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CHAPTER 5

Flying a Foiling Boat Between a Slamming Hull and a Ventilating Foil

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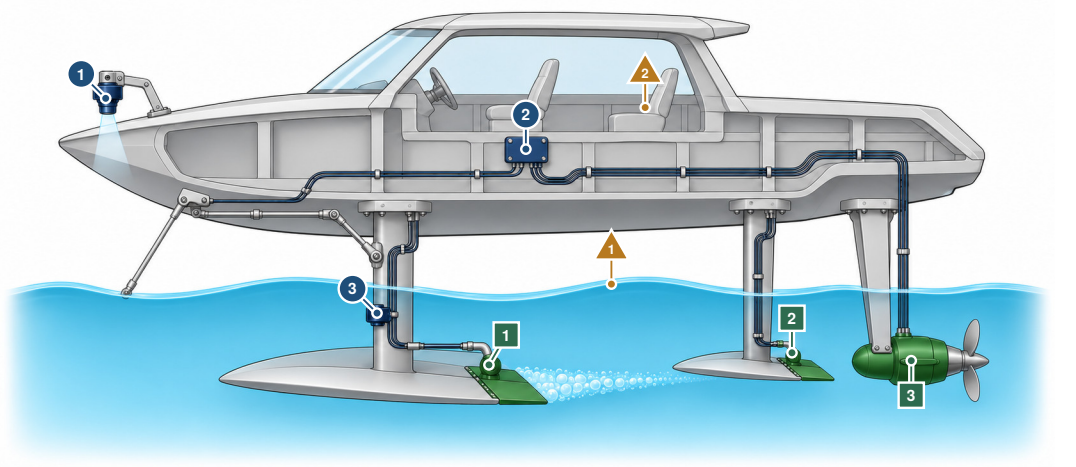
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CHAPTER 5

Flying a Foiling Boat Between a Slamming Hull and a Ventilating Foil



The controller moves 1 flap on the main foil 2 flap on the rear foil 3 pod motor and propeller

The controller reads 1 ultrasonic height sensor at the bow 2 inertial unit 3 speed log

What disturbs it 1 waves 2 a passenger walking aft

Notice the narrow band between the hull above the waves and the main foil below them, and the bubbles behind that foil, a hint of the air it draws when it flies too high. Illustration, not to scale.

IN PLAIN TERMS **Flying a Boat on Underwater Wings**

The main idea. A foiling boat rides on small wings under the water, so its hull flies above the waves. A controller tilts a flap on the main wing to hold the boat at the right height.

The challenge. Too low, the hull smacks into a wave, and too high, air reaches the wing and takes most of its lift. The controller must choose which waves to follow and which to ride over, and big waves are a reason to stop flying.

Why it matters. A wrong choice ends the flight in a crash, and a right one gives a smooth ride.

THREE WAYS TO READ THIS CHAPTER

Explore	12 min	the first page, the fact on a racing dinghy in the Introduction, the two history segments (Section 5.2), the try-it segments of cases 6 and 9 and the fact on the challenge (Section 5.6), and the key points
Study	50 min	the whole chapter with its three pause points and the twelve exercises at its end
Practice	20 min	the first page, the measured cases (Section 5.6), Technology in Practice (Section 5.7), Limitations (Section 5.8) and the open challenge

The control question A foiling boat flies in a band fixed by its struts, with a slamming hull below and a ventilating foil above, while the waves it meets are not fixed at all. Which waves should its height loop ride over level and which should it follow, and when is the right decision to stop flying?

Learning objectives

- Derive the free height stiffness from the surface factor and explain why a deep foil leaves the height an integrator.
- Compute the encounter frequency of a sea met from astern and from ahead, and use it with the band to choose between platforming and contouring.
- Explain a mechanical wand as a proportional loop whose linkage ratio is its gain and whose length is its setpoint.
- Compare a PID, a heave-rate cascade and an MPC with a preview on the same sea, and judge what the preview and the retuning are each worth.
- State the loop action of the height and pitch loops in the convention of Chapter 1.

Prerequisites Sections 1.3 (loop action), 1.4.3 (nested loops), 1.4.6 (complementary filter with a bias state, wave motion), 1.6.2 (velocity-form PID) and 1.6.4 (scenarios and the challenge). Section 1.6.3 is needed only for the MPC.

The app https://apmonitor.com/apps/hydrofoil-boat/

See also Volume 3, Chapter 2 for choosing an inner loop by where a disturbance enters and Volume 3, Chapter 3 for how fast an inner loop must be. Volume 5, Chapter 13 for inertial navigation through a lost measurement. Chapter 6 for wave motion that is real and not an error.

5.1 Introduction

At 20 kn the simulated launch flies with the keel at its bow 0.50 m above the water and its main foil 0.40 m under the surface, on a flap of 0.50° and 17.7 kW from the motor. Let the foil rise 0.30 m and it is within 0.3 chords of the surface, where air reaches it and it keeps 30 % of its lift. Let the boat sink 0.50 m and the keel is in the water at flying speed. The usable band is 0.80 m tall. In the 0.5 m sea of case 6, met from astern, a loop that holds the boat level over the waves lets a trough uncover the main foil, which ventilates at 11.20 s, and the hull slams into the next crest at 11.65 s. The same loop told to follow the surface flies the case's 40 s without either event, at a vertical acceleration of 2.67 m/s^2 at the passenger's seat.

Three beliefs about flying on foils are contradicted by the cases. The first is that a submerged wing has no height of its own. Near the surface it does, because lift falls as the foil rises: with the main foil 0.15 m deep the boat answers a lost 0.8 kN of lift by sinking 4.2 cm and staying there. The free height stiffness at that depth is 24.0 kN/m, while with the foil 0.70 m deep it is 0.39 kN/m and the hull is back in the water within 5 s. The second is that a good height loop rejects the waves. Whether it should depends on how fast the boat meets them, which sets whether a wave can be followed at all, and on how tall they are against the band. The third is that enough tuning flies any sea. In a 1.4 m sea from ahead, 33 795 settings tried at 20 kn flew no longer than 12.49 s of the minute asked.

The plant belongs to a wider class, lift surfaces that work near a boundary which removes their lift. Wing-in-ground-effect craft fly close over the water on a lift that depends on their height above it [1], and surface-piercing and fully submerged hydrofoils trade the free stiffness of the boundary against exposure to the waves [2, 3]. Ventilation is a change of flow regime with a region where both regimes are stable [4], and it bears on the safety and controllability of any lifting surface near a free surface [5]. The choice between holding a body still and letting it follow the terrain is a central trade of active vehicle suspension [6], and blending a position sensor with an inertial one through complementary filters is a long-established estimator [7].

DID YOU KNOW? A Racing Dinghy on a Wand

A class of one-person racing dinghy that flies on hydrofoils is described as the fastest one-person dinghy in the world, yet its rules cap the boat at 3.355 m in length, 2.25 m in beam and 8.25 m^2 of sail. A mechanical wand at its bow holds the ride height [8], as in case 4.

However, the hydrodynamics, the ventilation physics and the motion control of hydrofoil craft are reported in separate literatures [4, 9–11], and none of them lets a student fly the boat. This chapter measures what a mechanical wand, a proportional-integral-derivative (PID) loop and a heave-rate cascade can and cannot do for a foiling boat whose lift falls near the surface and collapses at it, on a browser simulator in which the boat, the sea, the instruments and the controllers share one model. The rigid-body equations, the Pierson–Moskowitz sea, the complementary filter and the PID law are established methods.

Section 5.2 follows the domain. Section 5.3 gives the boat and the sea as a nine-state model whose hard events are located inside the integration step, with a split between plant and instruments under which no law sees the true foil depths, and with the full set of equations and defaults needed to rebuild the boat. Section 5.4 shows that the free height stiffness falls by a factor of 62 between 0.43 and 2.0 chords of depth, and that the band between slam and ventilation decides the platform-or-contour choice only together with the encounter frequency. Section 5.5 describes the wand, the observers, the PID, the cascade, the fallback, the takeoff sequencer and an optional model predictive controller (MPC) with a preview. Section 5.6 reports ten cases and a challenge, each credited in the app by a completion rule. There the same contouring structure is clean on 7 of 17 draws of a sea under the PID and on all 17 under the cascade, and in a sea 1.75 times the band no setting in two searches of 33 795 each flies the minute. A cascade retuned by the MPC's own rule flies the 0.65, 0.8 and 1.0 m following seas clean at 0.93, 1.01 and 1.04 m/s^2, where the MPC rides 1.00 and 1.16 and ventilates. Section 5.7 names the height sensor, the flap servos and the ride control computer of real craft, and Sections 5.8 and 5.9 state the limitations and the conclusions.

5.2 Hydrofoils, Their Surface and Their Controllers

Hydrofoil craft were built and flown early in the twentieth century, and a survey of their development published by the American Society of Naval Engineers in 1985 runs to 58 pages [12]. Two families emerged. Surface-piercing foils cross the surface at an angle, so a boat that rises wets less foil and loses lift, and the height control is in the geometry. Fully submerged foils run below the surface, where the waves disturb them less, but they have no such geometric restoring force and fly only under an automatic control system [2, 3]. The simulated launch belongs to the second family, with a remnant of the first: the proximity loss that the surface imposes on a submerged foil.

HISTORY Measuring the Surface Loss (1955 and 1959)

A National Advisory Committee for Aeronautics report of 1955 investigated, in theory and experiment, how the free water surface changes the lift and drag of hydrofoils of aspect ratio 10 and 4. It found the agreement between theory and experiment satisfactory for engineering estimates of hydrofoil characteristics from aerodynamic data [9]. Ventilation was studied at the same time on surface-piercing struts, where cavities open to the atmosphere develop, and the conditions for their existence could be derived from the measurements. The same study concluded that further experiments were needed to define the inception of ventilation as a function of the boundary-layer state or the Reynolds number [13].

That loss, and the ventilation of struts near the surface, were first measured in the 1950s, as the history box above tells. Modern towing-tank experiments on a surface-piercing hydrofoil identify fully wetted, partially ventilated and fully ventilated regimes whose stability regions overlap, so that the flow shows hysteresis: ventilation forms when air reaches separated flow at sub-atmospheric pressure, and it is washed out by a re-entrant jet [4]. A review of ventilating lifting bodies sets out

the scaling that model tests must respect, among them the Froude and cavitation numbers [5]. The simulator's latch is a teaching caricature of that hysteresis, not a fit to it.

Control of fully submerged foil craft became a design subject of its own. A model of a fully submerged hydrofoil craft was flown under longitudinal motion control in following seas in experiments [10], the same authors designed a longitudinal controller around an optimal preview servo system [14], and the control of the vertical motion of a hydrofoil vessel has been treated as a design problem of its own [11]. The seakeeping, slamming and hydrofoil chapters of a monograph on high-speed marine vehicles connect the loads to automatic control [3]. A different line runs through small sailing craft. A racing dinghy class adopted hydrofoils and renewed interest in foiling, with full-scale tow tests of its T-foils and hull [15], and its hydrofoil control system is now tested on a full-scale rig [8]. The simulator's wand is a mechanical height control in the spirit of those small craft, a stick on the water linked to the flap. The irregular sea is the Pierson–Moskowitz spectrum of a fully developed wind sea [16], and passenger comfort is judged against the literature on whole-body vibration [17].

> ⧖ HISTORY **Feelers on the Water (1930s to 1960)**
>
> Before electronics, fully submerged foils were held at their depth by mechanical feelers on the water. One pioneer chose submerged foils to get away from the disturbing influence of the surface in waves, and tried several mechanical depth feelers on six test boats over eight years. They worked in calm water but not in slight seas, and he turned to surface-piercing foils instead. Another inventor showed a small craft at a boat show in New York in 1951. The forward feeler of his system sensed the oncoming waves ahead of the foils. Its spring-loaded heel smoothed out small waves while its buoyant float answered the larger ones. The United States Navy completed its evaluation of the most sophisticated mechanically controlled hydrofoil in 1960, by which time electronic control was well under way [18].

