Sailboat Aerodynamic Objects Case Study

Bill Crowther, 12th March 2025

bill.crowther@manchester.ac.uk

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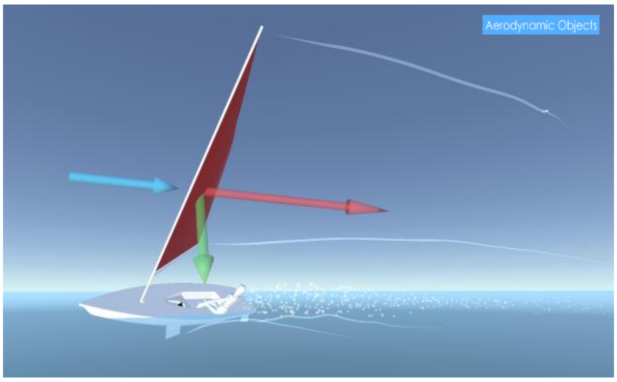
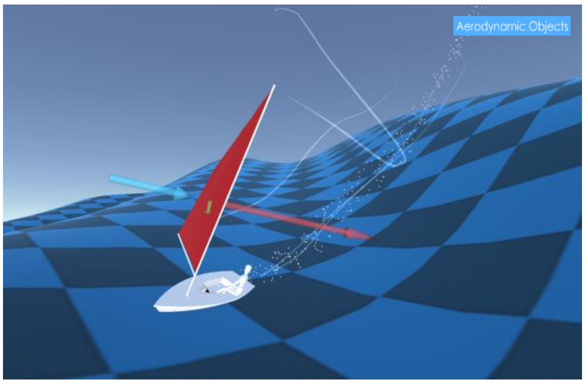




Introduction

A sailing boat is like an aircraft flying on its side on a water surface. The surfaces generate aerodynamic forces from the relative motion of the air and the lower surfaces generates hydrodynamic force due to the relative motion of the water. Aerodynamics and hydrodynamics are based on the same fluid dynamics principles, but the main difference that water is approximately 1000x as dense as air. This means that hydrodynamic surfaces on boats such as rudders are much smaller than the equivalent aerodynamic surfaces, such as sails.

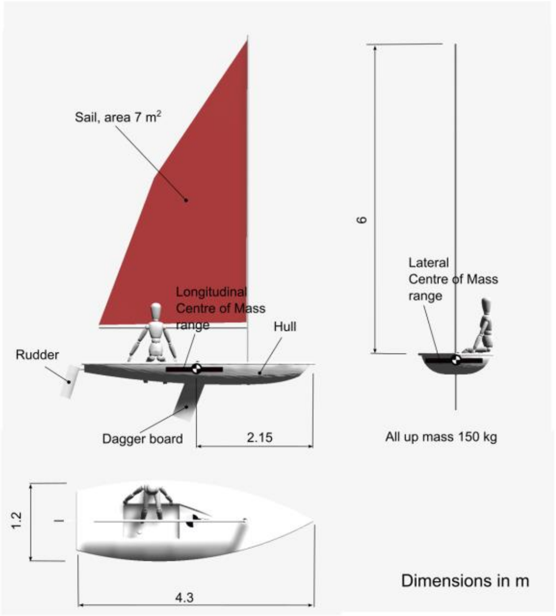


Figure 1 Outline dimensions and mass properties of a Laser class sailing dinghy

For this case study, we are using Aerodynamic Objects to model the physics of a Laser dinghy class of sail boat. Lasers are relatively small one or two person boats that are widely used for recreational and competitive sailing. The outline dimensions of a Laser are shown in Figure 1. The mass of the boat is around 70 kg, and with a single sailor the total mass is around 150 kg. The quoted ideal wind speed range for Lasers is 8 to 12 knots (4 to 6 m/s), depending on sail size choice and crew mass.

