Speedboat Aerodynamic Objects Case Study

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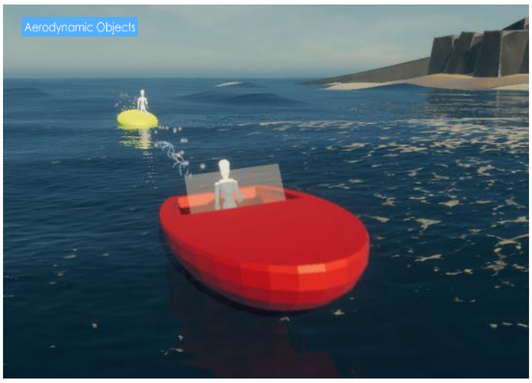

Introduction

The speed boat demo made with Aerodynamic Objects in Unity demonstrates the use of a simple ellipsoid hull and steerable under water propeller to make a high-performance boat. The boat has an all-up mass of 4 tonnes (4000 kg) and a nominal top speed of around 30 m/s (60 kts). Objects such as inflatables can be towed behind it using a towline. The outline dimensions of the boat are given in Figure 1.

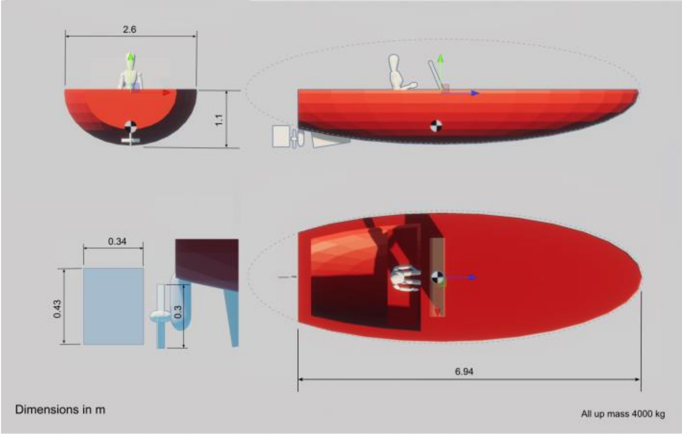

Figure 1 Speedboat general arrangement

Modelling

The speedboat aero/hydrodynamics is modelled using Aero Objects for the hull, keel, rudder and two propeller blades, Figure 2. A choice is made to scale and position the hull Aero Object so that it correctly models the geometry of the under surface of the boat, which makes the greatest contribution to buoyancy and hydrodynamic forces during normal operation. The use of an extended ellipsoid shape exaggerates the volume and surface area of the upper surface and rear of the boat and hence will give an increased aerodynamic drag under normal operating conditions. It also gives a relatively unrealistic centre of buoyancy when the boat is inverted, but since this only affects post dynamic upset behaviour its impact on model utility is relatively minor. The hull Aero Object includes models for Lift, Drag, Wave Drag, Rotational Damping, Buoyancy and uses Free Surface Physics to manage interaction with the water surface.

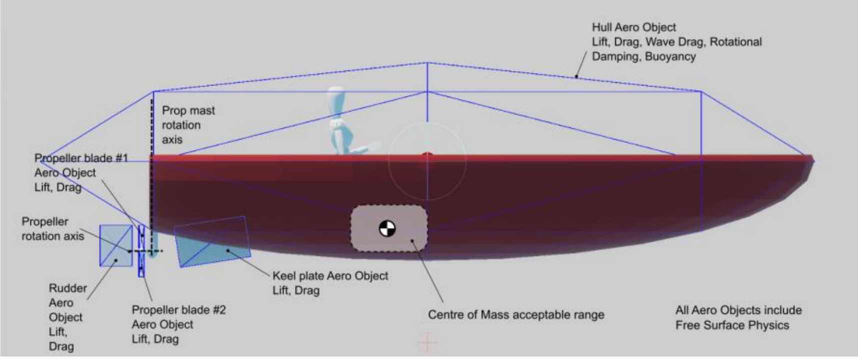

Figure 2 Aero/Hydrodynamic components used to model the speedboat

The boat has a keel plate that provides additional direction stability and roll damping. The keel plate also has a physical collider that allows the boat to slide over ramps etc without the propeller striking the ground. A rudder is fixed to the propeller mast and a combination of steering and thrust vectoring is obtained by rotation of the mast about its axis.

The coordinate system for the boat is centred at the centre of the bounding ellipsoid for the hull Aero Object, which is coincident with the origin of the hull mesh. Orientation is AO default, which is z forwards, y up, x right.

