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Aerodynamics of High-Speed Sponsons

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AERODYNAMICS OF HIGH-SPEED BOAT SPONSONS

by

Kevin P. Curran

A Thesis

Presented to the Graduate and Research Committee

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in Candidacy for the Degree of

Master of Science

in

Mechanical Engineering

Lehigh University

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Certificate of Approval

This thesis is accepted and approved in partial fulfillment of the requirements for the Master of Science.

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Abstract

Research undertaken at Lehigh University into the design of sponsons for high speed racing boats is described. Sponsons from a commercially available RC racing boat, the Eagle SGX-45, along with custom built sponson designs underwent wind tunnel testing. The aerodynamic stability of these sponsons was examined particularly as related to “ground” effects near the water surface.

Two different concepts for sponsons for high-speed boats were conceived with two overarching objectives - low drag and vehicle stability. The two different sponson concepts had very different behaviors, each benefitting a particular usage.

The goal of the first type of sponson design was to minimize lift gradient (lift force as a function of angle of attack) to effectively increase the longitudinal pitch stability of the boat. The results show that a new, more aerodynamically "neutral" sponson (with a lift coefficient nearly independent of angle of attack) could be made, and that it had considerably better aerodynamic performance than the commercial sponson.

The goal of the second type of sponson was to provide substantial aerodynamic lift, but only in ground effect. The boat would then be able to "fly" at an essentially constant height above the water surface, thus eliminating hydrodynamic drag and accordingly have very low total drag. Results from wind tunnel tests showed that a sponson in the shape of a small aspect ratio wing equipped with end plates had the desired characteristics.

Nomenclature

AR	Aspect ratio (-)
b	Wingspan (*m*)
C_L	Lift coefficient (-)
c	Wing chord length (*m*)
D	Drag force (*N*)
F_{oT}	Total drag area (m^2)
h	Height above water surface (*m*)
L	Lift force (*N*)
L/D	Lift/drag ratio (-)
q	Dynamic pressure (*Pa*)
S	Planform area (m^2)
v	Air velocity (*m/s*)
α	Angle of attack (°)
ρ_{air}	Air density (kg/m^3) (1.204 kg/m^3 @ 20 °*C*)

1. Introduction

The high-speed boats presently considered are manned or unmanned outriggers and hydroplanes. These tend to be the fastest boats at the present time, although some catamarans are also very fast. Outriggers generally consist of a center hull that is not in contact with water and two or more sponsons that ride in or on the water. The sponsons may be rigidly attached, or attached via a suspension system to the center hull [1]. Outriggers have proven to be very efficient for high speed racing boats, though a major challenge is to keep the craft stable and prevent them from flipping over.

It is well known that the glide ratio or lift-over-drag ratio, L/D, in water at high speed is considerably lower than in air. Extreme glider aircraft can have maximum L/D on the order of 70 [2]. From a rough estimate, the L/D of modern offshore race boats appears to be in the range 1.5-4[1]. However, tow tank tests on rectangular blocks show that L/D on the order 10 can be achieved in water for higher trim angles (on the order of 6 degrees) and lower lift coefficients [3]. High trim angles tend to lead to very high forces on the sponsons, and these can often make the boat pitch up so drastically that it flips over unless the sponsons are mounted with an adequate suspension.

Since L/D is likely to be considerably higher in air than in water, the total drag of a boat can often be reduced drastically if the air is carrying a substantial part of the weight of the vehicle. Aerodynamic support of the boat can be achieved with wings (in

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[1] Based on published numbers and the formula $L/D=mgv/(P_{eng}\eta)$ where m is mass, g is gravitational acceleration, v is speed, P_{eng} is engine power, and η is propeller and driveline efficiency (estimated at 75%).

ground effect or free stream), high pressure under the vehicle, lifting bodies, etc. A major difficulty is that many of these schemes lead to vehicles which are inherently unstable aerodynamically, in particular in pitch.

The present paper deals with two kinds of vastly different sponsons. The goal of the first design (Sponson *A*) was to minimize lift gradient (lift force as a function of angle of attack), whereas the goal of the second sponson (Sponson *B*) was to provide substantial aerodynamic lift but only in ground effect. These sponsons and the goals are discussed further below in two separate sections.

The sponsons discussed in the following sections operate at very low altitudes in the strong surface effect zone (SEZ), typically at values of $h/c < 0.1$, where h is height above water surface and c is wing chord length. Operating in SEZ, properly designed ground effect wings can have increased lift, reduced drag, and an increased lift to drag ratio over conventional wings in free stream [4]. The lift to drag ratio of Wing in Ground Effect (WIG) craft increases significantly as the flying height is decreased within the SEZ. Flying close to the water surface creates a region of higher pressure under the wing due to the blockage created between the wing and water surface. This effect can increase the lift significantly. Also the wing tip wash down velocity is decreased, therefore reducing induced drag and increasing the effective aspect ratio for the wing [5] [6]. The advantages and technology of WIG craft can be directly applied to the aerodynamics of high speed racing boats. The majority of a high speed boat is completely above the water surface and experiences aerodynamic ground effects similar to WIG craft.

2. Aerodynamic Pitch Stability and Sponson A

Aircraft are made aerodynamically stable in pitch by placing the center of mass ahead of the aerodynamic center of the vehicle, e.g. [7]. The aerodynamic center is the point around which the pitching moment does not change when the pitching angle of the aircraft is changed. The aerodynamic center of a large-aspect ratio unswept wing is at 25% of the chord behind the leading edge. With a horizontal tail mounted behind the wing the aerodynamic center is moved backwards.

