balanced by buoyancy. As the velocity increases, the pitch angle and hydrodynamic resistance increases. During the transition phase, the pitch angle increases rapidly while the draft decreases. During the taxiing phase, the draft is shallow, and the main force acting on the bottom of the fuselage is the hydrodynamic lift acting on the forebody; During the takeoff phase, to achieve optimal aerodynamic lift, the pilot needs to pulling the control stick.

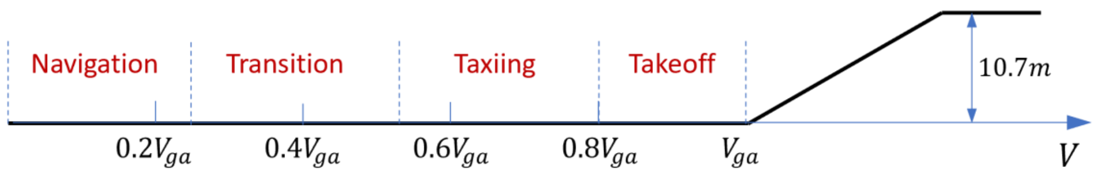

Figure 5 - Takeoff process of a seaplane

When the taxiing velocity is between $0.4V_{ga}$ and V_{ga}, the aircraft has a stability range of pitch angle. If the aircraft is disturbed within this range of pitch angle, the influences of the disturbance will quickly decay, and the aircraft will return to equilibrium state. However, if the disturbance is out of this range, porpoising may occur. As shown in Figure 6, for the same seaplane, the stable boundaries are different for different velocities. The stability boundary depends on the characteristics of the seaplane, and the larger the range between two boundaries, the better the stability [1][8].

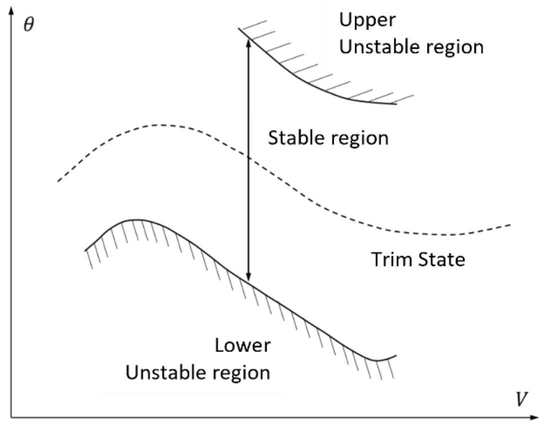

Figure 6 - Stability boundaries of seaplane during water surface taxiing

The stability boundaries can be determined through three methods: theoretical calculation, water tunnel test, and flight test.

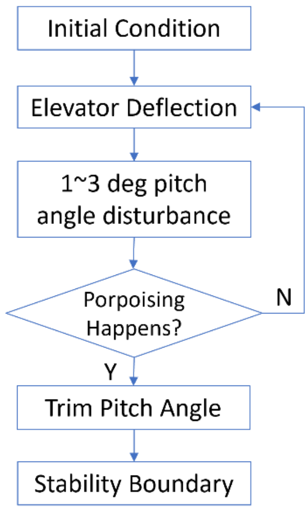

Figure 7 - Flow chart for determining stability boundaries

This paper determines the stability boundaries by numerical simulation of the water tunnel test method, as shown Figure 7. Firstly, set the initial equilibrium state; set the elevator deflection and apply a pitch angle disturbance of 1-3 degrees; conduct time-domain simulation and determine whether porpoising has occurred; If porpoising occurs, the determined pitch angle in that state will be the stability boundary; If porpoising does not occur, increase the elevator deflection and continue the simulation.

3.2 Control Requirement and Control Law

Seaplanes typically adopt a conventional stable configuration, and the tail volume ratio is slightly higher than that of conventional land-based aircraft, therefore, the short period frequency and damping ratio are usually sufficient. However, during water surface takeoff and landing, periodic "pitch and heave" motions may occur due to the influence of hydrodynamics, buoyancy, and waves.