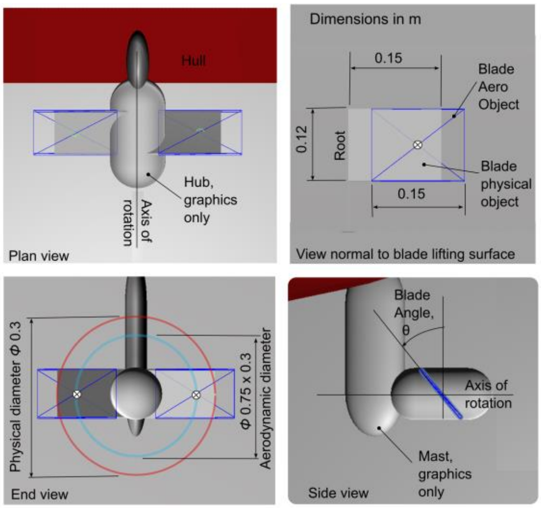

Figure 3 Detailed arrangement of speedboat propeller

The detailed arrangement of the propeller is shown in Figure 3. An Aero Object is centred at the 75% radius location of each blade, consistent with the approximate radial location of the mean aerodynamic chord for a rotating wing. Note that the blue graphic associated with the blade Aero Object is there to visually represent the reference lengths and areas of the object being modelled. The object centre is used as the reference location for measuring velocity relative to the surrounding fluid. The blade angle θ sets the pitch of the propeller, where pitch in m is given by $p = 0.75\, \pi D \tan\theta$.

The Centre of Mass (CoM) range indicated in Figure 3 represents the CoM range over which boat performance is acceptable. With a high CoM the boat has reduced hydrostatic stability, will tend to pitch up with increasing throttle and roll out of the turns due to centrifugal force. With the CoM at the same height as the centre of action of the propeller, coupling due to propulsive forces is minimised. Shift of the CoM aft of the centre of buoyancy of the hull (centre of hull Aero Object) means that the hydrostatic trim of the boat is nose up, which is helps in preventing the boat ‘nosing in’ at high speeds and in the presence of waves.

Theory

The theory in this section is included because it is used for subsequent analysis the performance of the propeller propulsion model as a function of propeller rotational speed, propeller blade pitch and boat speed. It is not used as part of the propeller model itself and its understanding is not essential to using propellers, however it does take some of the mystery out of how to choose an appropriate propeller for a given boat and required performance.

A propeller is defined by its diameter D (or radius R), number of blades, N, pitch P and blade mean chord c (or equivalently by its solidity σ). Pitch is measured in distance units and represents the distance the propeller would move axially after one rotation in the fashion of a screw. Solidity is the ratio of total blade area to the area of the propeller disc.

For the present model, the propeller is modelled using rectangular, untwisted blades with a blade aspect ratio AR_b.

By definition, for a propeller with N blades, solidity is given by

$$\sigma = \frac{A_b}{A_d} = \frac{Nc}{\pi R}$$

EQ 1

where c is the blade chord. Rearranging gives

$$c = \frac{\sigma \pi R}{N}$$

EQ 2

Blade aerodynamics is modelled using a single aerodynamic control point located according to common practice at 75% blade radius. From geometry, assuming that the plane of an untwisted blade is parallel to the propeller disc as defined in Figure 3, the twist angle θ of the blade is given by

$$\theta = \tan^{-1}\frac{0.75\pi D}{P}$$

EQ 3

The propeller model includes internal calculation of thrust coefficient, C_T, torque coefficient using the following definitions.

$$C_T = \frac{T}{\rho n^2 D^4}$$

EQ 4

$$C_Q = \frac{Q}{\rho n^2 D^5}$$

EQ 5

where T is the thrust, Q is the torque, ρ is the fluid (water) density, $n = \omega/2\pi$, and D is the diameter.

The advance ratio of the propeller is defined as

$$J = \frac{V_a}{nD}$$

EQ 6

where V_a is the free stream speed.

Finally, the propulsive efficiency of the propeller η_p is defined as follows:

$$\eta_p = \frac{\text{propulsive power out}}{\text{shaft power in}} = \frac{TV_a}{Q\omega} = \frac{C_T J}{C_Q 2\pi}$$

EQ 7

The propulsive efficiency is by the above definition zero when the advance ratio is zero (water speed is zero), however the propeller is still producing a static thrust so is doing useful work on the water, but the boat is not moving.

Results

Propeller efficiency as defined by EQ 7 for three different propeller blade angles of 20, 30 and 40° is shown in Figure 4. These results were obtained for a fixed prop speed of 5000 RPM. The boat was fixed in place and water speed set using an AO Uniform Flow flow primitive. Recalling that Advance Ratio is proportional to boat speed for a constant propeller rotation rate, the propeller with lower pitch (smaller blade angle) is more efficient at producing thrust at lower forward speeds, and the higher pitch propeller is more efficient at high speeds. Note that the efficiency for the lower pitched props drop to zero at higher speeds – it is not just that they are less efficient at high speeds, they are unable to produce positive thrust at high speeds, thus the maximum speed of the boat is geometrically limited by the propeller pitch (and max rotation rate).