Outriggers often have two sponsons mounted well ahead of the center of mass of the vehicle, plus some sponson(s) towards the rear. If the front sponsons provide an aerodynamic lift force which increases with angle of attack, then they are highly destabilizing for the vehicle in pitch. Sponson A, which is shown in Figure 1, was designed to provide very little lift, and in particular a small lift gradient. Ideally the lift gradient would be zero for a wide range of angles of attack, or

$$\frac{\partial L}{\partial \alpha} = 0$$

where L is lift (perpendicular to the free stream far ahead of the sponson) and α is angle of attack. Low lift gradient was achieved by letting the tail converge into a point, thus avoiding any trailing edge which could provide a Kutta condition.

Further requirements on a forward sponson are good hydrodynamic performance and low aerodynamic drag. Hydrodynamic performance is achieved using mainly flat running surfaces with sharp edges (avoiding any Coanda effect). Low drag was achieved using an elongated teardrop shape with a well-rounded bow, and a long tail cone. The aerodynamic performance of this sponson is shown in Figure 2, Figure 3, and Figure 4. The details of the wind tunnel testing are described in Appendix A.

The aerodynamic performance of Sponson A was compared with that of a sponson from a common high-speed RC boat, the Eagle SGX-45 from Competition Marine Designs, Inc. in free stream and in ground effect, simulating all typical operating conditions.

2.1 Sponson A

A new sponson, called Sponson A in this paper, was developed to be "aerodynamically neutral", such that the lift was almost independent of angle of attack. Sponson A was 375 mm from tip to tail and had a max width of 86 mm with a planform area of 0.0236 m^2. It is shown in Figure 1.

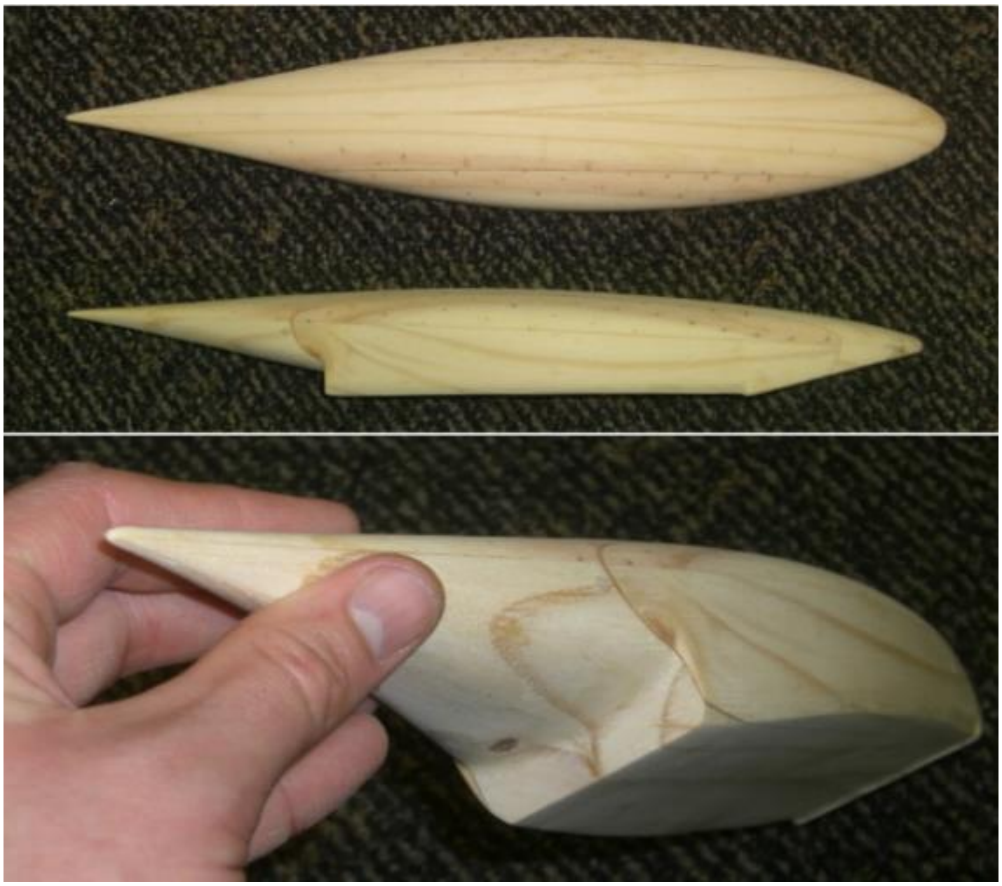

Figure 1: Sponson A: designed to have no aerodynamic lift and low aerodynamic drag, yet good hydrodynamic performance.

2.1 (a) Sponson A in Free Stream

Figure 2 shows Sponson A results from free stream wind tunnel testing. For angles of attack (as measured between the water surface and the sponson's flat bottom) between approximately 0° and 10° the lift and drag are almost constant. Between 0° and 10° the lift coefficient increases from 0 to 0.027. The total drag area between these angles increases from approximately 0.00075 m^2 to 0.0009 m^2. For these angles of attack the sponson can be considered nearly aerodynamically neutral in free stream. The increases in lift and drag with angle of attack are not significant.