Modelling

The Aerodynamic Object components used to model the fluid dynamic properties of the laser model are shown in Figure 2. The sail is approximated by a thin ellipsoid with aspect ratio approximately equal to the actual sail aspect ratio and aerodynamic centre approximately collocated with the sail aerodynamic centre. The ellipsoid model adequately captures the overall lift, drag and pitching moment characteristics of the sail over the entire angle of attack range, however it doesn't capture detailed effects like vortex lift from swept edges. The model also does not at present recognise the change in camber of the sail as a function of lift magnitude and direction. The sail is articulated around the mast. A sail angle of 0 degrees corresponds to the boom being parallel to the longitudinal axis of the boat. The sail angle can be varied between +/-100 degrees.

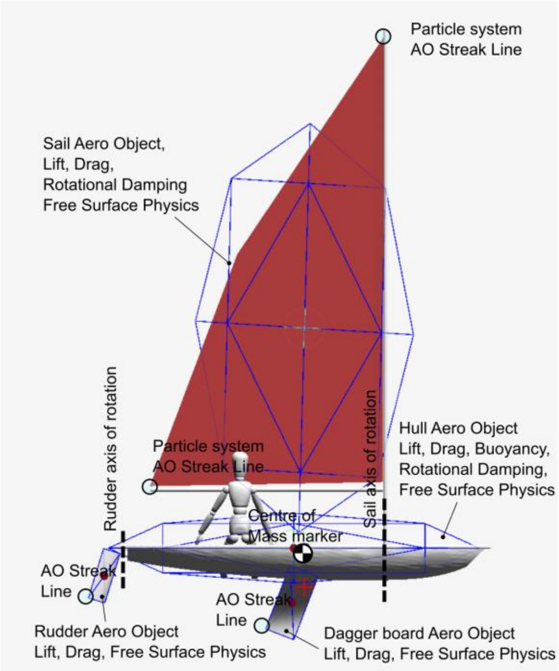


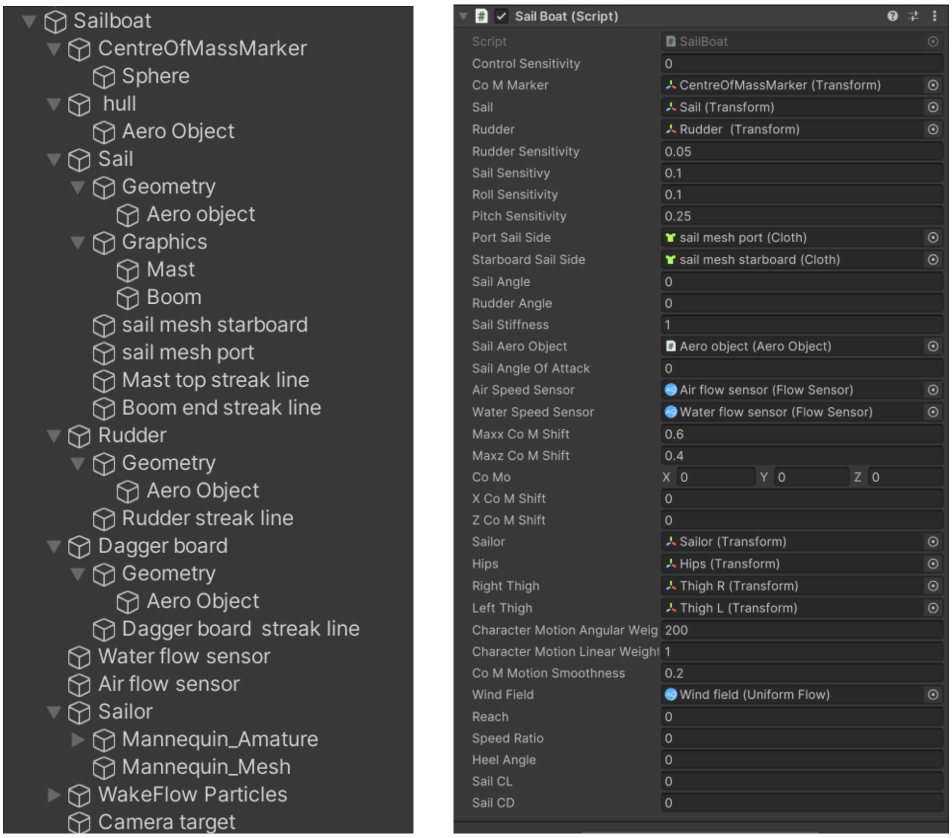
Figure 2 Aerodynamic Object components used to model a Laser class dinghy