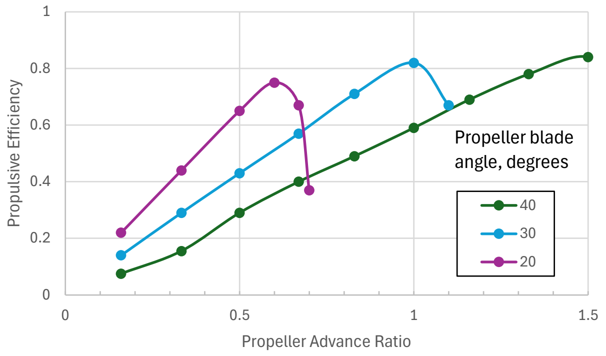

Figure 4 Propeller propulsive efficiency as a function of advance ratio for three different blade angles

Complete results for the case shown in Figure 4 including both thrust coefficient and torque coefficient for the propeller are shown in Figure 5. Note that for 40° pitch case, the thrust coefficient (and hence thrust for constant rotational speed) *increases* with forward speed to start with. Thus whilst the aggressively pitched propeller gives a higher top speed, it has lower acceleration at low speed. This is a common trade in propeller selection whether for boat or aircraft applications.

Lastly, an unconstrained test was taken with the boat free to move through stationary water to evaluate achieved top speed for each of the propeller variants, Figure 5. The maximum speed with a blade pitch of 20° is around 15 m/s whereas the maximum speed for a blade pitch of 40° is around 35 m/s. In each case most of the additional speed comes from the last 20% of the throttle range (propeller rotational) speed. This is due to combination of thrust being proportional to the square of speed and the increase in propulsive efficiency as forward speed increases.

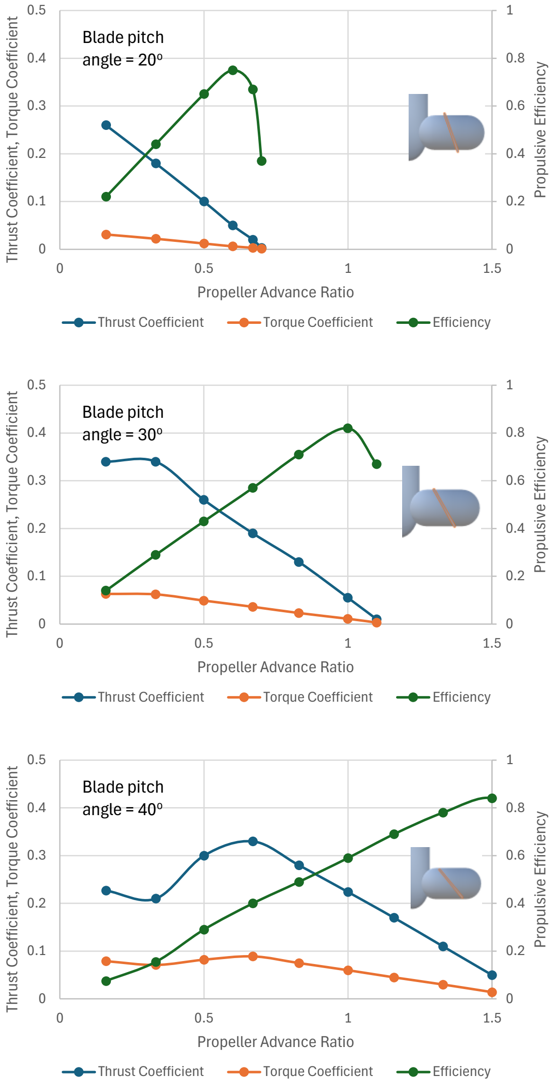

Figure 6 Performance evaluation of propellers with blade angles of 20, 30 and 40°

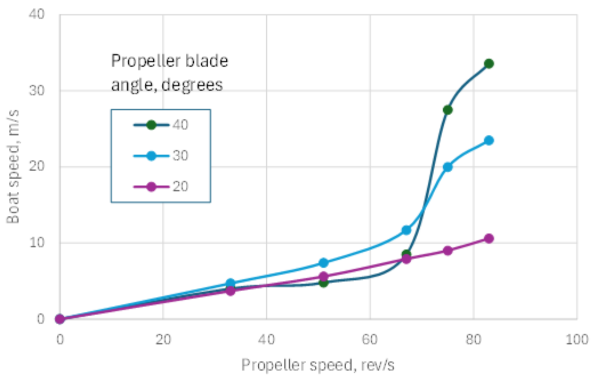

Figure 5 Speed boat maximum water speed as a function of propeller rotation speed

Conclusion

- A high-performance boat model has been developed in AO using a simple ellipsoid hull geometry and kinematic propeller.
- A CoM placement envelope for acceptable compromise between stability, static trim and trim during turning manoeuvres has been established.
- The propeller model has been analysed using traditional propeller theory and understanding developed of the need to choose propeller pitch based on a compromise between requirements for thrust at low speeds and efficiency at high speeds.

Further work

- Evaluate effect of hull shape (beam over length ratio and depth over length ratio) on maximum speed and handling qualities
- Evaluate handling qualities in increasingly large sea states (waves)
- Experiment with adding hydrofoils to lift the hull out of the water (see FoilBoard demo)