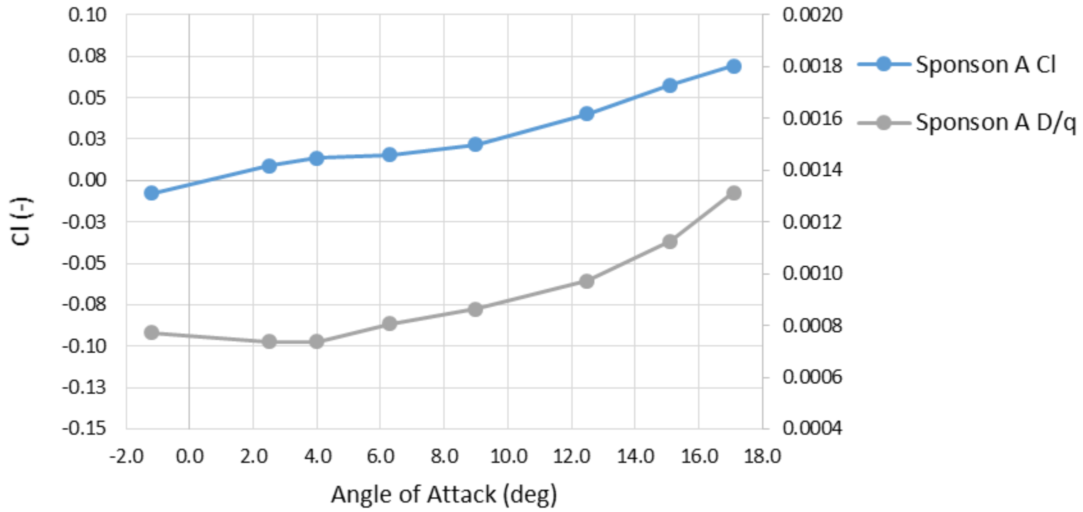

Figure 2: Aerodynamic lift and drag of Sponson A in free stream

2.1 (b) Sponson A in Ground Effect

To determine the aerodynamic characteristics of Sponson A in ground effect a second model was manufactured. This model was placed below the sponson being measured to simulate the symmetric ground plane as shown in Appendix A. The separation distance was measured between the back of the two bottom running surfaces of the sponsons. The measured separation distance between the sponsons is equivalent to twice the distance between the sponson and the symmetric simulated ground plane (i.e., the simulated distance above the water surface is half of the separation distance).

As shown in Figure 3, at an elevation of 10 mm, the lift coefficient variance between 1° and 7° angle of attack was approximately 0.03, similar to the variance in lift coefficient in free stream. The change in lift force with angle of attack was not significant in ground effect, therefore Sponson A meets the stability criteria for being essentially aerodynamically neutral also in ground effect. For higher angles of attack, the lift force decreased with increasing elevation, also making the sponson height stable; this will be discussed in more detail in conjunction with Sponson B.

The total drag area (Figure 4) did have a dependence upon angle of attack, which is unfavorable, however the dependence was small for small angles of attack.