The hull is modelled as a cigar-shaped ellipsoid that provides a good representation of the hull lower surface, which is important for calculation of buoyancy. The need to use symmetrical objects does mean that there is non-physical addition of volume above the deck plane, however this only contributes to buoyancy when the boat is inverted, and when the boat is the right way up, contributes only to aerodynamic drag, which is small compared to the hydrodynamic drag of the submerged portion.

The daggerboard and rudder are model using aero objects with rectangular reference areas. The rudder is articulated about a vertical axis at the stern of the boat. The rudder and dagger board do not contribute towards the buoyancy of the boat.

The centre of mass (CoM) of the boat can be varied dynamically within user specified longitudinal and lateral ranges. The sailor mannequin provides an approximate animation of the crew movement needed to achieve the required CoM shift by leaning in and out and by shifting fore and aft. As a limitation, there is no animation for the sailor to swap sides on the boat - the sailor always sits on the port side. CoM can be controlled by the user at run time using the arrow keys on the keyboard. Keeping the boat reasonably trimmed using CoM movement is essential to effective sailing at anything but very low wind speeds. This is quite challenging to do from the keyboard and effectively limits the maximum sailable wind speed in the simulation. Implementation of closed loop control of pitch and roll using CoM shift is relatively straightforward to do and would be a useful addition to the model.

For visualisation purposes, the model has streak line generators at the tip of the sail, tip of the boom and on the tips of dagger board and rudder. For reasons of efficiency, AO particle system components do not interact with the surface physics component, hence Streaklines may cross fluid boundaries in realistic situations with large waves. This is clearly non-physical, but generally not visually distracting.

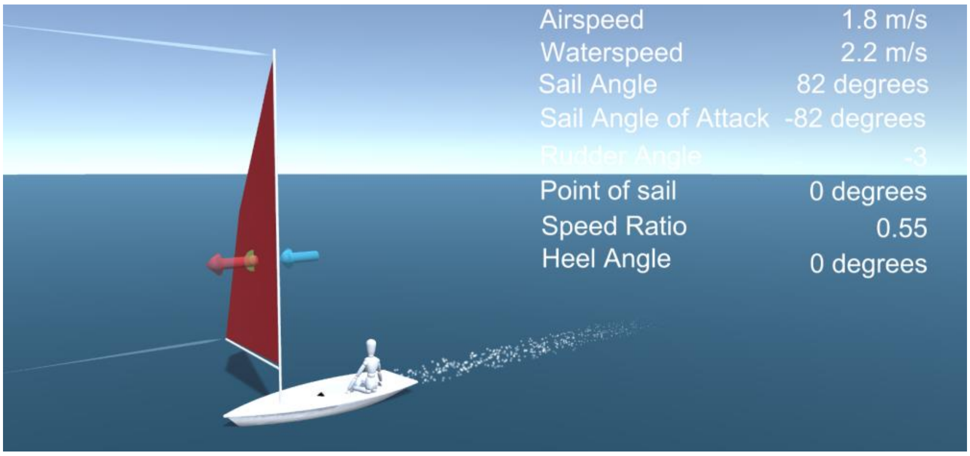


- Sailboat
  - CentreOfMassMarker
    - Sphere
  - hull
    - Aero Object
  - Sail
    - Geometry
      - Aero object
    - Graphics
      - Mast
      - Boom
    - sail mesh starboard
    - sail mesh port
    - Mast top streak line
    - Boom end streak line
  - Rudder
    - Geometry
      - Aero Object
    - Rudder streak line
  - Dagger board
    - Geometry
      - Aero Object
    - Dagger board streak line
  - Water flow sensor
  - Air flow sensor
  - Sailor
    - Mannequin_Amature
    - Mannequin_Mesh
  - WakeFlow Particles
  - Camera target