5.3 The Boat and the Sea as Modeled

The launch is a generic design with teaching values throughout, as shown in Figure 5.1. A main foil of 0.8 m^2 and chord 0.35 m sits under the center of mass and carries the weight. A rear foil of 0.25 m^2 and chord 0.25 m, 2.6 m aft, is the stabilizer and carries almost nothing in trim, so the main foil alone fixes the takeoff speed. Both hang 0.90 m below the keel on struts, and each has a flap. An electric pod on the rear strut drives the boat, an ultrasonic sensor at the bow measures the ride height, an inertial measurement unit (IMU) measures pitch, pitch rate and vertical acceleration, a log measures speed, and a wand pivoted at the bow trails forward to the water. The frame has x forward and z up from the mean water line, and the pitch θ is positive bow up.

Each variable carries its role in Table 5.1. Nine states are integrated: the position along the course x and the speed V, the height z of the center of mass and its rate w, the pitch θ and its rate q, the two flaps δ_f and δ_r, and the delivered thrust T. The ventilation latches, the hull's contact with the water and the slam count are discrete states kept between steps.

5.3.1 Rigid-Body Motion

The boat moves in surge, heave and pitch under the foil forces, the hull's contact forces, the thrust and the weight, as shown in Equation (5.1).

$$\begin{aligned} m\dot{V} &= T - D_f - D_r - R_{hull} - D_{air} \\ m\dot{w} &= L_f + L_r + F_{hull} - mg \\ I_{yy}\dot{q} &= \textstyle\sum_j \left(r_{x,j} F_{z,j} - r_{z,j} F_{x,j} \right) \\ r_x &= x_b \cos\theta - z_b \sin\theta, \quad r_z = x_b \sin\theta + z_b \cos\theta \end{aligned} \tag{5.1}$$

where $\dot{x} = V$, $\dot{z} = w$, $\dot{\theta} = q$, and the sum runs over the two foils, their struts, four hull stations and the pod, each at its body offset (x_b, z_b) from the center of mass rotated into the world frame. The center

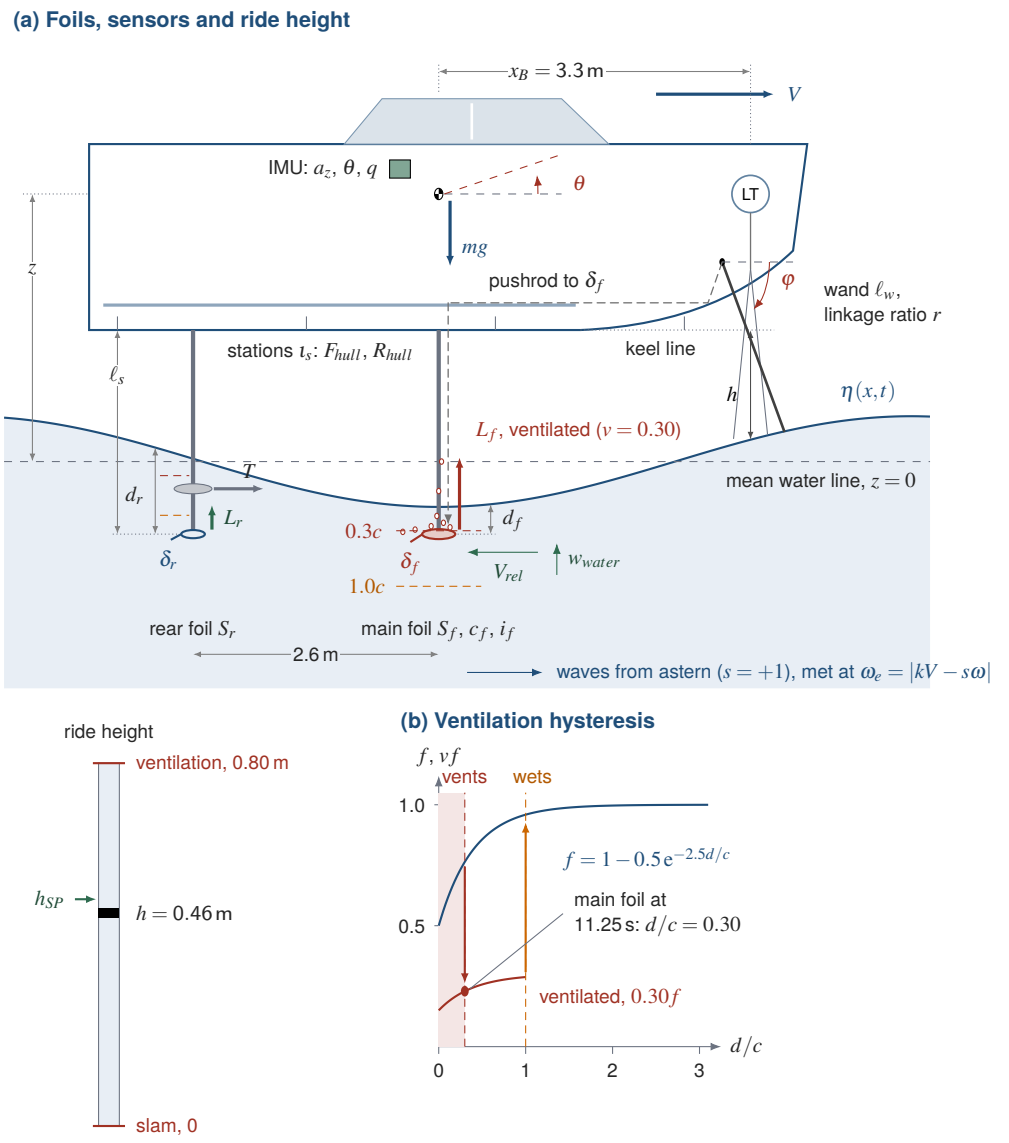


Figure 5.1 (a) The launch as the Sea view draws it at the ventilation of case 6 (platforming, $t = 11.25$ s). The center of mass at height z and pitch θ carries the weight mg and the IMU. The main foil, in a trough at depth d_f under the local surface $\eta(x,t)$, has passed its ventilation depth $0.3c$ and keeps $v = 0.30$ of its lift L_f until it is deeper than $1.0c$, while the rear foil at depth d_r makes L_r. Each foil sees the water at V_{rel} with the orbital velocity w_{water} and carries a flap, δ_f or δ_r. The pod gives the thrust T at speed V. The bow sensor LT measures the ride height h of the keel line above the water, shown on the gauge at lower left between a slam (0) and a ventilation (0.80 m) with its setpoint h_{SP}. The wand of length ℓ_w at angle φ moves the main flap through a pushrod of ratio r. (b) The declared surface factor $f(d/c)$ with its ventilated branch and the two hysteresis arrows. Vertical scale exaggerated and the boat drawn level. Not to scale.

of mass is 0.60 m above the keel, the foils $\ell_s + 0.60\,\text{m} = 1.50\,\text{m}$ below it and the pod 1.45 m below it. A passenger of 85 kg who walks x_p aft moves every body offset by $85x_p/m$, 5.3 cm per meter walked.

Table 5.1 Variables by Role, With Their Values in Trim at 20 kn and 0.5 m

Variable	Role	Trim	Range
h	CV, ride height at the bow	0.50 m	SP 0.1–0.9 m
θ	CV, pitch	0°	SP −3 to 5°
V	CV, speed	20 kn	SP 0–30 kn
δ_f	MV, main flap	0.50°	±15°
δ_r	MV, rear flap	0.12°	±10°
u_T	MV, throttle	29.6 %	0–100 %
H_s	DV, significant wave height	0	0–1.4 m
—	DV, wake, spray, gust, slowdown	events	—
x_p, w_d	DV, passenger aft, weed	0, 0	0–4 m, 0–40 %
z, w	states, heave	1.10 m, 0	—
θ, q	states, pitch	0, 0	—
x, V	states, surge	—, 10.29 m/s	—
T	state, thrust	1035 N	$\le T_{avail}(V)$
d_f, d_r	outputs, foil depths	0.40 m, 0.40 m	truth only
a_{seat}	output, seat acceleration	0	rms scored

5.3.2 Foil Lift Near the Surface

Each foil makes a lift from the speed of the water past it, its effective angle, the surface factor and the ventilation factor, as shown in Equation (5.2).

$$\begin{aligned} L_i &= \tfrac{1}{2}\rho V_{rel}^2 S_i C_{L\alpha}\,\mathrm{sat}_{\alpha_s}(\alpha_{e,i})\, f(d_i/c_i)\, v_i \\ \alpha_{e,i} &= \theta + i_i + k_\delta \delta_i + (w_{water} - \dot{z}_i)/V_{rel} \\ f(d/c) &= 1 - A_s\, \mathrm{e}^{-B_s d/c} \\ D_i &= \tfrac{1}{2}\rho V_{rel}^2 S_i \left(C_{D0} + \frac{(C_L f v)^2}{\pi AR_i\, e} \right) \end{aligned} \tag{5.2}$$

where d_i is the depth of foil i under the local surface, $V_{rel} = \max(0.5,\ \dot{x}_i - u_{water})$ is the speed of the water past it with the orbital velocities u_{water} and w_{water} taken at its depth, $\dot{z}_i$ is the foil's own vertical velocity, sat_{α_s} caps the angle at the stall $\alpha_s = 8°$, $AR_i = S_i/c_i^2$ and $e = 0.85$. The heave rate in α_e is the foil's natural damping, and each strut adds a drag of $\frac{1}{2}\rho V_{rel}^2 (0.2\,\mathrm{m})\, 0.012$ per meter wetted. The surface factor, with $A_s = 0.5$ and $B_s = 2.5$, is 0.697 at 0.2 chords, 0.857 at 0.5, 0.959 at 1 and 1.000 at 3. It is a declared teaching form with the shape of the measured free-surface loss [9] and has not been fitted to any data. Weed on the main foil multiplies its lift coefficient by $1 - w_d$ and adds $0.03\, w_d$ to its profile drag.

5.3.3 Ventilation as a Latch

The ventilation factor is a latch with hysteresis, as shown in Equation (5.3).

$$v_i = \begin{cases} 0.30 & \text{latched: set if } d_i < 0.3c_i,\ \alpha_{e,i} > \alpha_v \\ & \text{and cleared if } d_i > 1.0c_i \\ 0 & d_i \le 0 \text{ (out of the water)} \\ 1 & \text{otherwise} \end{cases} \tag{5.3}$$

where $\alpha_v = 2°$. For the main foil the latch sets shallower than 0.105 m and clears deeper than 0.35 m. The latch is evaluated after each integration step, with the crossing instant interpolated inside the step, so the right-hand side stays smooth within a step. The thresholds and the retained fraction are teaching values. Real ventilation depends on the strut, the speed, the cavitation number and the history of the flow [5, 13].

5.3.4 The Hull, the Hump and the Slam

The hull is a V-bottom of 20° deadrise represented by four buoyant stations, and its resistance scales with the weight it still carries, as shown in Equation (5.4).

$$\begin{aligned} F_{hull} &= \textstyle\sum_{s=1}^{4} \max\left(0,\ K_b \iota_s^2 + C_b\, \iota_s \dot{\iota}_s\right) \\ R_{hull} &= F_{hull}\left(0.25\, Fn^2 + r_h\, \mathrm{e}^{-((Fn-0.45)/0.15)^2}\right) \\ Fn &= V/\sqrt{g\, L_h} \\ D_{air} &= \tfrac{1}{2}\rho_a C_a A_a\, V|V| \end{aligned} \tag{5.4}$$

where ι_s is the immersion of station s below the local surface, $K_b = 55\,300\,\mathrm{N/m^2}$, $C_b = 10\,300\,\mathrm{N\,s/m^2}$, $L_h = 7.4\,\mathrm{m}$, $r_h = 0.10$, and $\rho_a C_a A_a = 1.2 \times 2.4\,\mathrm{m^2}$. Because the resistance falls as the foils unload the hull, the sum of hull and foil drag peaks before takeoff. A run is foilborne once the hull has been clear of the water for 0.5 s. Five keel points are watched, and one that enters the local surface while the boat is foilborne at a closing speed above $v_{slam} = 0.5\,\mathrm{m/s}$ is a slam, located inside the step, which ends the clean run and pauses the simulation. A slower contact is a touchdown. The slam speed is a teaching value. Real slamming loads come from the high-speed craft rules of the classification societies and from the analyses that underlie them [3].