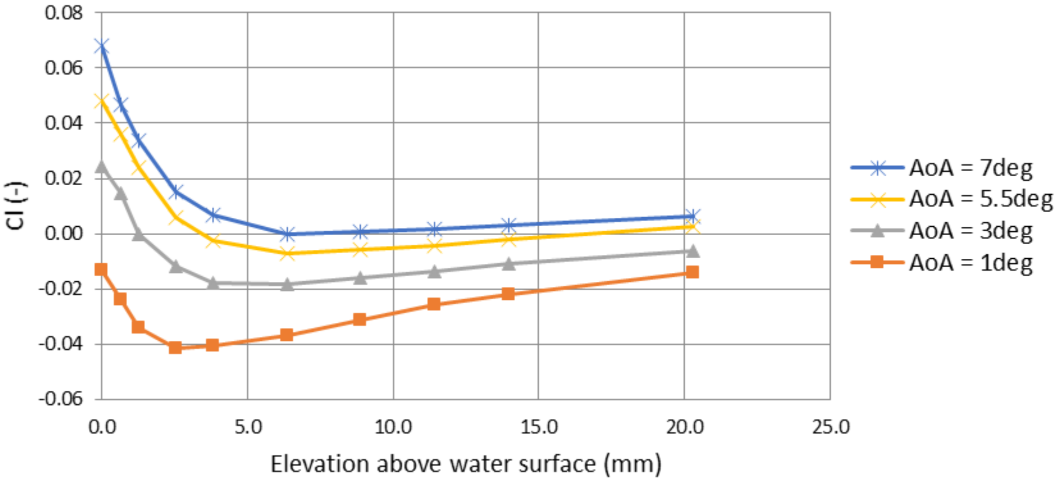

Figure 3: Aerodynamic lift for Sponson A in ground effect

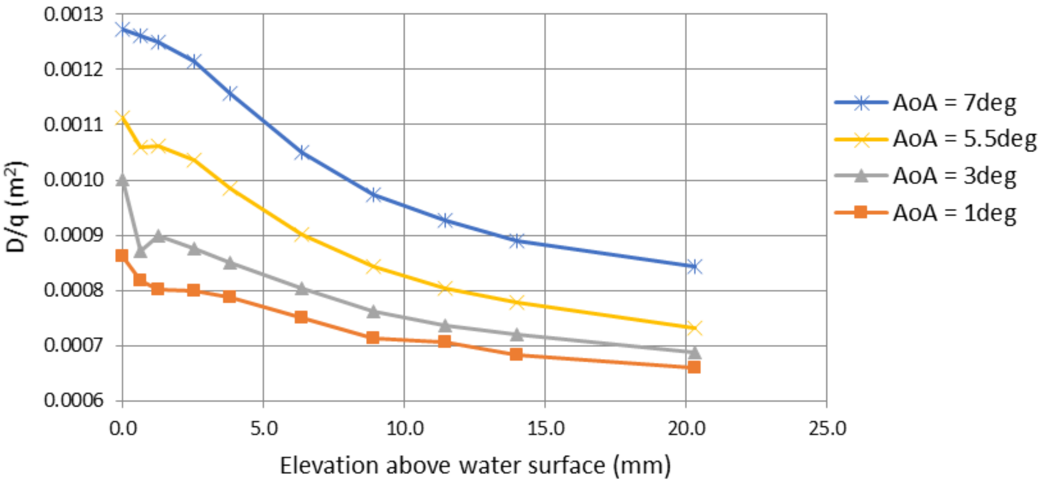

Figure 4: Aerodynamic drag for Sponson A in ground effect

2.2 Eagle SGX-45

The Eagle SGX-45 is a modern RC boat capable of speeds approaching 200km/hr. The model boat is an outrigger with an engine mounted in the center hull and a prop mounted at the rear of the center hull. It is commonly used for RC boat racing.

Sponsons from the Eagle SGX-45 were purchased and mounted with attachments for use in the wind tunnel. The attachments were made to be small and at the rear of the models to minimally interfere with the sponson aerodynamics. The SGX-45 sponsons are shown in Figure 5. Each sponson had a maximum width of 70 mm and a length of 424 mm with a planform area of 0.0257 m^2. Compared to the planform area of Sponson A (0.0236 m^2) the difference was less than 10%.

Figure 5: Sponson from commercially available RC outrigger race boat, the Eagle SGX-45.

2.2 (a) SGX-45 Sponson in Free Stream

As shown in Figure 6, the coefficient of lift for the Eagle SGX-45 sponson in free stream (without ground effect) is heavily dependent upon angle of attack (again defined between the water surface and the sponson's bottom running surface). Between 0° and 10° the lift coefficient varied between approximately -0.015 and 0.090, a change of 0.105. Between 0° and 10° Sponson A varied 0.027, or about a quarter of the amount of the SGX-45 sponson variance in lift coefficient. The total drag area of the Eagle sponson, shown in Figure 7, was also dependent on angle of attack, having a total drag area of approximately 0.00115 m^2 at 0° and 0.00155 m^2 at 10° (an increase of 35%).

The lift and drag of Sponson A depends much less on angle of attack than the SGX-45 sponson. Also the total drag area of Sponson A was approximately 40% less than the SGX-45 sponson at low angles of attack in free stream. The reduced drag advantage increased with increasing angle of attack. In free stream, the SGX-45 sponson is far from aerodynamically neutral. Due to the strong dependence of lift on angle of attack, the sponson would move the aerodynamic center forward and thus contribute to longitudinal instability in pitch.