Sail Boat (Script)

Script	SailBoat
Control Sensitivity	0
Co M Marker	CentreOfMassMarker (Transform)
Sail	Sail (Transform)
Rudder	Rudder (Transform)
Rudder Sensitivity	0.05
Sail Sensitivy	0.1
Roll Sensitivity	0.1
Pitch Sensitivity	0.25
Port Sail Side	sail mesh port (Cloth)
Starboard Sail Side	sail mesh starboard (Cloth)
Sail Angle	0
Rudder Angle	0
Sail Stiffness	1
Sail Aero Object	Aero object (Aero Object)
Sail Angle Of Attack	0
Air Speed Sensor	Air flow sensor (Flow Sensor)
Water Speed Sensor	Water flow sensor (Flow Sensor)
Maxx Co M Shift	0.6
Maxz Co M Shift	0.4
Co Mo	X 0 Y 0 Z 0
X Co M Shift	0
Z Co M Shift	0
Sailor	Sailor (Transform)
Hips	Hips (Transform)
Right Thigh	Thigh R (Transform)
Left Thigh	Thigh L (Transform)
Character Motion Angular Weig	200
Character Motion Linear Weight	1
Co M Motion Smoothness	0.2
Wind Field	Wind field (Uniform Flow)
Reach	0
Speed Ratio	0
Heel Angle	0
Sail CL	0
Sail CD	0

a) Scene hierarchy for Sailboat object *b) Inspector view for Sailboat class*



Airspeed	1.8 m/s
Waterspeed	2.2 m/s
Sail Angle	82 degrees
Sail Angle of Attack	-82 degrees
Rudder Angle	-3
Point of sail	0 degrees
Speed Ratio	0.55
Heel Angle	0 degrees

c) Game view HUD

Unity implementation

The Sailboat is implemented as a prefab in the Sailboat Demo Scene in Aerodynamic Objects. An overview of the scene hierarchy for the sailboat object, inspector view for the sailboat class and example game view is shown in Figure 3. The scene also contains a Water System object which defines the water surface behaviour and a Uniform Flow flow primitive object that defines the wind field. Aerodynamic Objects has its own simplified Water System with limited graphics capability for prototyping. This can be swapped out for other custom water systems as required.