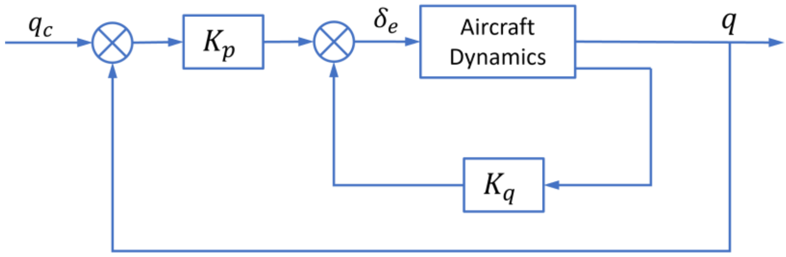

Figure 8 – Block diagram of proportional pitch rate command augmentation system

To control the pitch attitude, this paper adopts the pitch rate command augmentation system, as shown in Figure 8. The reason why integral command augmentation system was not adopted is that the aircraft dynamic model has certain errors, under the action of the integrator, the elevator will deflect, causing the steady-state error to approach 0, this additional control surface deflection may cause the aircraft to enter sustained oscillation.

4. Typical Example

4.1 Example aircraft

This paper takes a seaplane, as shown in Figure 9, as an example to verify the designed control law. The basic parameters of the seaplane are shown in Table 1.

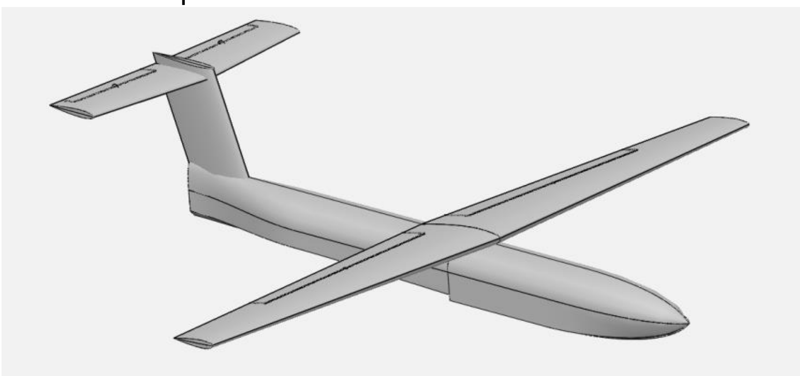

Figure 9 – General Configuration of the example aircraft

Table 1 - Basic parameters of the example aircraft

Parameter	Value	Unit
Weight	50000	kg
Wing Aera	170	m^2
Wingspan	39	m
Length	36	m
Mean Aerodynamic Chord	4.51	m
Engine Power	3100*4	kW
Propeller Efficiency	0.81	-
Pitch Inertia Mass	2217780	$kg \cdot m^2$
Get away velocity	53	m/s

4.2 Flight Control Law

According to the selected control law structure, this paper determines the pitch rate feedback gain K_q and proportional gain K_p at different velocities, as shown in Table 2.

As the velocity increases, K_q decreases linearly first. At a velocity of 36.4m/s, K_q increases suddenly, and then decreases gradually. As the velocity increases, K_p also decreases linearly first, increases suddenly at a velocity of 36.4m/s, and then increases linearly.

The reason why both gains change suddenly at 36.4m/s is that, at this velocity, the aircraft's rear body is out of water, and the nose-down pitching moment caused by the rear body hydrodynamic force will disappear, resulting in a sudden change in the aircraft's dynamics model.

Table 2 – Control gain at different velocities

Velocity(m/s)	K_q	K_p
28	-2.011	-19.306
30.5	-3.410	-22.826
33	-4.957	-26.037
35.5	-5.913	-26.360
36.4	-6.349	-28.119
36.5	-0.550	-24.232
38	-0.611	-23.208
40.5	-0.625	-20.485
43	-0.634	-18.160
48	-0.712	-14.625
53	-0.942	-12.080

4.3 Effects of Control Law

The trimmed pitch angle and stability boundary during water surface taxiing of the seaplane without and with control law are shown in Figure 10 and Figure 11, respectively.