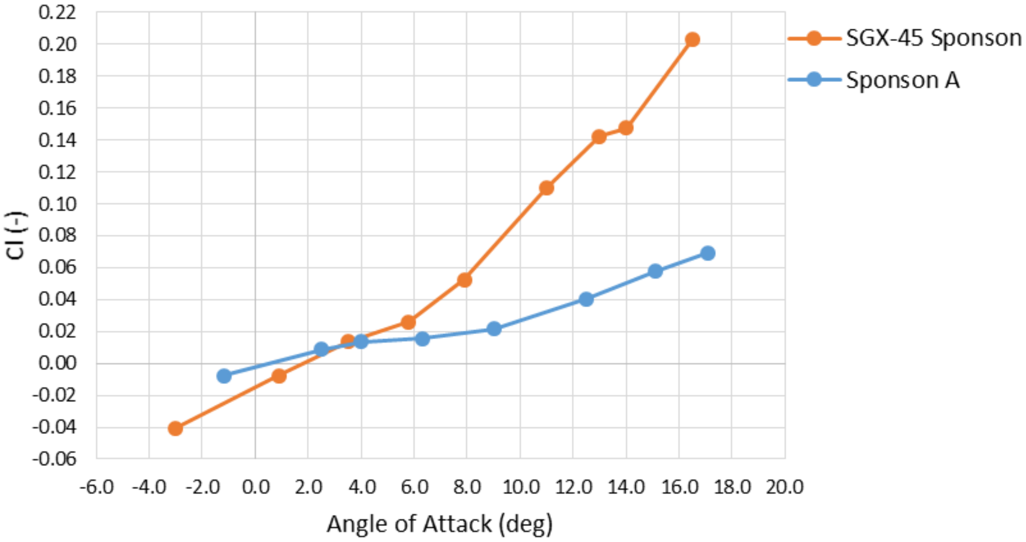

Figure 6: Aerodynamic lift of Sponson A and SGX-45 sponson in free stream

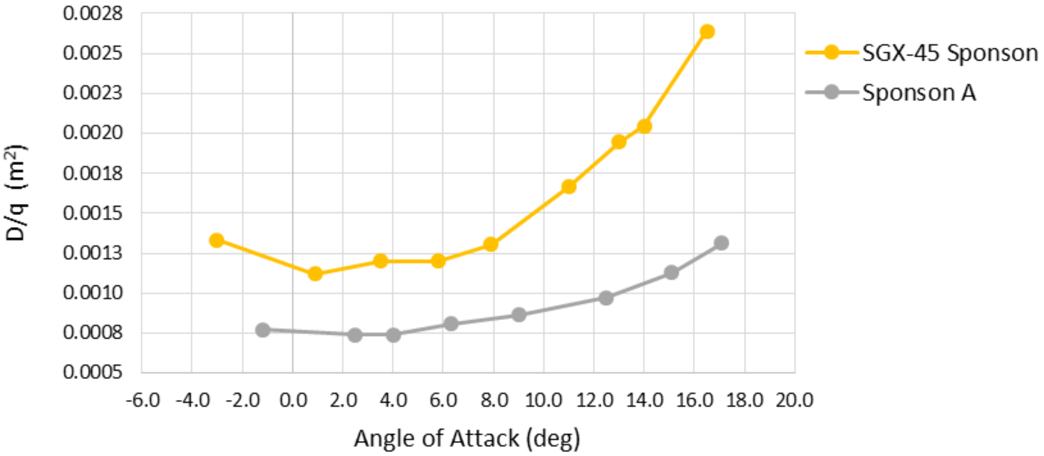

Figure 7: Aerodynamic drag of Sponson A and SGX-45 sponson in free stream

2.2 (b) SGX-45 Sponson in Ground Effect

To test the SGX-45 sponson in ground effect as a function of angle of attack and elevation above the water surface the reflection method was again used. The SGX-45 right sponson was mounted to the sting probe and the SGX-45 left sponson (a mirror of the right sponson) was mounted upside down underneath the right sponson. The results of testing the SGX-45 sponson at multiple angles of attack and at varying heights above the simulated water surface are shown in Figure 8 and Figure 9.