Results

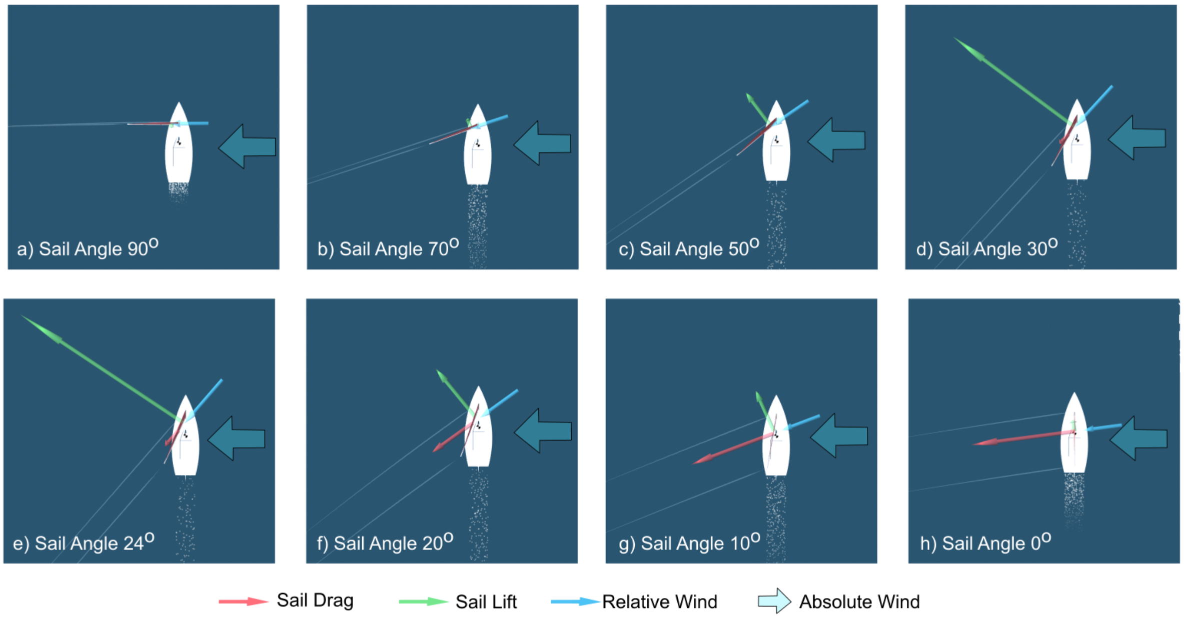


Figure 4 Visualisation of effect of varying sail angle on sail aerodynamic forces whilst sailing at 90° to the wind. Wind speed 4 m/s. Heel angle = 0. Streaklines sources located on mast tip and boom tip. Rear wake visually indicative of speed relative to water (particle spawn rate and life is the same for all cases).

Characterisation of performance whilst sailing at 90 degrees to the wind is shown in Figure 4 and Figure 5. In this experiment, the boat is constrained laterally to motion along a 90-degree tack at zero heel (roll angle) and zero yaw. Pitch angle, and vertical and longitudinal displacement are unconstrained. The independent variable is sail angle. Results are steady state but reached by dynamic transition from a previous state with forward velocity consistent with sailing practice. Results represent the best outcome in terms of maximum speed ratio for a given sail angle.

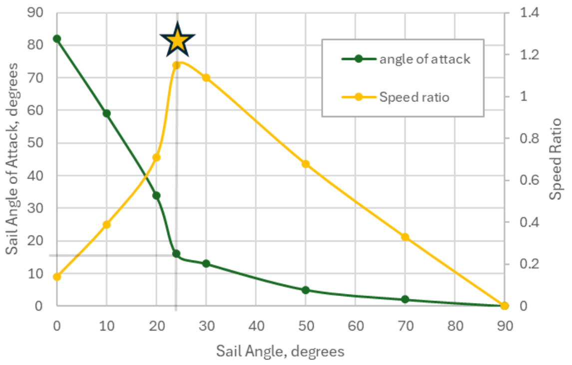


Figure 5 Sail angle of attack and ratio of boat water speed to absolute wind speed (speed ratio) for varying sail angle whilst sailing at 90° to the wind. Wind speed 4 m/s. Heel angle 0

The optimum sail angle for the given test case is around 24 degrees. At this condition, the speed ratio is a maximum, achieving a value of around 1.2. The sail angle of attack is around 16 degrees.