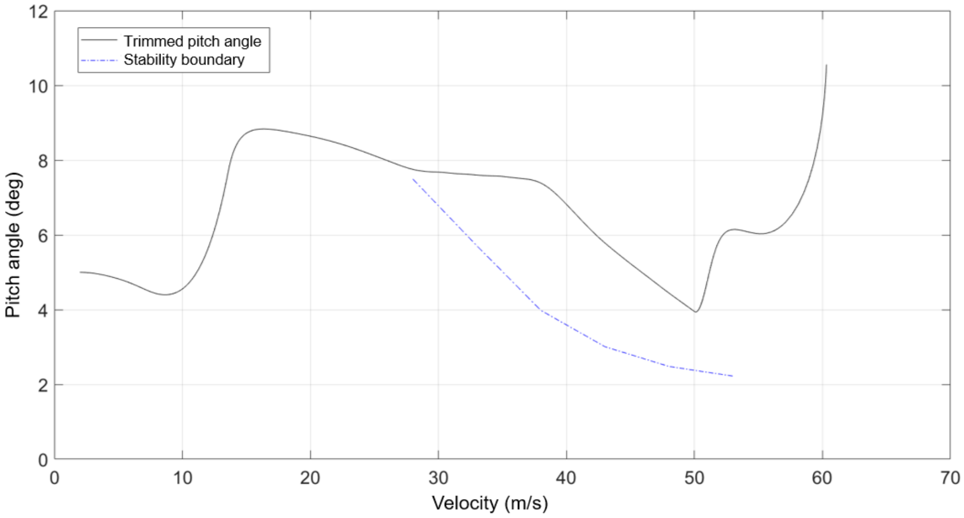

Figure 10 - Trimmed pitch angle and stability boundary of seaplane without control law

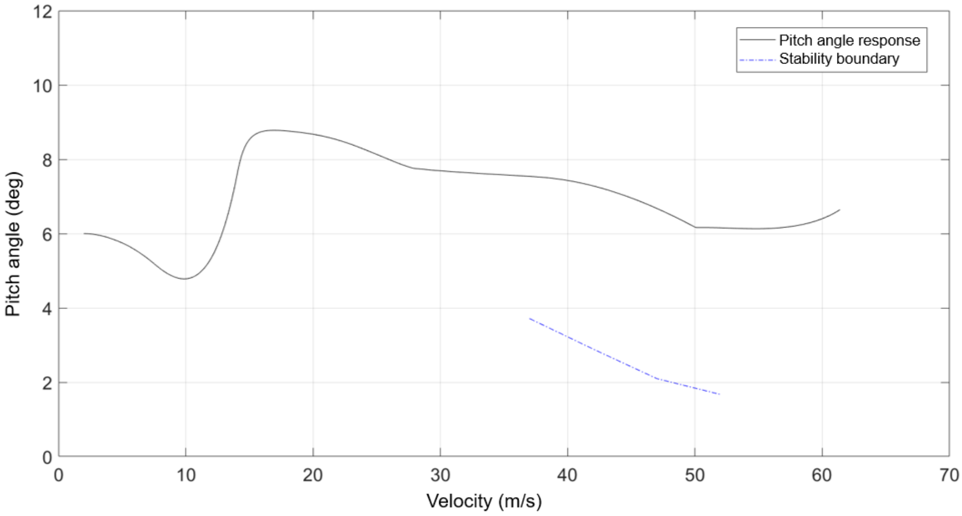

Figure 11 - Trimmed pitch angle and stability boundary of seaplane with flight control law.

By comparison, it can be seen that, as the velocity increases, the trimmed pitch angle of seaplane with control law is much smoother than that of seaplane without control law, indicating that the designed control law can effectively improve the handling quality during high-speed water surface taxiing.

The distance between the trimmed pitch angle and stability boundary of seaplane with control law is larger than that of seaplane without control law, indicating that the stability margin of seaplane is higher, i.e., the control law can improve stability during water surface taxiing.

5. Conclusion

During water surface takeoff, seaplanes may experience porpoising which affects flight safety. To improve the stability and safety of seaplane during takeoff, this paper built a dynamic model and designed a control law. The simulation results show that the designed control law can improve the stability of seaplanes during medium to high velocity taxiing, but at low speeds, the control law does not have a significant effect due to the low control surface aerodynamic efficiency.

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7. Copyright Statement

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