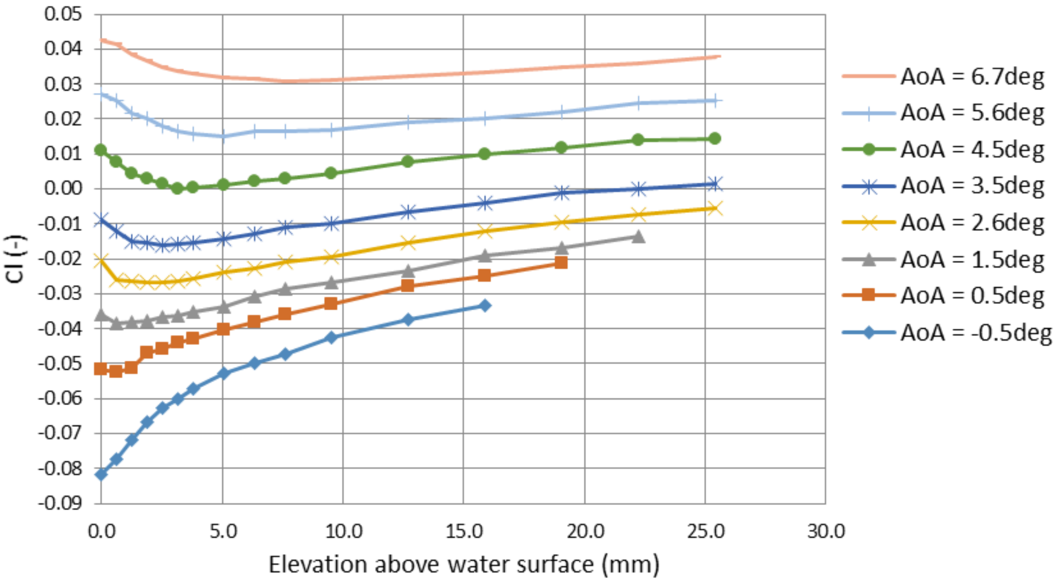

Figure 8: Aerodynamic lift for the Eagle SGX-45 sponson in ground effect

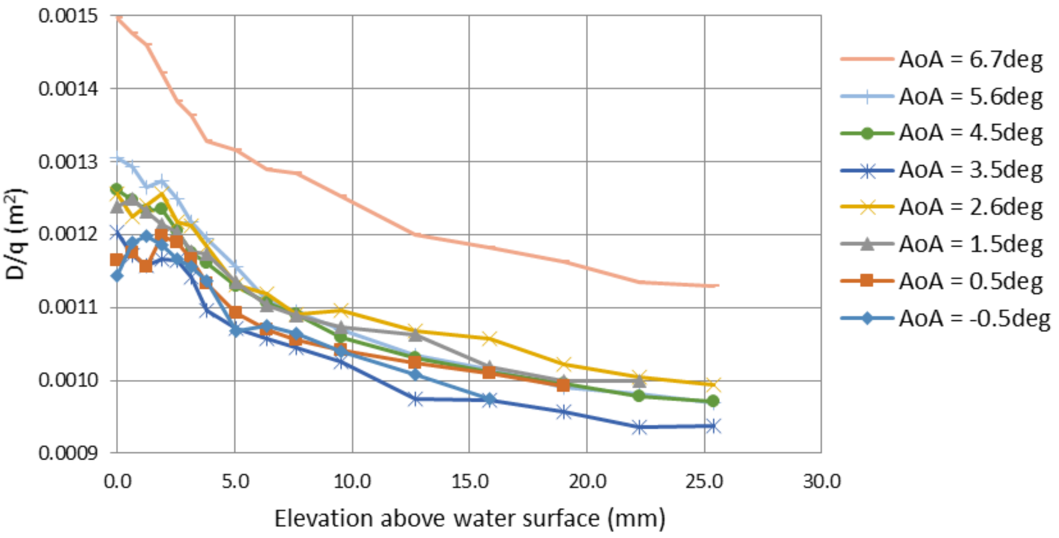

Figure 9: Aerodynamic drag for Eagle SGX-45 sponson in ground effect

The lift coefficient was dependent upon angle of attack in ground effect for the SGX-45 sponson. At 12.5 mm elevation above the water surface the lift coefficient varied from -0.037 to 0.032 for angles from -0.5° to 6.7°. The lift coefficient also increased as the elevation above the water surface increased. This is an unfavorable result as will be discussed in more detail in the next section. The total drag area of the SGX-45 sponson was also dependent upon angle of attack in ground effect. The drag increased over 20% between -0.5° and 6.7° angle of attack. The SGX-45 sponson is not aerodynamically neutral in ground effect either.

Sponson A had approximately 43% the variance in lift coefficient (0.03) of the SGX-45 sponson (0.07) between 1° and 7° at 10 mm elevation. The lift coefficient for Sponson A is thus less dependent of angle of attack than the SGX-45 sponson in ground effect.

Sponson A had less drag for every angle of attack at each separation distance, Figure 4 and Figure 9. The SGX-45 sponson had approximately 30% more drag than Sponson A. This effect is favorable for Sponson A as less drag on the sponsons increases boat efficiency.

3. Aerodynamic Lift and Sponson B

Sponson B was designed with a completely different set of goals. This sponson was designed for relatively calm water where pitch excursions of the boat are expected to be small. The goal was to get essentially all required lift of the sponson from aerodynamics. In other words, the sponson should be flying over the water with no part touching the water surface. The total drag would then be expected to be extremely low. The main requirement apart from large aerodynamic lift and low drag is that the sponsons should remain at a desired altitude above the surface in a stable fashion. This requires that the lift increases when the sponson approaches the water surface, and that it decreases when the sponson climbs to higher elevations. For a sponson to maintain a stable height above the water surface, the slope of the lift coefficient as a function of increasing elevation must be negative:

$$\frac{\partial L}{\partial h} < 0$$

where h is the elevation (or the distance between the trailing edge of the sponson's bottom and the water surface, disregarding the end plates). To achieve this objective a sponson in the shape of a small aspect ratio wing with end plates was created. The end plates force the flow to be relatively two-dimensional (2D) when in close proximity to the water surface. Air underneath the airfoil is forced into a channel bounded by the end plates, the water surface, and the airfoil. As the height above the water is increased the 2D channel is allowed to disperse into three-dimensional (3D) flow. The 2D flow was expected to yield higher lift than the 3D flow, thus being able to provide the desired lift reduction with increasing altitude.

The airfoil NACA-4418 was chosen due to its relatively flat bottom surface at moderate angles of attack. A wooden model (and later a PLA rapid prototype plastic model) was created. The planform area was 0.023187 m^2 and the chord and width (or wingspan) were 152.27 mm. This results in an aspect ratio of 1, as shown in the equation below:

$$AR = \frac{b^2}{S}$$

where b is span and S is planform area.

3.1 Sponson B in Free Stream

Sponson B without end plates was first tested in free stream in the wind tunnel at various angles of attack. From these results, shown in Figure 10, the highest lift/drag ratio was found to occur at approximately 5.5° angle of attack. End plates were created for the NACA-4418 airfoil at this angle to maximize lift/drag ratio for Sponson B. The end plates on the airfoil can be seen in Appendix A.

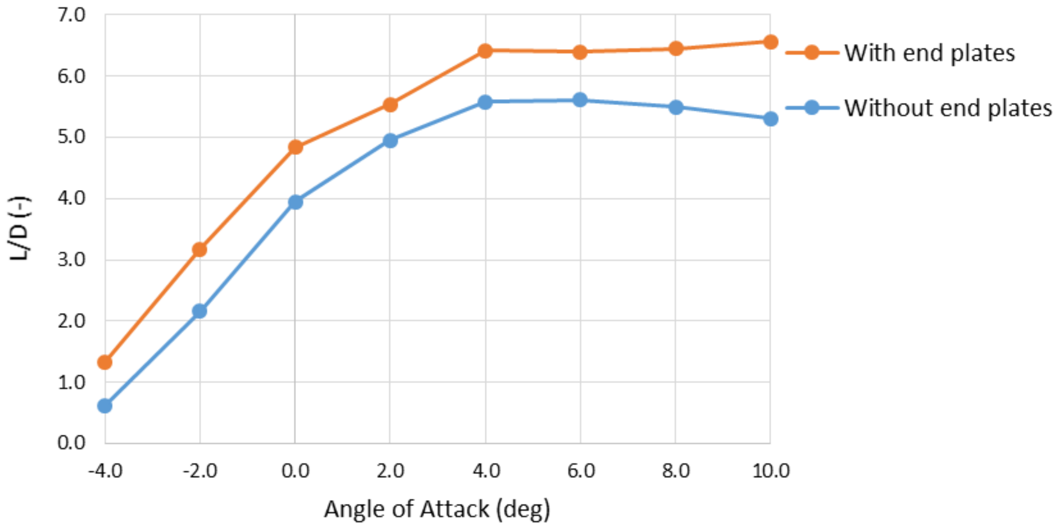

Figure 10: Lift/drag ratio for Sponson B in free stream

For the NACA-4418 sponson in free stream the $\partial C_L/\partial \alpha$ was found to be approximately 0.034 deg^{-1} without the end plates and 0.046 deg^{-1} with the end plates, a 35% increase. The lift coefficient was also found to increase with the addition of the end plates. With end plates the C_L was 64% higher at 0° angle of attack.