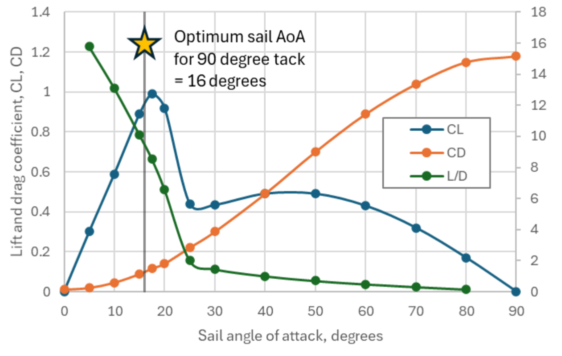


Figure 6 Sail aerodynamic performance as a function of sail angle of attack

The aerodynamic performance of the sail with changing angle of attack is shown in Figure 66. The sail has a maximum lift coefficient (blue curve, left hand axis scale) of around 1.0 and this is achieved at angle of attack of around 17 degrees. The sail maximum drag coefficient (orange curve, left hand axis scale) is around 1.2 and occurs at an angle of attack of 90 degrees. The maximum lift to drag ratio of around16 occurs close to zero degrees angle of attack since the sail is uncambered. Introduction of sail camber would usefully move the angle of attack for best L/D to the right. Note that the peak sailing performance for a 90-degree tack identified in Figure 5 corresponds to operating at a sail angle of attack just below the angle of attack for sail maximum lift. Optimum sailing performance in this case is biased more strongly towards achieving maximum lift rather than maximum lift to drag ratio.

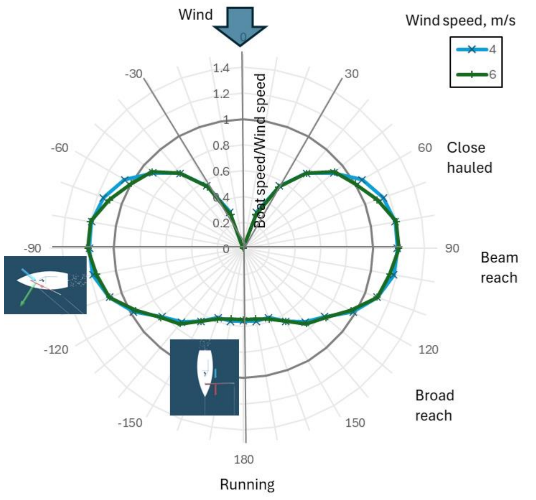


Figure 7 Point of Sail Polar Diagram for a Laser class dinghy obtained by simulation using Aerodynamic Objects

A point of sail polar diagram for the modelled Laser is shown in Figure 7. In this diagram, wind is blowing top to bottom and the angle of the radial lines is the angle of sailing (point of sail) relative to the wind direction. A point of sail of 180 degrees is running directly with the wind, an angle of 90 degrees is running directly across the wind and an angle of 0 is going directly into wind. The radial axis is speed ratio, which is the ratio of the boat speed relative to the absolute wind speed. The water is stationary and hence the boat speed is the speed relative to the water. The solid circle represents a speed ratio of unity – the boat is travelling at the same speed as the wind. Polars are plotted for two different wind speeds (4 and 6 m/s).

The polar diagram obtained from simulation is similar in form to that expected from practice. Of note is that the maximum speed is obtained by sailing 90 degrees to the wind (speed ratio of 1.2) and the down wind speed ratio is approximately 0.5 (boat travelling at half the wind speed). The minimum stable point of sail achieved in simulation was around 30 degrees. However, with trim drag (which was not present in the artificially constrained simulation test case) this angle will increase. A more typical minimum point of sail in practice for this type of boat is around 60 – 70 degrees.

Conclusion

1. A simple model of a Laser class sailing dinghy has been developed using Aerodynamic Objects for aero and hydrodynamic components and simulated using Unity. The dinghy is controlled via sail angle and rudder angle, with attitude trim obtained by centre of mass shift. The sail is approximated as an elliptical flat plate with same aspect ratio as the actual sail.
2. An evaluation of the sailing performance at a point of sail of 90 degrees shows that the maximum speed ratio is obtained at a sail angle of attack of around 16 degrees, which corresponds to the maximum lift condition for the wing.
3. A point of sail vector diagram has been produced via simulation that is similar in form to published data for similar sailing boats. The overall maximum speed ratio of 1.2 occurs at an angle of 90 degrees to wind. The maximum speed ratio down wind is around 0.5 and the closest point of sail upwind is around 30 degrees.

Further work

- Develop closed loop control of attitude trim using CoM shifting
- Introduce variable camber in the sail profile due to sail deflection under load
- Evaluate scaling of model to larger boats and inclusion of a foresail