5.3.5 Actuators

The flaps and the thrust follow their commands through lags and limits, as shown in Equation (5.5).

$$\begin{aligned} \dot{\delta}_i &= \mathrm{clip}\left(\frac{\mathrm{clip}(\delta_{i,cmd}, \pm\delta_{i,max}) - \delta_i}{\tau_s},\ \pm\dot{\delta}_{max}\right) \\ \tau_T \dot{T} &= u_T\, T_{avail}(V) - T \\ T_{avail} &= \min\left(T_{max},\ \eta P_{max}/\max(1, V)\right) \end{aligned} \tag{5.5}$$

where $\tau_s = 8\,\mathrm{ms}$ is a 20 Hz servo, $\dot{\delta}_{max} = 60^\circ/\mathrm{s}$, $\tau_T = 0.3\,\mathrm{s}$, and the delivered thrust is $\min(T, T_{avail})$. The thrust limit of 4.5 kN binds below 8.00 m/s and the power limit of 60 kW with $\eta = 0.6$ above it.

5.3.6 The Sea

The sea is a long-crested sum of sixteen linear waves on deep water, from astern ($s = +1$) or ahead ($s = -1$), as shown in Equation (5.6).

$$\begin{aligned} \eta(x,t) &= \textstyle\sum_k a_k \cos\psi_k, \quad \psi_k = k_k x - s\,\omega_k t + \phi_k \\ S(\omega) &= \tfrac{5}{16} H_s^2\, \omega_p^4\, \omega^{-5}\, \mathrm{e}^{-1.25(\omega_p/\omega)^4} \\ a_k &= \sqrt{2S(\omega_k)\Delta\omega_k}, \qquad k_k = \omega_k^2/g \\ (u,w)_{water} &= \textstyle\sum_k s\, a_k \omega_k\, \mathrm{e}^{k_k z}(\cos\psi_k,\ \sin\psi_k) \\ \omega_e &= |kV - s\,\omega| \end{aligned} \tag{5.6}$$

where $\omega_p = 2\pi/T_p$ with $T_p = c_T\sqrt{H_s}$ and $c_T = 5.0\,\mathrm{s/m^{1/2}}$, the orbital velocities are taken at depth z, and ω_e is the frequency at which a boat at speed V meets a wave of frequency ω. The frequencies lie on a geometric grid from 0.9 to 5 rad/s, jittered inside each band, and the phases come from the scenario's seed. The spectrum is the Pierson–Moskowitz form [16], and the amplitudes are rescaled so that the variance is exactly $(H_s/4)^2$. A boat at 20 kn meets the peak of a 0.5 m sea from astern at 1.54 rad/s and from ahead at 5.09 rad/s, the peak of a 0.2 m sea from astern at 5.47 rad/s and that of a 1.4 m sea from ahead at 2.25 rad/s. A new sea state is approached at 0.3 m per minute with the phases continuous, a run that starts foilborne fades its sea in over 3 s, and a wake is one extra wave train of period 4 s under a Gaussian envelope of 2 s.

Table 5.2 Model Parameters. H Marks the Hidden Ones, and the Rest Are Adjustable

Symbol	Meaning	Value	Unit
m, I_{yy}	mass, pitch inertia	1600, 4500	kg, kg m^2
z_K	center of mass above the keel (H)	0.60	m
ℓ_s	strut, keel to foil	0.90	m
x_B	bow sensor ahead of mass center (H)	3.3	m
ρ, g	density, gravity (H)	1025, 9.81	kg/m^3, m/s^2
S_f, c_f, i_f	main foil area, chord, incidence	0.80, 0.35, 4	m^2, m, °
x_f	main foil ahead of mass center (H)	0	m
S_r, i_r	rear foil area, incidence	0.25, 0	m^2, °
c_r, x_r	rear foil chord, position (H)	0.25, −2.6	m
$C_{L\alpha}$, α_s	lift slope, stall angle	5.0, 8	rad^{-1}, °
k_δ, C_{D0}	flap effectiveness, profile drag	0.5, 0.008	—
A_s, B_s	surface loss at the surface, decay	0.5, 2.5	—, per chord
d_v, d_w	ventilates, wets again	0.3, 1.0	chords
α_v, v	ventilation angle, lift kept	2, 0.30	°, —
$\delta_{f,max}$, $\delta_{r,max}$	flap limits	15, 10	°
τ_s, $\dot{\delta}_{max}$	servo lag, rate limit	8, 60	ms, °/s
T_{max}, P_{max}, η	thrust, power, efficiency	4.5, 60, 0.6	kN, kW, —
τ_T	thrust lag	0.3	s
K_b, C_b	station buoyancy, damping (H)	55300, 10300	N/m^2, N s/m^2
r_h, v_{slam}	hump height, slam speed	0.10, 0.5	—, m/s
k_n	instrument noise multiplier	1	—
c_T	peak period per $\sqrt{H_s}$	5.0	s/m$^{1/2}$
—	sea build rate	0.3	m/min

5.3.7 Instruments

The controllers read a packet and nothing else. The bow sensor reports the height of the keel line above the water under the bow, $h_m = h + n_h$, with colored noise of 1 cm standard deviation, and reports nothing for the spray time after a spray event. The IMU reports the pitch ($\pm 0.05°$), the pitch rate ($\pm 0.1\,°/\mathrm{s}$) and the vertical acceleration ($\pm 0.02\,\mathrm{m/s^2}$ plus a bias of $0.02\,\mathrm{m/s^2}$), and the log reports the speed ($\pm 0.05\,\mathrm{m/s}$). Each noise is a first-order filtered Gaussian from the seeded generator, so a run repeats exactly after Reset. The wand is a mechanism, not an instrument: its angle below the horizontal is the one at which a stick of length ℓ_w from a pivot 3.0 m ahead of the center of mass and 0.30 m above the keel reaches the local surface, without noise. The true foil depths, the ventilation state, the sea, the weed and the passenger never reach a controller.

5.3.8 Parameters and Numerics

Every parameter appears in Table 5.2. Hidden parameters fix the geometry and are not shown, while the others are adjustable in the Parameters panel. Integration uses fourth-order Runge–Kutta on a fixed step of 2 ms, the controllers execute every 20 ms, and samples are logged at 50 Hz. At half the step the first ventilation of case 6 moves from 11.1985 s to 11.1987 s and its slam from 11.6470 s to 11.6444 s, and the slam of case 9 from 6.1421 s to 6.1418 s. A foilborne start is trimmed in calm water by Newton iteration on the two flaps and the thrust, and a start at rest floats on the hull.

5.3.9 Assumptions

The boat moves in surge, heave and pitch only, running straight into or away from a long-crested sea, so roll, yaw, leeway and oblique waves are absent. The lift is quasi-steady, with no unsteady lift lag, no added mass and no downwash from the main foil onto the rear one, which is least defensible at the 2.6 Hz wand oscillation of case 4. The surface factor and the ventilation latch are declared forms, and the ventilated flow has no partial regime and no dependence on speed. The waves are linear and do not break, and the boat does not change them. The hull has buoyancy and damping but no planing lift, so its contribution near takeoff is approximate, and its resistance curve is declared. The slam speed and the comfort limit are teaching values.

Table 5.3 Free Height Stiffness at 20 kn in Calm Water (Case 3 Geometry)

h (m)	d_f (m)	d_f/c_f	Stiffness (kN/m)	Damping (kN s/m)	τ (s)
0.75	0.15	0.43	24.00	23.3	1.0
0.50	0.40	1.14	3.43	27.0	7.9
0.20	0.70	2.00	0.39	27.6	70.5

5.4 Dynamic Character of the Flying Boat

5.4.1 Takeoff Speed and the Hump

The main foil at its stall angle, 1.5 chords deep, carries the 15.70 kN weight from the takeoff speed of Equation (5.7), which is 14.48 kn.

$$V_{to} = \sqrt{\frac{mg}{\frac{1}{2}\rho S_f C_{L\alpha} \alpha_s f(1.5)}} = 7.449\,\mathrm{m/s} \tag{5.7}$$

At the stall it can lift 10.2 kN at 6 m/s, 18.1 kN at 8 m/s and 40.7 kN at 12 m/s, where the boat trimmed with the foil 1.5 chords deep flies at 3.06° of effective angle. In trim at 0.5 m the main flap moves from 5.30° at 16 kn to 0.50° at 20 kn and –2.11° at 24 kn, while the power rises from 13.2 to 17.7 and 25.7 kW, and the ratio of weight to thrust falls from 16.3 to 12.6. With the main flap held at 15°, as the takeoff sequencer holds it, the steady resistance peaks at 2253 N at 8.0 kn (a Froude number of 0.48), falls to 1804 N at 11.0 kn, and the hull clears the water at 12.5 kn. Below 8 m/s the pod delivers 4.5 kN at full throttle, so 50 %, 2250 N, stops short of the hump and 55 % passes it.

5.4.2 A Stiffness the Surface Gives and Takes Away

A small rise of the boat brings the main foil closer to the surface and lowers f, so the lift falls and the boat sinks back. The slope of the lift against height is the free stiffness, and the heave rate in α_e supplies a damping. Both are measured at 20 kn in calm water by perturbing the trimmed state, as listed in Table 5.3. The stiffness falls from 24.0 to 0.39 kN/m between ride heights of 0.75 and 0.2 m while the damping stays between 23 and 28 kN s/m, so the time constant of the free height grows from 1.0 s to 70.5 s. Deep, the height is in effect an integrator of the lift error.

🕮 **Pause.** Try Exercise 5.2 before reading on.

The stiffness does not make the boat stable on its own. With both flap commands and the throttle fixed, the linearization at 20 kn and 0.5 m has eigenvalues at $0.085\,\mathrm{s}^{-1}$ and $0.148 \pm 0.437j\,\mathrm{s}^{-1}$, and at 16 kn at $0.126\,\mathrm{s}^{-1}$ and $0.209 \pm 0.357j\,\mathrm{s}^{-1}$, because height, drag and speed are coupled through the hull and the thrust. Released from the 16 kn trim with the flap moved by 0.05°, the boat reaches 0.616 m at 5 s and is back on its hull by 20 s. Every case therefore runs with some loop closed, if only the pitch and speed loops.

5.4.3 The Band and the Encounter Frequency

The ride height is defined at the bow sensor as the height of the keel line above the water there. In calm level flight the keel touches at $h = 0$ and the main foil reaches 0.3 chords at $h = \ell_s - 0.3c_f = 0.795$ m, so the band is 0.80 m. In waves the surface under the bow and under the foil differ, and the band is a statement about the wave height measured from crest to trough against 0.80 m. Platforming holds the boat level and lets the waves pass between hull and foil, which works while they are smaller than the band. Contouring follows the surface, which works while they come slower than the loop can move the boat. From astern the boat overtakes the long waves of a large sea and meets them slowly, 1.54 rad/s for the 0.5 m sea of case 6, while the short waves of a small sea arrive fast, 5.47 rad/s for a 0.2 m sea. From ahead every wave is met faster.

5.5 Implemented Control System

Every law runs every $\Delta t_c = 20\,\text{ms}$ on the packet of the previous section. The height loop drives the main flap, the pitch loop the rear flap and the speed loop the throttle. The header's Manual mode gives all three stations to the student, and the Hand height controller gives only the main flap while the pitch and speed loops keep running. Every law tracks its station when it is not in command, so Manual to Auto and a change of structure are bumpless.

5.5.1 The Wand

The wand is a proportional controller made of a stick and a pushrod, as shown in Equation (5.8).

$$\delta_f = \delta_n - r(\varphi - \varphi_n), \qquad \frac{\partial \delta_f}{\partial h} \approx -\frac{r}{\ell_w \cos\varphi} \tag{5.8}$$

where φ is the wand's angle below the horizontal, $\delta_n = 0.5^\circ$ is the trim flap at 20 kn, $\varphi_n = 53^\circ$ and the linkage ratio r (default 0.6) is the gain per degree. The boat settles where the flap holds the weight, which at 20 kn is near φ_n, so the pivot flies about $\ell_w \sin\varphi_n$ above the water and the ride height about $\ell_w \sin\varphi_n - 0.30\,\text{m}$: 0.50 m for the default $\ell_w = 1.0\,\text{m}$ and 0.66 m for 1.2 m. The length is the setpoint. The gain per meter at the default is 57 °/m of flap.