3.2 Sponson B in Ground Effect with and without End Plates

The potential advantages of ground effect aerodynamics are clearly shown in Figure 11. When the airfoil is flying very close to the simulated ground plane (i.e. the water surface) the drag is low and the lift is high. As the elevation is increased the drag increases and the lift decreases. Both with and without end plates the airfoil has the desired characteristic that the aerodynamic lift decreases as the height above the water surface increases.

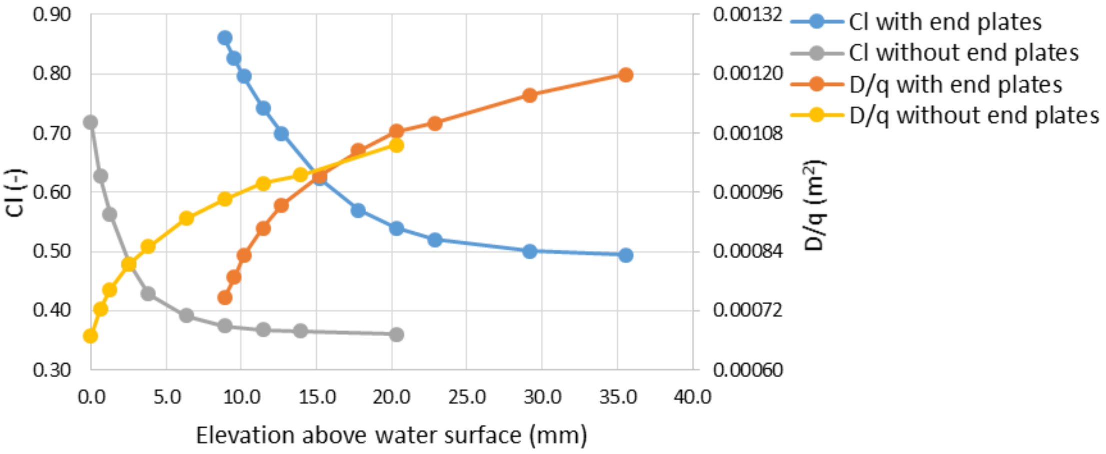

Figure 11: Aerodynamic lift and drag for Sponson B at 5.5° angle of attack

The height stability of the sponson without side plates is only found at small separation distances. The bare airfoil has a steep negative slope between elevations distances of 0mm and about 7mm, Figure 11. An airfoil would likely have difficultly running at this small of a distance above the water surface. Any small wave or water disturbance would bring the airfoil into contact with the water, greatly increasing drag momentarily.

Using end plates on Sponson B, the lift/drag ratio was increased significantly at elevation heights between 8 mm and 20 mm as shown in Figure 12. Elevation heights lower than 8 mm were not possible in the reflection testing as the bottoms of the end plates were nearly in contact when the trailing edge was at 8 mm. At 11.5 mm elevation, the lift coefficient was increased by approximately 114% by the addition of end plates, while the drag was decreased by approximately 8%. Part of the drag is likely parasitic and caused by the large end plates.

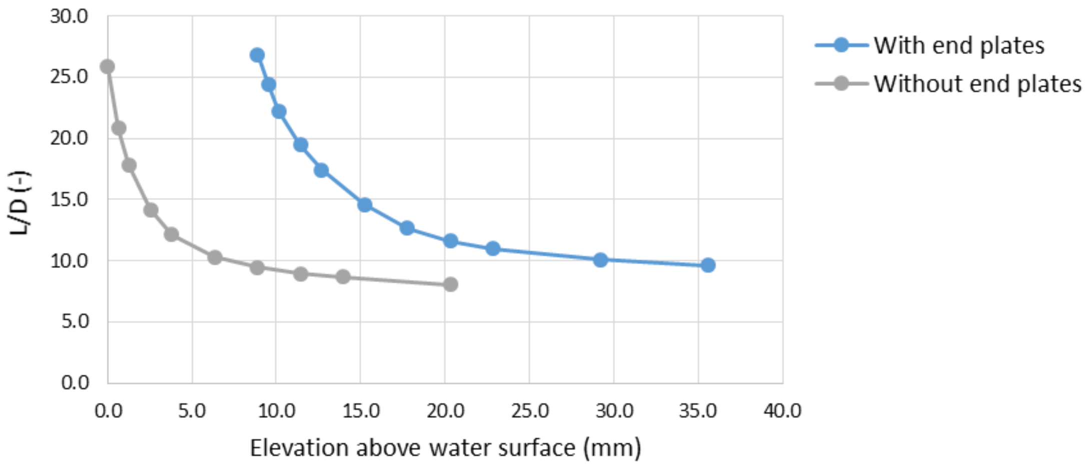

Figure 12: Lift/drag ratio for Sponson B at 5.5° angle of attack with and without end plates

As shown in Figure 12, the airfoil with the end plates displayed a more favorable negative slope at higher separation distances than the sponson without end plates. The negative slope for the sponson with end plates continued for a larger total separation distance than without end plates. The lift/drag slope for the bare sponson declined to $\partial(L/D)/\partial(h) = -0.70\ \text{mm}^{-1}$ at 5 mm elevation while with end plates the slope declined to $-0.70\ \text{mm}^{-1}$ at approximately 16.5 mm.