5.5.2 Height Estimates

The electronic loops read complementary observers of $H = h_m - x_B \sin\theta$, the keel line's height at the station of the mass center, given in Equation (5.9). Each is the filter with a bias state of Section 1.4.6 with a third pole at the crossover.

$$\begin{aligned} \dot{\hat{H}} &= \hat{v} + 3\omega_c e, \qquad \dot{\hat{v}} = a_z - \hat{b} + 3\omega_c^2 e, \qquad \dot{\hat{b}} = -\omega_c^3 e \\ e &= H - \hat{H}, \qquad \hat{h} = \hat{H} + x_B \sin\theta_m \end{aligned} \tag{5.9}$$

where $\hat{b}$ estimates the accelerometer's bias and all three poles sit at $-\omega_c$, so a constant bias leaves no steady error. The observers are advanced by a semi-implicit Euler step every Δt_c. Below ω_c the estimate follows the sensor, and above it the IMU [7]. The platform observer runs at $\omega_c = 0.6\,\text{rad/s}$ (adjustable), the contour observer at 8 rad/s, and a third at 0.15 rad/s whose residual is the surface under the bow. Its mean square, averaged over 8 s, gives the wave-height estimate $\hat{H}_s = 4\sqrt{\overline{\eta^2}}$. The heave rate used by the cascade is $\hat{v} + x_B q_m \cos\theta_m$ from the platform observer. With the sensor blind, every observer coasts on the IMU and its last bias estimate. Volume 5, Chapter 13 meets the same loss under water, where its Doppler log loses the seabed.

5.5.3 PID and Cascade

The PID is the shared velocity-form law of Section 1.6.2, Equations (1.19) to (1.22). Its error is $e_k = h_{SP,k} - \hat{h}_k$ on the height estimate, its derivative acts on the measurement through a first-order filter of 0.1 s, its output range is the main flap's $\pm\delta_{f,max}$ and its tracking time is τ_I. Its output bias is $\delta_{map}(V_m)$, the flap that holds 0.5 m in calm water at the measured speed, tabulated once from the declared model from 14 to 30 kn. The defaults are $K_c = 20^\circ/\text{m}$, $\tau_I = 2\,\text{s}$ and $\tau_D = 0.2\,\text{s}$. A larger flap means more lift and a higher boat, so the loop is reverse acting, $a = +1$ in the convention of Section 1.3. The cascade replaces the single loop by two, as shown in Equation (5.10).

$$\begin{aligned} v_{SP} &= \text{clip}\big(K_h(h_{SP} - \hat{h}),\ \pm 1.5\,\text{m/s}\big) \\ \delta_{f,cmd} &= \delta_{map}(V_m) + \text{PI}_w\big(v_{SP} - \hat{\dot{h}}\big) \end{aligned} \tag{5.10}$$

where $K_h = 4\,\text{s}^{-1}$ and the inner PI has a gain of 8° per m/s and $\tau_{I,w} = 1\,\text{s}$, in the same velocity form and also reverse acting. The inner loop works on the IMU's heave rate, which the waves do not disturb directly and which survives the loss of the height sensor. Choosing an inner loop by where the disturbances enter is the subject of Volume 3, Chapter 2.

5.5.4 Wave Handling, Fallback and the Other Loops

The height estimate is the platform one, the contour one, or the one chosen by the schedule (Auto), which contours once $\hat{H}_s$ exceeds 0.37 m and platforms again below 0.33 m, a switch height of 0.35 m with 0.02 m of hysteresis. With the sensor lost, Hold flap freezes the last command, and Fly on IMU keeps the PID or cascade closed on the coasting platform estimate at the ride-height setpoint. The pitch loop is the same PID on the IMU's pitch to the rear flap. More rear flap lifts the stern and lowers the bow, so a bow-high error asks the rear foil for more lift and the loop is direct acting, $a = -1$. Its settings are $K_c = 2$, $\tau_I = 2\,\text{s}$, $\tau_D = 0.1\,\text{s}$ and a derivative filter of 0.05 s. The speed loop is a PI on the log to the throttle, at 7.7 % per knot and $\tau_I = 5\,\text{s}$.

🕮 **Pause.** Try Exercise 5.3 before reading on.

The takeoff sequencer is a phase register with minimum dwell times. Above 60 % of the takeoff speed it enters HUMP and holds the main flap at 15° to unload the hull. At 95 % of the takeoff speed, before the hull unsticks, it enters FOILBORNE and hands the flap to the height loop, whose setpoint ramps from the measured height to the target at 0.25 m/s. It returns to DISPLACEMENT below 85 % of the takeoff speed with the keel down. With the speed setpoint below 95 % of the takeoff speed it lands the boat instead, ramping the setpoint at 0.15 m/s to –0.05 m and centering the flap once the hull is in. The takeoff speed is the declared boat's 14.48 kn, so a lighter boat lifts off with the flap still held at 15°. At 1200 kg, case 2's PID at 75 % throttle climbs to a 1.38 m ride height and ventilates the main foil at 4.2 s.

5.5.5 Model Predictive Control

The fifth height controller is an MPC on the main flap, built on the general setup of Section 1.6.3 [19, 20]. Every Δt_c it solves a quadratic program over $N = 105$ steps of $T_p = 40\,\text{ms}$, a horizon of 4.2 s, and applies the first move. The flap is constant over each of eight move blocks, whose lengths in steps run 1, 2, 3, 5, 8, 13, 21 and 52. The pitch and speed loops, the sequencer and Hold flap act as shipped and take precedence over the plan, and the PID's and the cascade's tuning and wave handling leave the panel, because both loops then only track the applied flap and the MPC has its own observer.

The controller's model is the declared boat. The forces of Equations (5.1) to (5.5) are differentiated numerically at the declared parameters, in calm water with no passenger and no weed, about the foilborne trim at $h = 0.5\,\text{m}$ and $\theta = 0$, at each speed from 15 to 30 kn, once at load, and interpolated at the measured speed, which gives Equation (5.11).

$$\begin{aligned} x &= [z,\ w,\ \theta,\ q,\ \delta_f,\ \delta_r,\ d,\ g,\ m]^\top \\ \dot{w} &= \mathbf{a}^\top \xi + d + g - a_z \eta_f, \quad \dot{q} = \mathbf{c}^\top \xi + m - c_z \eta_f \\ \tau_s \dot{\delta}_f &= u - \delta_f, \qquad \tau_s \dot{\delta}_r = K_\theta(\theta + T_\theta q) - \delta_r \\ \dot{d} &= 0, \qquad \dot{g} = -g/\tau_g, \qquad \dot{m} = 0 \end{aligned} \tag{5.11}$$

where every variable is a deviation from the trim at the measured speed, $\xi = [z, w, \theta, q, \delta_f, \delta_r]^\top$, $\mathbf{a}$ and $\mathbf{c}$ hold the derivatives of the heave and pitch accelerations with respect to ξ (first entries a_z, c_z), u is the flap command and η_f the surface at the main foil, which enters as a negative heave. The rear flap follows the shipped pitch loop's proportional and derivative action ($K_\theta = 2$, $T_\theta = 0.1\,\text{s}$, integral left out), d and m are constant heave and pitch disturbances that make the controller offset-free [21], and g is a heave disturbance that fades with $\tau_g = 0.1\,\text{s}$, the orbital push of the waves, which reverses within half an encounter period. The model is sampled exactly with a zero-order hold at T_p for the plan and at Δt_c for the estimator. At 20 kn its derivatives agree with hand formulas from the declared parameters within 0.9 % (65.87 m/s^2 of heave acceleration per radian of flap). After a 0.3° flap step in calm water its heave matches the engine's within 1 % to 0.5 s and 2 % at 1 s, then runs ahead, 8.2 cm against 7.1 cm at 2 s and 14.1 cm against 9.1 cm at 4 s, because the pitch integral and the change of the surface factor with depth are left out.

The plan judges the keel's height above the mean water at the bow, $\bar{h}$, at the main foil's station, k_f, and at the stern, k_s, 3.6 m aft of the center of mass, and the heave rate w, with the objective and limits of Equation (5.12).

$$\begin{aligned}
\min\ & \textstyle\sum_{k=1}^{N} \big[Q_h(\bar{h}_k - h_{SP})^2 + Q_w w_k^2 \\
& + Q_k(\bar{h}_k - h_{SP} - \hat{\eta}_{f,k})^2 \big] + \textstyle\sum_{j=1}^{8} S\,(u_j - u_{j-1})^2 \\
& + \textstyle\sum_{b=f,s} \big(\rho\, \varepsilon_b^2 + \sigma \varepsilon_b\big) \\
\text{s.t. } & \hat{\eta}_{f,k} + k_{lo} - \varepsilon_f \le k_{f,k} \le \hat{\eta}_{f,k} + k_{hi} + \varepsilon_f \\
& k_{s,k} \ge \hat{\eta}_{s,k} + k_{lo} - \varepsilon_s, \quad \varepsilon_b \ge 0, \quad |u_j| \le \delta_{f,max} \\
& |u_1 - u_0| \le \dot{\delta}_{max} \Delta t_c \\
& |u_j - u_{j-1}| \le \tfrac{1}{2} \dot{\delta}_{max} T_p (n_{j-1} + n_j), \quad j \ge 2
\end{aligned} \tag{5.12}$$

where $\hat{\eta}_{f,k}$ and $\hat{\eta}_{s,k}$ are the water the plan expects under the foil's station and the stern at step k, $k_{lo} = 0.10$ m is a slam margin, $k_{hi} = 0.70$ m keeps the main foil 0.20 m deep, above its 0.105 m ventilation depth, ε_f and ε_s are single slacks, each covering its band over all N steps, u_j is the flap of block j with n_j steps and u_0 the command applied now. The weights are $Q_h = 100$, $Q_k = 100$, $Q_w = 30$, $S = 20$, $\rho = 10^5$ and $\sigma = 10^3$. The Q_k term is a partial contour, which leans the plan toward the expected water by $Q_k/(Q_h + Q_k)$, one half, and leaves it exactly at the setpoint in calm water. The flap's box is hard and read as the shipped loops read it, and the servo's 60 °/s is hard as a ramp, 1.2° for the first move and the travel between two block centers for the later ones.

The controller reads the packet only. Its own observer of the form of Equation (5.9) lowers its crossover from 2 to 0.3 rad/s over 3 s, so it learns the accelerometer's bias early and is inertial over the sea's 0.9 to 5 rad/s, and the bow reading against its height is the surface under the bow. A steady-state Kalman gain computed at 20 kn corrects the state from that height and rate and the IMU's pitch and rate.

The preview is the water the bow sensor has already measured, logged against the distance run and read back 3.3 m behind the sensor for the main foil and 6.9 m behind it for the stern, as if the surface stood still, as in preview control on a measured road [14, 22]. Chapter 12 reads its seam preview by place in the same way. At 20 kn the foil's water is known 0.32 s ahead, and past that the latest reading is held. Waves travel, and that is the preview's declared error: on the predicted change of the water at the foil it is 0.104 m rms 0.16 s ahead on case 6's sea against 0.145 m for assuming no change, equal to it 0.32 s ahead (0.087 and 0.088 m), and worse than holding the reading from ahead (case 9, 0.184 against 0.093 m). Switching the preview Off leaves the plan the water under the bow now, held over the horizon, which is what a contouring loop knows.

The controller accepts a plan whose solver status is optimal, whose numbers are all finite, whose planned flaps sit in the box and whose opening entry equals the move. When a plan fails these tests the cascade, whose inner PI has tracked the applied flap exactly, flies the flap and the historian records the event until a later plan passes. On every entry to MPC control the command blends from the cascade's law to the plan's over 0.3 s, never faster than the servo. Over seven forced fallbacks on case 6's sea and four in the 0.8 m sea the blend lowers the mean peak seat acceleration in the 1.5 s after resumption from 2.61 to 2.01 m/s^2 and from 4.87 to 3.87 m/s^2.

A 20 ms grid of 75 steps ventilates in the 0.8 m following sea at 14.4 s where the 40 ms grid flies clean, and 38 or 105 steps of 40 ms give the same seat accelerations within 0.01 m/s^2, so the horizon covers the longest encounter period compared, 4.09 s. The weights were picked once on case 6's seed from 108 settings, 37 passing, by a rule: no slam or ventilation at 0.5, 0.65 and 0.8 m, then the least seat acceleration at 0.5 m. The margin entered the rule only after five grids on 0.5 m alone had picked weights that ventilate at 0.65 m, so the results at 0.65 and 0.8 m are in-sample.

In Chrome 157 the solves of case 10 take 1.7 % of a core at real time and 5.4 % at the top speed of five times, the largest 3.3 ms, and the page keeps 60 frames per second.

Table 5.4 The Eleven Cases

#	Case as shipped	Teaching point
1	At rest, Hand height controller, throttle 75 %, flap 6°, 0.1 m sea	takeoff by hand
2	At rest, PID with the sequencer, hand throttle 40 %	hump, handover
3	Flying at 0.75 m, flap fixed, 0.5° less flap at 3 s	free stiffness
4	Wand, calm, gust of 1.5 m/s at 5 s	a mechanical P loop
5	PID, 0.3 m sea astern, spray 2 s at 10 s, Hold flap	sensor loss
6	PID platforming, 0.5 m sea astern, 40 s	platform or contour
7	Cascade, calm, pitch loop P only, pitch SP 1.5° at 3 s	pitch and heave
8	PID, no integral, passenger 3 m aft at 5, weed 20 % at 15 s	integral action
9	Suggested design, 1.4 m sea ahead, seed 2, 60 s	a sea to leave
10	MPC with the preview On, case 6's sea, 40 s	a look-ahead
11	Challenge: sea astern 0.2 to 0.5 m, wake at 30, spray at 45 s	the whole problem

5.5.6 The Three Models

The plant is everything in Section 5.3. For the wand, the PID and the cascade the control model is implicit in the tuning, with the static flap map as the only part of the plant they hold, computed from the declared parameters at load with no passenger and no weed. The MPC holds the declared boat of Equation (5.11), and the sequencer that serves every electronic structure holds the declared takeoff speed. A learner's change to the boat is therefore model error for every law. Set before Run, a mass of 1900 kg or the passenger 3 m aft leaves the PID's and the cascade's events and seat rms in the seas of cases 6 and 10 as they were with the map rebuilt for that boat, and moves their flap travel by under 2 %, because the integral carries what the map misses. The observers carry a double integrator with a bias, which knows nothing of the foils. No law is told the foil depths or the ventilation state, so a ventilated foil reaches a controller only through the IMU and the height sensor, as a sudden fall.

5.6 Eleven Cases, Measured

The cases appear in Table 5.4. Each quoted value comes from the engine of Section 1.6.1 driven from a script, stepped exactly as the page steps it, on the case's own seed, with any setting a sentence names entered before the run. Vertical accelerations are root mean square values at the seat, 1 m ahead of the center of mass, while foilborne.

5.6.1 By Hand, Over the Hump and Onto the Foils

In case 1 the hull is clear at 8.53 s at 17.1 kn with the throttle still at 75 %, and the flap that lifted it out is too much for the rising speed. The main foil ventilates at 8.83 s, and the boat porpoises in and out for the rest of the minute at 7.60 m/s^2 while the speed runs to 32.6 kn. With the speed loop holding 18 kn and the flap at 3° the boat is foilborne from 7.08 s and never slams, although it still ventilates at 7.35 s, and with 5° it slams at 21.41 s. In case 2, at 40 % throttle the boat is doing 6.28 kn at 15 s with 1796 N of drag and the hull carrying 13.4 kN, 50 % stops at 7.5 kn, and 55 % is foilborne at 18.20 s. With 75 % from the start the sequencer takes the boat off at 7.63 s without a ventilation, between 0.42 and 0.85 m. Without the sequencer the PID meets the unsticking hull with its whole error and overshoots to 1.04 m, ventilating at 7.75 s, while the cascade without it stays between 0.42 and 0.77 m.

5.6.2 Stiffness, the Wand and the Pitch Coupling

In case 3 the 0.5° flap step at 0.75 m takes 0.785 kN off the main foil. The boat drops from 0.750 to 0.708 m within a second and is still at 0.709 m at 14.9 s. From 0.5 m it sinks to 0.245 m by 8 s and to the water by 15 s, and from 0.2 m it is in the water, at –0.211 m, by 8 s. In case 4 the wand flies at 0.50 m with a length of 1.0 m, at 0.34, 0.65 and 0.72 m with 0.8, 1.2 and 1.3 m. Up to a ratio of 2.6 it rides out the gust, at 0.64 m/s^2. At 2.7 an oscillation of 2.55 to 2.74 Hz grows into a porpoise of 0.69 Hz and 1.27 m, which ventilates at 17.73 s and slams at 18.17 s. The instant is sensitive because 2.7 lies just past the threshold: at half the step the boat slams at 16.76 s without ventilating first. In

case 7 a proportional pitch loop of gain 0.5 reaches 0.31° of the 1.5° step by 12 s, because the rear foil resists being pitched. A 0.5 s integral reaches 1.478° with the rear flap at −2.50°, while the height loop moves the main flap from 0.41° to −2.77° and holds the ride height between 0.473 and 0.511 m. Each degree of pitch adds 3.68 kN at the main foil and each degree of main flap 1.84 kN, so the pairing costs about two degrees of main flap per degree of pitch.

5.6.3 Sensor Loss and Steady Disturbances

In case 5 the bow sensor is blinded for 2 s at 10 s. Holding the flap, the boat climbs on a wave with nothing to stop it: the main foil ventilates at 11.17 s and the hull slams at 11.80 s. Flying on the IMU, the PID still ventilates at 11.18 s but does not slam, and the cascade on the IMU flies the 25 s clean at 0.59 m/s^2. A shadow platform observer blinded at 10 s wanders 3.2 cm from the true height in the case's sea in those 2 s, and 2.2 cm in calm water. In case 8, with no integral action, the passenger leaves the boat 0.563 m high with the bow up 0.41° and the weed leaves it at 0.478 m. A 2 s height integral brings it to 0.500 m by 29.9 s, and with a pitch integral too the pitch is back to 0.00°, with the rear flap at 1.40° and the main flap at 2.43°. Integral action stops at the flap's authority: with 40 % weed at 18 kn the flap reaches its 15° stop and the hull slams 0.74 s after the weed arrives, while at 20 kn the flap holds at 7.1°.

5.6.4 Platforming Against Contouring

Case 6 shows the platform-or-contour choice on one sea, as shown in Figure 5.2. Platforming with the 0.6 rad/s cutoff, the PID holds the boat near its height over the mean water while a trough, with the surface 0.200 m below the mean over the main foil, uncovers the foil to 0.104 m. It ventilates at 11.20 s, the boat drops, and the stem meets the next crest, 0.280 m above the mean, at 11.65 s and 0.77 m/s. Figure 5.3 shows the app at that ventilation. Contouring, the same PID flies the 40 s clean between 0.19 and 0.79 m at 2.67 m/s^2. The cutoff is the same choice on a dial: at 1, 1.5 and 3 rad/s the boat flies clean at 1.15, 1.29 and 1.93 m/s^2. The cascade contours at 1.38 m/s^2, while its platforming ventilates later, at 21.69 s. In a 0.2 m sea the comfort ranking reverses, 0.87 m/s^2 platforming against 2.31 contouring, because the small waves arrive at 5.47 rad/s and pass under the hull anyway.

Pause. Try Exercise 5.1 before reading on.

The lesson holds on the case's sea, and the structure decides how far it generalizes. Over 17 draws of the same sea state (the case's seed and seeds 1 to 16), PID platforming ventilates on all 17 and slams on 8, PID contouring is clean for 40 s on 7 and ventilates on 10, and cascade contouring is clean on all 17. From ahead the 0.5 m sea is met at 5.09 rad/s, and the PID's contouring slams at 7.35 s, sooner than its platforming ventilates (34.82 s), while the cascade's contouring flies the 40 s clean at 2.94 m/s^2. The app therefore teaches the choice from astern, where the long waves are slow enough to follow, and states the head-sea result in its limitations. Chapter 6 meets the same question on a vessel whose wave motion is real and not an error.

> **TRY IT IN THE APP 6 · Waves: Hold the Height, or Follow the Sea**
>
> Load the case and press Run. Watch the main foil on the Sea view as a trough passes over it: at 11.20 s it ventilates and turns red, and at 11.65 s the hull slams into the next crest. Press Reset, set In waves to Contour and run again. The boat flies the 40 s clean, at a seat acceleration of 2.67 m/s^2.

5.6.5 A Sea Nothing Tried Could Fly

Case 9 sends the challenge's suggested design into a 1.4 m sea from ahead, 1.75 times the band, on draw seed 2, and asks for 60 s clean at 20 kn. At 20 kn the boat meets 44 waves in the minute at the bow, 19 of them taller than the band from crest to trough and the tallest 1.83 m, and the part of the sea met faster than 3 rad/s has a significant height of 1.03 m on its own. Platforming cannot hold the boat level over waves that tall, and contouring can follow the long waves but not the fast remainder. The suggested design slams at 6.14 s at 2.0 m/s, as shown in Figure 5.4.

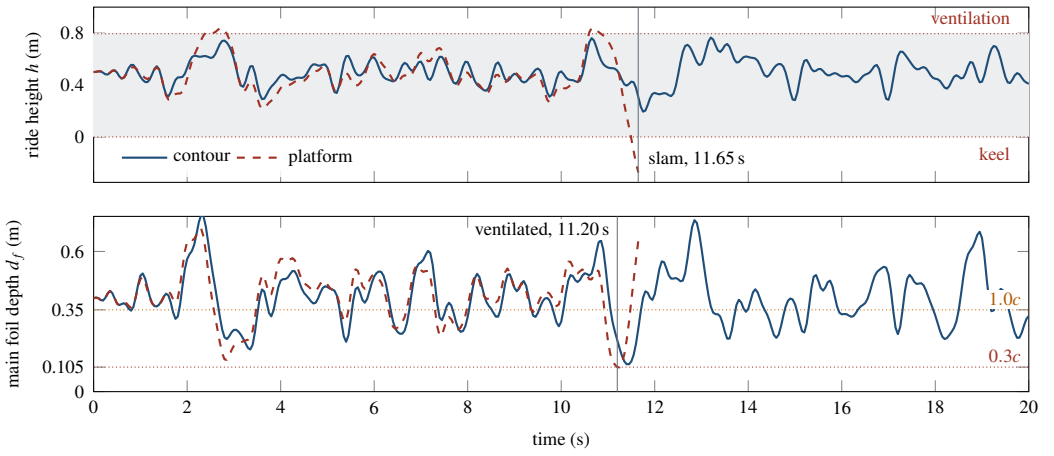


Figure 5.2 Platforming against contouring on the 0.5 m sea of case 6, PID, the same seed. Platforming (red, dashed) lets a trough uncover the main foil past $0.3c$ at 11.20 s and slams on the next crest at 11.65 s, where the run stops. Contouring (blue, solid) keeps the foil above $0.3c$ and the ride height inside the band. The bow can pass the calm-water band without an event, because the surface under the foil differs from that under the bow. The limit lines are dotted. Data from the engine every 0.05 s.

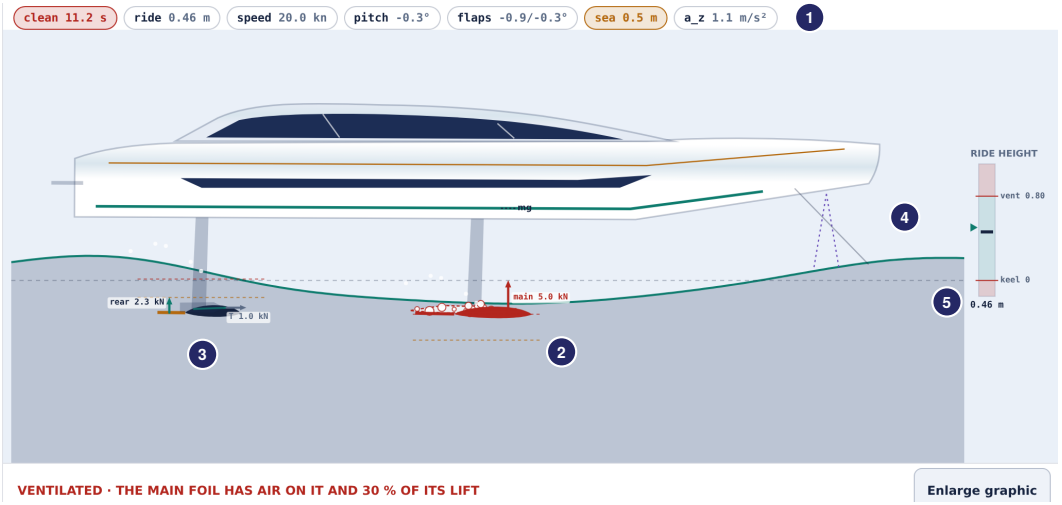


Figure 5.3 Case 6 at its ventilation, $t = 11.25$ s, on the Sea view, cropped to the plant view. The PID platforms on a 0.5 m sea from astern at 20 kn. (1) The badges show 11.2 s clean, flaps at −0.9 and −0.3° and 1.1 m/s^2. (2) The main foil is 0.10 m under a trough, drawn red under an air sheet with bubbles up its strut, and its lift arrow shows 5.0 kN against (3) the 2.3 kN of the rear foil and the mg tick at 15.7 kN. (4) The bow sensor's beam and the wand reach down to the water at the bow. (5) The gauge shows the true ride height at 0.46 m inside the band from a slam at 0 to a ventilation at 0.80 m, and the status line below reads VENTILATED. The trends and the scorecard of the full window are cut.

The infeasibility is a statement about a search, not a proof. A first sweep held the speed at 20 kn and drew 27 795 settings of every control in reach (the structure including the hand and the wand, the wave handling, the cutoff, the ride height, the pitch setpoint, every gain including zero, the hand flap

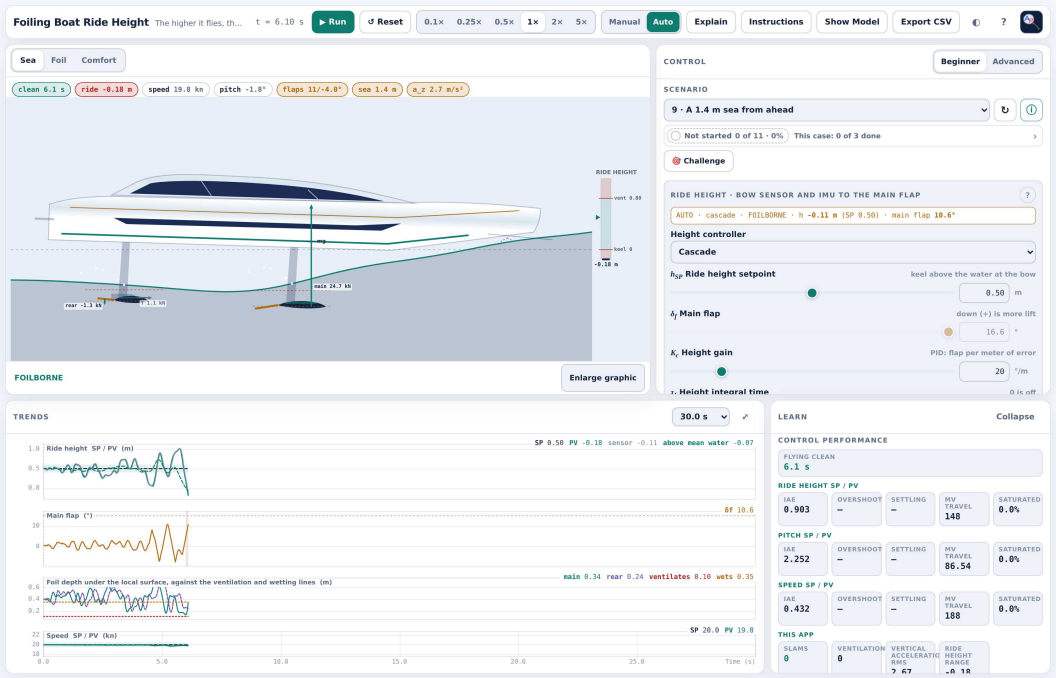


Figure 5.4 Case 9 at $t = 6.10$ s, 0.04 s before its slam, on the Sea view. The suggested cascade with automatic contouring runs into a 1.4 m sea from ahead at 19.8 kn. The bow is over a rising crest: the keel line at the sensor is 0.18 m below the water there while the stem, whose keel rises toward the bow, is still 0.10 m clear, so the gauge reads below its slam mark before any contact. The main flap stands at 10.6° on its way to the 15° command, and the main foil, 0.34 m deep, makes 24.7 kN against the 15.7 kN weight while the rear foil pushes down with 1.3 kN and the bow pitches 1.8° down. The badges show 6.1 s clean and 2.7 m/s^2, and the trends cover the 6.1 s flown.

and the passenger's place), followed by ten rounds of hill-climbing from the best: none of the 33 795 runs flew past 12.49 s. A second sweep of the same size freed the speed from 14.5 to 30 kn and the hand throttle. A hill-climb tuned to this one draw found 59.07 s with a soft PID at about 26 kn, but the ten best settings of that search fly a median of 4.2 to 5.8 s on fifteen other draws of the same sea and none flies the minute on any of them: the search found a passage through these particular waves, not a way to fly the sea. The case rewards the seaman's decision. With the speed setpoint at 12 kn before the run, the boat never leaves its hull and the longest moment with the hull clear is 0.07 s, with no slam in the minute, while slowing from flight at 3 s brings the hull down onto a crest at 4.61 s. The same suggested design flies the challenge's 0.5 m sea from astern clean.

> **TRY IT IN THE APP** **9 · A 1.4 m Sea From Ahead**
>
> Load the case and press Run. The suggested design slams at 6.14 s. Press Reset, set the Speed setpoint to 12 kn and run again. The boat never leaves its hull, and the minute passes with no slam. Slowing below the takeoff speed is the decision this case rewards.

5.6.6 Predictive Control Against the Cascade

Case 10 flies case 6's sea under the MPC, then without the look-ahead, then on the cascade. Table 5.5 sets the MPC at case 10's settings against the shipped cascade and three classical rows, one fixed setting each, with the same seed, instruments and noise. The retuned cascade was chosen from 192

Table 5.5 Seat Acceleration (m/s^2 rms) of a Clean Run, Otherwise the Time in Seconds of the First Slam (s) or Ventilation (v), 20 kn

	Shipped		Re-	Plat.	Cont.	MPC		
Sea	Auto	Cont.	tuned	$+\hat{\eta}$	$+\Delta\hat{\eta}$	On	Off	Off_0
case 6's, 0.5 m	1.30	1.38	0.90	0.71	0.81	0.74	0.98	14.4v
0.65 m astern	1.36	1.42	0.93	11.0v	0.88	1.00	14.5v	13.9v
0.8 m astern	2.7v	1.45[a]	1.01	11.0v	0.94	1.16	14.4v	2.8v
1.0 m astern	2.7v	2.7s	1.04	2.7v	2.7v	14.4v	14.4v	2.7v
1.2 m astern	2.7v	2.7s	37.5s	2.7v	2.7v	2.7s	2.7s	2.7v
0.5 m ahead	2.83	2.94	2.02	18.8v	34.8v	2.03	2.51	7.1v
case 9	6.1s	6.1s	5.9v	5.1v	5.1v	6.1s	6.2s	5.7v
challenge[b]	1.32	1.35	0.91	0.61	0.78	0.74	1.05	33.9v
1.2 m wake[b]	1.33	1.37	0.92	34.9s	0.80	34.0v	34.0v	31.4s

Case 6's seed, 40 s, except case 9 and the challenge (seed 2, 60 s). Plat. $+\hat{\eta}$ and Cont. $+\Delta\hat{\eta}$: the cascade with the previewed water or its change on its setpoint (script only). Off: the water under the bow now held. Off_0: the mean water (the first Off). The MPC planned every 20 ms, 2,000 to 3,000 plans a run, no fallback, 0.19 to 0.22 ms a plan headless. [a] One touchdown below the slam speed. [b] Classical rows with Fly on IMU, the MPC with Hold flap. Last row: the challenge with a 1.2 m wake.

settings, 50 passing, by the MPC's rule: $K_h = 2\,\text{s}^{-1}$, an inner gain of 16° per m/s, $\tau_{I,w} = 1$ s, Auto and $\omega_c = 0.3$ rad/s, within the panel's ranges and with no preview. The two feedforward rows exist only in the measurement script and add the MPC's own preview to the cascade's setpoint: the previewed water at the foil at a gain of 0.5 while platforming, and the best of 72 forms under the rule, 0.75 times its previewed change while contouring.

On case 6's sea the MPC flies clean at 0.74 m/s^2 with 556° of flap travel, against 1.30 m/s^2 and 729° for the shipped cascade on Auto, and its plan presses on a band at 67 of its 2,000 decisions, by at most 3.6 cm. Without the look-ahead it still flies clean, at 0.98 m/s^2 with 781°, so the preview accounts for 0.24 of the 0.56 m/s^2 by which the MPC beats the shipped cascade there. At 0.65 m Off ventilates at 14.5 s where On is clean. A first Off, against the mean water, also dropped the water under the bow now and so ventilated on case 6's sea at 14.4 s for a reason other than the missing look-ahead.

The MPC is not the only structure that flies the taller following seas. The retuned cascade, with no preview, flies 0.65, 0.8 and 1.0 m astern clean at 0.93, 1.01 and 1.04 m/s^2, where the MPC rides 1.00 and 1.16 and ventilates at 14.4 s, and in the 1.2 m sea it lasts to 37.5 s where the MPC slams at 2.7 s. The contouring cascade with the previewed change rides 0.65 and 0.8 m at 0.88 and 0.94 m/s^2. The platforming feedforward matches the MPC on case 6's sea, 0.71 against 0.74 m/s^2, and beats it on the challenge, 0.61 against 0.74, but ventilates at 11.0 s at 0.65 m. Figure 5.5 shows two of these seas. By seat acceleration the MPC is the smoothest of the panel's settings only on case 6's sea and the challenge, and the script's platforming feedforward is smoother on both. What the MPC brings is the flap's box, the servo's rate and both keel bands as limits of one plan, a slack that states by how much a band cannot be met, and, against the shipped Auto, the 0.8 m sea flown clean and the 1.0 m sea to 14.4 s where Auto ventilates at 2.7 s in both. Its peak seat acceleration is higher than the shipped cascade's at 0.65 m, 5.8 against 4.5 m/s^2.

Case 9 and following seas of 1.2 m and more defeat every row. In case 9 the MPC slams at 6.1 s as the shipped cascade does, with 18 slams and 21 ventilations in the minute against 15 and 16 if the run continues and a slack of 0.78 m. With the challenge's wake at its 1.2 m maximum the MPC ventilates at 34.0 s where the shipped Auto flies clean, since an approaching wave train is where the frozen surface errs most. No fix measured keeps the other seas within the budget: a slack every second step flies that wake but slams at 1.0 m and costs 6.3 ms a solve, and previews blended or fading ventilate at 0.65 or 0.8 m. In case 8 the MPC is still 3.4 cm low at 29 s, where the PID with a 2 s integral is within 0.5 cm by 10 s.

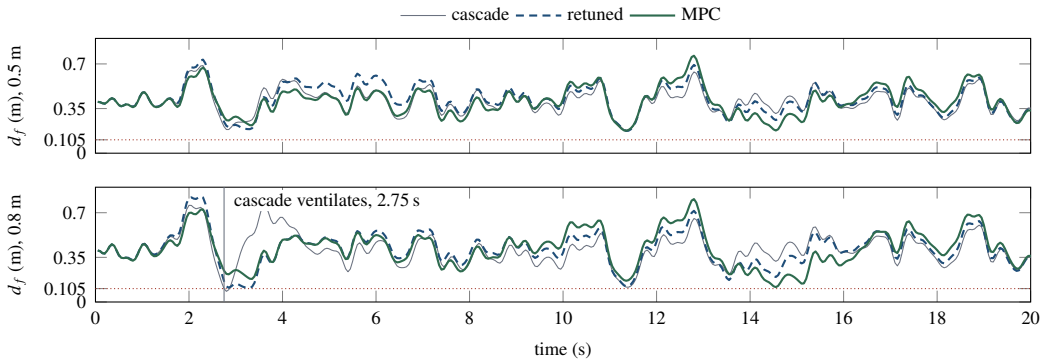


Figure 5.5 Main foil depth under the local surface on case 6's 0.5 m sea (top) and on the same seed at 0.8 m (bottom), from astern at 20 kn, under the shipped cascade on Auto (gray, thin), the cascade retuned by the MPC's rule (blue, dashed) and the MPC with its preview (green, thick solid), with the ventilation depth $0.3c$ dotted. In the taller sea the shipped cascade ventilates at 2.75 s, while the retuned cascade and the MPC keep the foil deeper than $0.3c$, with least depths of 0.110 and 0.111 m over the 40 s. Data from the engine every 0.05 s.

Table 5.6 The Challenge on Its Sea (Seed 2) and Over Sixteen Seas

Configuration	Clean (s)	a_{seat} (m/s^2)	Verdict	Pass of 16
PID, platform, Hold flap (shipped)	40.9	1.32	fails	1
cascade, Auto, Fly on IMU (suggested)	60.0	1.32	passes	12
cascade, Auto, Hold flap	46.3	1.40	fails	—
cascade, platform, Fly on IMU	40.9	0.87	fails	7
cascade, contour, Fly on IMU	60.0	1.35	passes	12
PID, Auto, Fly on IMU	57.8	2.60	fails	—
wand	60.0	4.18	fails (comfort)	—
MPC, preview On, Hold flap	60.0	0.74	passes	—

5.6.7 The Challenge

The challenge flies 60 s at 20 kn on a sea from astern that builds from 0.2 toward 0.5 m, through a 0.5 m wake at 30 s and 2 s of spray on the sensor at 45 s. Its target is the whole minute foilborne with no slam and no ventilation and a seat acceleration of at most 1.5 m/s^2, and its score is the seconds flown clean. The comfort limit is a teaching value. Ratings of discomfort under whole-body vibration come from the literature and standards on human vibration [17]. The challenge is void if a model parameter, the sea, the wake or the spray is changed. The sea is one fixed draw, seed 2, chosen because it shows the result that most draws show, and Table 5.6 lists eight configurations on it with the pass count over sixteen seas where it was measured. As shipped, the PID platforms and freezes the flap in the spray, and it ventilates at 40.91 s as the sea passes 0.405 m. The suggested design, the cascade with automatic contouring and the IMU fallback, flies the minute clean at 1.32 m/s^2. Each part matters on this sea, and contouring throughout also passes, a result the application states, and so does the MPC. Figure 5.6 draws the table as bars.

> ✦ **DID YOU KNOW? A Stick That Flies but Shakes**
>
> From the simulator: on the challenge's sea the wand, a stick and a pushrod with no electronics, flies all 60.0 s with no slam and no ventilation. It still fails, at a seat acceleration of 4.18 m/s^2 against the limit of 1.5, which the suggested cascade meets at 1.32 (Table 5.6).

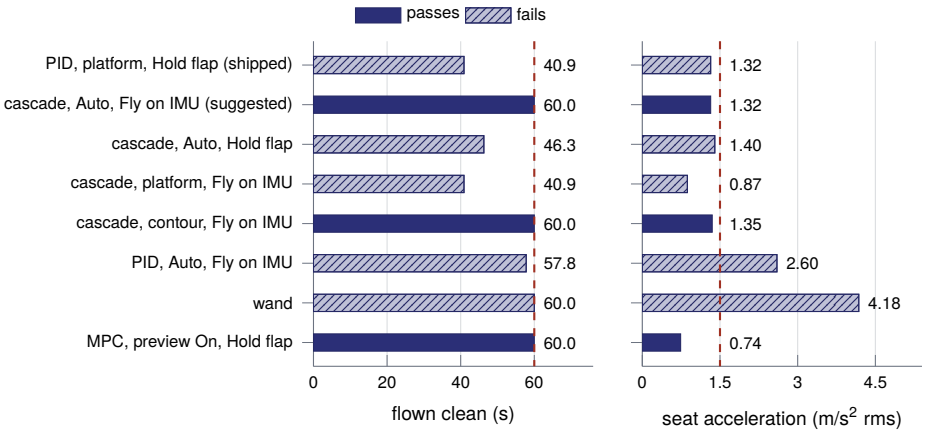


Figure 5.6 The eight configurations of Table 5.6 on the challenge's sea, drawn as bars, solid for a pass and hatched for a fail. Left: the seconds flown clean, against the 60 s the challenge asks (dashed line). Right: the seat acceleration, against the comfort limit of 1.5 m/s^2 (dashed line). A value left of a dashed line is printed just right of it. Notice that the wand flies the whole minute and fails on comfort alone, and that the shipped and the platforming configurations stop at the same 40.9 s.

5.7 Technology in Practice

The launch of Section 5.3 is read by a bow height sensor, an inertial unit and a speed log, and moved by two foil flaps and an electric pod. Figure 5.7 draws its loops with real devices in their place.

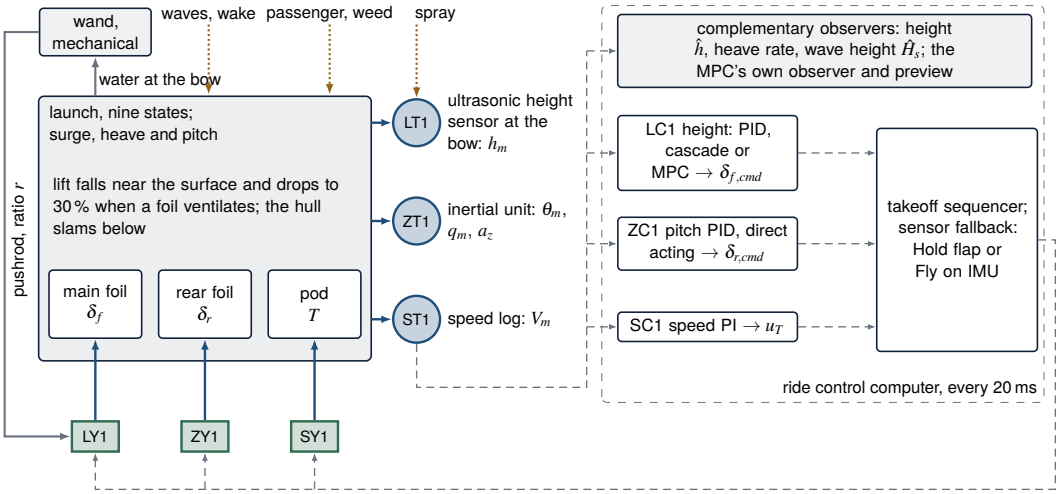
What Measures It

Every height law of Section 5.5 rests on the bow sensor LT of Figure 5.1. Its 1 cm of colored noise and the spray event of case 5 stand for the noise and the lost echoes of a real ultrasonic sensor. Naval hydrofoils sensed pitch and roll with a vertical gyroscope and heave with a servoed accelerometer beside the height sensor [18], the same set as the IMU and LT here.

> **TECHNOLOGY** **Sensor: Ultrasonic Ride-Height Sensor**
>
> An ultrasonic sensor times a sound pulse from a piezoelectric transducer to the surface and back, and the time of flight gives the distance. Its calibration rests on the speed of sound in the air, which changes with the air's temperature and pressure. Foam can fool it, and every echo instrument has a dead zone close to its face [23]. Sonic height sensors flew on the early electronically controlled hydrofoils, and one naval craft changed to a radar height sensor to eliminate noise and heavy rain interference [18]. On a trend such interference shows as noise or as a lost reading, which is how the spray of case 5 blinds the bow sensor for 2 s.

What Moves It

The model drives each flap through an 8 ms lag, a rate limit of 60 °/s and a stop at 15° or 10°, and the pod through a 0.3 s thrust lag under its thrust and power limits. On a small foiling dinghy a mechanism does the height loop's job. At rest its wand at the bow lies almost horizontal and pushes the front foil's flap fully down for the most lift, and as the boat rises the wand turns toward the vertical and reduces the flap [8]. The wand of Equation (5.8) is that linkage.



LY1, ZY1: main and rear flap servos, lag 8 ms, 60 °/s, stops at ±15° and ±10°. SY1: pod motor drive, thrust lag 0.3 s, 4.5 kN and 60 kW. Wand: a stick from the bow to the water, linked to the main flap with ratio r, in place of LC1.

Figure 5.7 The loops of the chapter with real devices in place of the schematic's symbols. LT1 reads the ride height at the bow with an ultrasonic sensor, ZT1 the pitch, pitch rate and vertical acceleration with an inertial unit and ST1 the speed with a log. One ride control computer (dashed frame) runs the observers, the height, pitch and speed loops (LC1, ZC1, SC1), the takeoff sequencer and the sensor fallback every 20 ms. LY1 and ZY1 are the servos of the main and rear flaps and SY1 the pod's motor drive. Notice that the wand reaches the main flap through a pushrod and no computer, and that spray on the bow sensor is the only disturbance that enters at an instrument.

TECHNOLOGY Final Element: Foil Flap on a Hydraulic Servo

The naval hydrofoils of a 1974 survey made their lift control with trailing-edge flaps or with whole foils pivoted in incidence. An electrohydraulic servo valve drove each control surface from a hydraulic supply at 3000 psi with redundant pumps. In rough water the outboard flaps of one craft were bottoming quite frequently, the sign that they lacked authority [18]. A flap held at its stop shows on a trend as a flat line while the height error grows, as when 40 % weed at 18 kn drives the main flap of case 8 to its 15° stop.

Where the Controller Runs

The autopilots of naval hydrofoils in 1974 were analog, hard-wired for each ship from plug-in modules, and four servo amplifiers drove the control surfaces, one on each foil and the rudder, through electrohydraulic servo valves [18]. An electronic ride control built for a small foiling dinghy runs on a single-board computer: one software node reads each sensor, a PID node computes the flap, and knobs on the boat set the gains [8]. No open source consulted gives the cycle time of a ride control computer. The PID, the cascade, the MPC, the pitch and speed loops and the sequencer of this chapter all run every 20 ms, with the observers in the same cycle.

What Is Modernizing It

Three developments bear on the chapter's question. The first is radar height sensing in place of sonic, chosen on one naval craft to remove noise and rain interference [18]. The second is the digital autopilot. A universal digital autopilot program for naval hydrofoils, started in 1972, ran a background program that checked every element ten times a second and switched to a backup circuit when it found a fault [18]. The third is electronic ride control on small sailing craft. An ultrasonic sensor and an attitude sensor replace the wand, damping the height signal makes the boat platform and

amplifying it makes it contour, and the sailor can change both the ride height and the response to the sea while sailing [8]. The wave handling of Section 5.5 is a choice of the same kind, made by the controller instead of the sailor.

> **IN PRACTICE** **Design Rules for a Foil Control System**
>
> A 1977 specification for naval hydrofoil control systems asked each loop for a gain margin of 2 to 1 upward and 4 to 1 downward and a phase margin of 30 degrees. The effective strut length had to be at least 1.4 times the significant wave height that 90 percent of the seas stay below. In contouring, strut immersion could vary at most 25 percent more than the wave height for waves met slower than 5 rad/s. The document defines a foil broach as a foil that comes near or clear of the surface and loses its lift, and a hull slam as the impact on the next wave that follows it [24], the sequence of case 6.

5.8 Limitations

The boat is a consistent teaching design, not a model of any craft, and its dimensions, foil sizes, struts and limits were chosen so that the lessons appear. The surface factor and the ventilation latch are declared forms that have not been checked against measured data, so the depth at which the lift starts to fall, the retained 30 % and the wetting depth are plausible rather than predicted, and the flow has no partially ventilated regime. The lift is quasi-steady, the waves are linear and the boat has three degrees of freedom, so the wand's fast oscillation, the steep crests of case 9 and any oblique sea are where the model is weakest.

The cases rest on fixed draws of a random sea, and two of their lessons are draw-dependent and stated so: the PID's contouring is clean on 7 of 17 draws of the sea of case 6, and the challenge's suggested design passes on 12 of sixteen. The infeasibility of case 9 is the result of two searches of 33 795 settings, not a proof. The ride height is measured at one point, so in steep waves it can read below the slam mark with no contact, as in Figure 5.4. Several true quantities in the CSV export, the foil depths and lifts among them, carry no `truth_` prefix, although no controller reads them.

The MPC's model is linear about one trim and leaves out the surge, the orbital angle of attack except through a disturbance fading in 0.1 s, the surface factor's change with depth, ventilation and the stall, so it predicts no ventilation. Its frozen-surface preview errs by 0.104 m rms 0.16 s ahead on case 6's sea, and its results at 0.65 and 0.8 m are in-sample.

> **OPEN CHALLENGE** **Predicting When a Foil Ventilates**
>
> The triggers of natural ventilation are diverse and seemingly stochastic, which makes its onset hard to predict. The most complete map of the flow regimes holds only for the foil and aspect ratio it was measured on. A recent towing-tank study found that two paths to the same steady condition can end in different regimes, and that the onset depends on small disturbances of the free surface [25]. Progress would be ventilation maps that carry over to new foils, to waves and to a moving craft, so that a latch like the one of this chapter could be fitted rather than declared.

5.9 Conclusion

A foiling launch flies in a band 0.80 m tall between a slam and a ventilation, and this simulator lets a student find the band by losing it. Near the surface the foil gives the boat a free stiffness of 24.0 kN/m, which falls to 0.39 kN/m with the foil two chords deep, so a deep foil needs a controller. A wand makes that controller from a stick, with its ratio as the gain and its length as the setpoint, until a ratio of 2.7 porpoises the boat out of the water. In a 0.5 m sea from astern platforming ventilates at 11.20 s and slams at 11.65 s while contouring flies clean, and the cascade on the IMU's heave rate contours that sea clean on all 17 draws against 7 for the PID. In a 1.4 m sea from ahead no setting found flies the minute, and the right decision is to slow below the takeoff speed. An optional MPC rides case 6's sea at 0.74 m/s^2 against the shipped cascade's 1.30, but a cascade retuned by the same rule rides the 0.65 to 1.0 m following seas more smoothly, so the MPC adds limits and a slack in one plan rather

than comfort. Further work would add roll and oblique seas, an unsteady lift lag, a partially ventilated regime fitted to towing-tank data, and the planing lift of the hull. The simulator shows that a height loop on a lift surface near a boundary has to choose which disturbances to reject.

KEY POINTS

- A foiling boat flies in a narrow band: too low and the hull slams, too high and the main foil draws air and loses most of its lift.
- Near the surface the foil gives a free stiffness of 24.0 kN/m, which falls to 0.39 kN/m two chords deep, so a deep foil needs a controller.
- In a 0.5 m sea from astern contouring flies clean while platforming ventilates and slams, and the cascade is clean on all 17 draws against 7 for the PID.
- In a 1.4 m sea from ahead nothing tried flies the minute, and the right decision is to slow below the takeoff speed.

Where else this applies. Volume 7, Chapter 11 trades a still body against a wheel that follows the road, also with a preview, and Chapter 6 chooses which wave motion a vessel should leave alone.

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5.10 Exercises

5.1 ⌕ Concept check · 2 min

The PID flies at 20 kn in a 0.2 m sea from astern. Which wave handling gives the lower vertical acceleration at the seat, and why?

(a) Contouring, because following the surface keeps the main foil at one depth under every wave

(b) Contouring, because a small sea from astern is overtaken slowly enough for every wave to be followed

(c) Platforming, because the short waves are met near 5.5 rad/s and are small enough to pass under the hull

(d) Platforming, because the integral action of the PID removes the wave error that contouring adds

5.2 ⌕ Concept check · 1 min

With both flaps fixed at 20 kn, the boat trimmed at a ride height of 0.75 m settles within about a second after a small loss of lift, while the boat trimmed at 0.20 m keeps sinking toward the water. What makes the difference?

(a) At 0.20 m the heave damping is much smaller, so the boat is free to accelerate

(b) At 0.20 m the main foil works close to its stall, so it cannot add lift by angle

(c) At 0.20 m the rear foil carries the weight, and the main foil adds no restoring force

(d) At 0.20 m the main foil is two chords deep, where the surface factor hardly changes with depth

5.3 ⌕ Concept check · 2 min

The pitch loop drives the rear flap from the measured pitch, positive bow up. A positive rear flap lifts the stern. In the convention of Section 1.3, which statement about its action is right?

(a) Direct acting, $a = -1$: more rear flap lowers the pitch, so the output rises when the pitch is above its setpoint

(b) Reverse acting, $a = +1$: more rear flap raises the pitch, so the output rises when the pitch is below its setpoint

(c) Reverse acting, $a = +1$: the height loop on the main flap is reverse acting, and both flaps push the boat upward

(d) Either action works, because the integral term learns the sign of the process gain during the run

5.4 Theory and calculation · 6 min

Take the main foil as carrying the whole weight mg of the default boat ($m = 1600\,\mathrm{kg}$, $g = 9.81\,\mathrm{m/s^2}$) at fixed speed and angle, so that its lift is proportional to the surface factor $f(d/c) = 1 - A_s \mathrm{e}^{-B_s d/c}$ with $A_s = 0.5$, $B_s = 2.5$ and chord $c = 0.35\,\mathrm{m}$. In level flight a rise Δh of the boat reduces the foil depth d by Δh.

(a) Show that the free stiffness is $k = mgA_sB_s\mathrm{e}^{-B_s d/c}/\big(c\,f(d/c)\big)$ and evaluate it at $d = 0.15$, 0.40 and 0.70 m. Give three significant figures. *Checkpoint:* 23.2, 3.31 and 0.379 kN/m.

(b) Compute the ratio of the stiffness at 0.15 m to that at 0.70 m and compare it with the measured stiffnesses of Table 5.3. *Checkpoint:* 61.1 against $24.00/0.39 = 61.5$.

(c) With the measured damping of 27.0 kN s/m and stiffness of 3.43 kN/m at the 0.50 m ride height, find the time constant of the free height. *Checkpoint:* 7.9 s.

5.5 Theory and calculation · 6 min

The sea's peak period is $T_p = c_T\sqrt{H_s}$ with $c_T = 5.0\,\mathrm{s/m^{1/2}}$, a deep-water wave of frequency ω has the wavenumber $k = \omega^2/g$, and a boat at speed V meets it at $\omega_e = |kV - s\omega|$, with $s = +1$ from astern and $s = -1$ from ahead. The boat flies at 20 kn, which is 10.29 m/s.

(a) For $H_s = 0.5\,\mathrm{m}$ find the peak period, the peak frequency and its wavenumber. *Checkpoint:* 3.54 s, 1.78 rad/s and 0.322 rad/m.

(b) Find the encounter frequency of that peak from astern and from ahead, and the encounter period from astern. *Checkpoint:* 1.54 rad/s and 5.09 rad/s; 4.09 s.

(c) Repeat the encounter frequency from astern for $H_s = 0.2\,\mathrm{m}$, and compare all three with the platform observer's 0.6 rad/s and the contour observer's 8 rad/s. *Checkpoint:* 5.47 rad/s.

5.6 Theory and calculation · 6 min

The wand sets the main flap to $\delta_f = \delta_n - r(\varphi - \varphi_n)$, with φ its angle below the horizontal, $\varphi_n = 53^\circ$, the linkage ratio r in degrees of flap per degree of wand, and the pivot 0.30 m above the keel. The boat settles near φ_n, so the pivot flies about $\ell_w \sin\varphi_n$ above the water.

(a) Find the wand's gain $\partial\delta_f/\partial h = r/(\ell_w\cos\varphi)$ in degrees of flap per meter for $r = 0.6$ and $\ell_w = 1.0\,\mathrm{m}$, and compare it with the PID's default $K_c = 20^\circ/\mathrm{m}$. *Checkpoint:* 57.1 °/m, 2.9 times the PID's.

(b) Predict the ride height $\ell_w \sin\varphi_n - 0.30\,\mathrm{m}$ for wand lengths of 0.8, 1.2 and 1.3 m, and compare with the heights measured in case 4: 0.34, 0.65 and 0.72 m. *Checkpoint:* 0.339, 0.658 and 0.738 m.

(c) Find the gain at $r = 2.7$ with the default length. *Checkpoint:* 257 °/m.

5.7 App challenge · 8 min

Load scenario 3, The free stiffness: open loop near the surface and deep. The boat flies at 0.75 m with the main flap fixed by hand, and the flap moves 0.5° up (less lift) at 3 s. Use the default seed and speed 1, run the whole 15 s and export the CSV file.

(a) Read the true ride height, column `h_m`, in the rows at 2.90 s and 8.00 s. *Checkpoint:* 0.750 m and 0.709 m, within 0.003 m.

(b) Press Reset, set the Ride height setpoint to 0.50 m, which is the height the boat starts trimmed at, run the 15 s again and export. Read `h_m` at 4.00, 8.00 and 14.90 s. *Checkpoint:* 0.434, 0.245 and −0.004 m, within 0.005 m.

(c) Explain the two responses with the time constants of Table 5.3.

5.8 App challenge · 9 min

Load scenario 6, Waves: hold the height, or follow the sea. The PID platforms with a cutoff of 0.6 rad/s on a 0.5 m sea from astern at 20 kn. Use the default seed and speed 1.

(a) Run as shipped until the run stops. Read the Flying clean tile and the time on the clock when the run pauses. *Checkpoint:* 11.2 s clean, paused at 11.65 s, within 0.05 s.

(b) Press Reset, set In waves to Contour and run the whole 40 s. Read the Slams, Ventilations and Vertical acceleration rms tiles. *Checkpoint:* 0, 0 and 2.67 m/s^2, within 0.02 m/s^2.

(c) Press the reload button, set the Platform cutoff to 1.5 rad/s, keep Platform and run the whole 40 s. Read the same tiles. *Checkpoint:* 0, 0 and 1.29 m/s^2, within 0.02 m/s^2.

Explain the three results with the encounter frequency of this sea.

5.9 App challenge · 8 min

Load scenario 10, MPC: the water the bow has already measured. The MPC flies case 6's 0.5 m sea from astern with its preview On. Use the default seed and speed 1 and run each case for the whole 40 s. Read the Vertical acceleration rms tile each time, within 0.02 m/s^2.

(a) Run as shipped. *Checkpoint:* 0.74 m/s^2, no slam or ventilation.

(b) Press Reset, set the MPC preview to Off (Advanced level) and run again. *Checkpoint:* 0.98 m/s^2, no slam or ventilation.

(c) Press Reset, set the Height controller to Cascade and run again. *Checkpoint:* 1.30 m/s^2, no slam or ventilation.

(d) Compute the share of the MPC's advantage over the cascade that the preview accounts for, defined as (Off − On)/(Cascade − On) from the three readings. *Checkpoint:* 43 %, within 4 points.

5.10 Application area · 4 min

The declared boat's takeoff speed is 14.48 kn. The sequencer enters HUMP above 60 % of it, returns to DISPLACEMENT below 85 % with the keel down, and lands the boat when the speed setpoint is below 95 %.

(a) Compute the three speeds in knots. *Checkpoint:* 8.69, 12.31 and 13.76 kn.

(b) In case 9's 1.4 m head sea, setting the speed setpoint to 12 kn before Run keeps the hull in the water with no slam, while slowing from flight at 3 s puts the hull down onto a crest at 4.61 s. What does this tell a skipper about when to take the decision?

5.11 Application area · 3 min

The app models ventilation as a latch that sets when the foil is shallower than 0.3 chords with an effective angle above 2°, keeps 30 % of the lift, and clears only below 1.0 chord. Name two things a real ventilating foil depends on that the latch leaves out, and say why the hysteresis matters to a height loop that has just lost lift.

5.12 Review the agent · 5 min

An AI assistant reviews this chapter's results and writes: "On case 6's sea the MPC rides at 0.74 m/s^2 against 1.30 m/s^2 for the cascade, a 43 % cut in seat acceleration. Replace the cascade with the MPC in every following sea up to 1.0 m." Find the flaw and say how you would check the recommendation.