For 5.5° angle of attack Sponson B was found to be height stable in ground effect with and without end plates. However, the sponson was height stable at much higher elevations with the end plates. Varying angles of attack were not tested with end plates, though a similar investigation using smaller end plates suggests negative angles of attack could result in instabilities [8].

3.3 Sponson B End Plate Effects Using Flaps

The trailing edge of the airfoil (Sponson B) was made with a moveable flap. The flap length was 30% of the chord, with a pivot on the camber line of the airfoil. Trials were performed on Sponson B with the flap at different angles to examine the changes in lift and drag from these positions. The flap angle was measured from the original chord line. Testing of the airfoil with end plates and flaps down at various angles is shown in Figure 13-Figure 15. **Note:** The models used for flap angle had increased parasitic drag due to the attachment of the end plates to the flap models. The pivot and attachment screws extended past the end plates as shown in Appendix A.

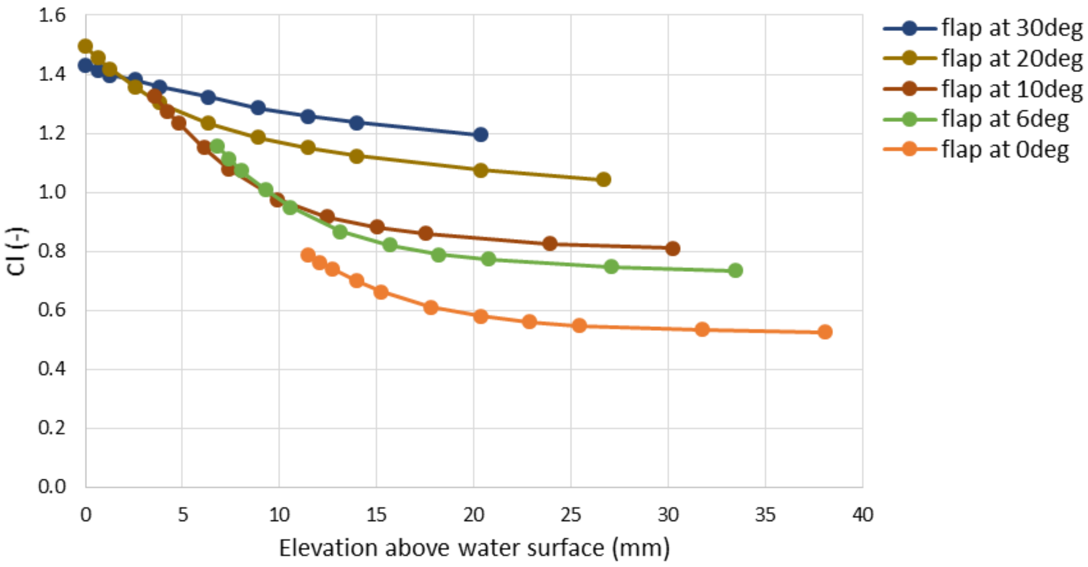

Figure 13: Aerodynamic lift for Sponson B with end plates and flaps down at angles from 0° to 30°

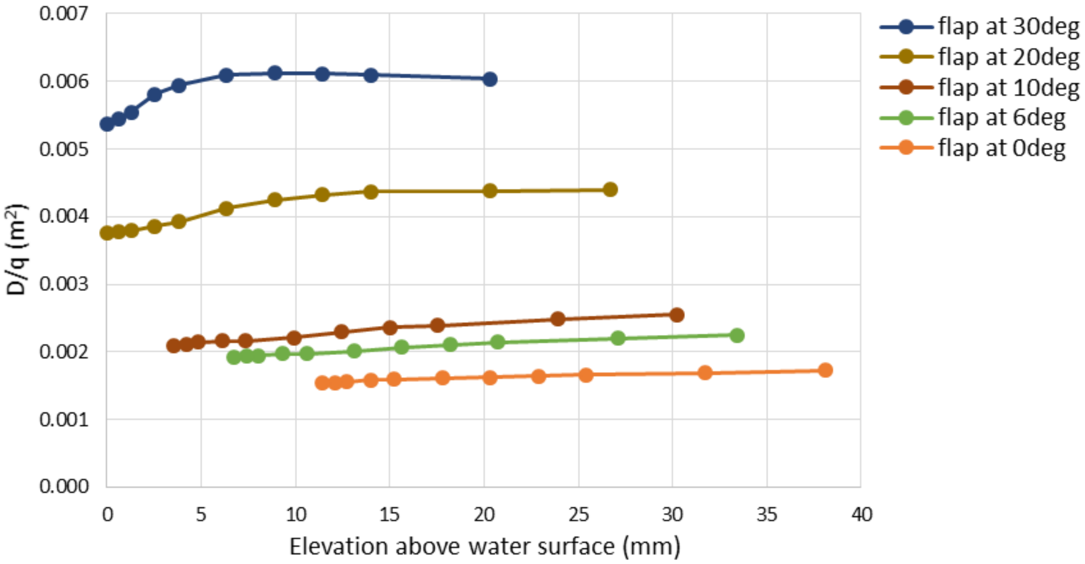

Figure 14: Aerodynamic drag for Sponson B with end plates and flaps down at angles from 0° to 30°

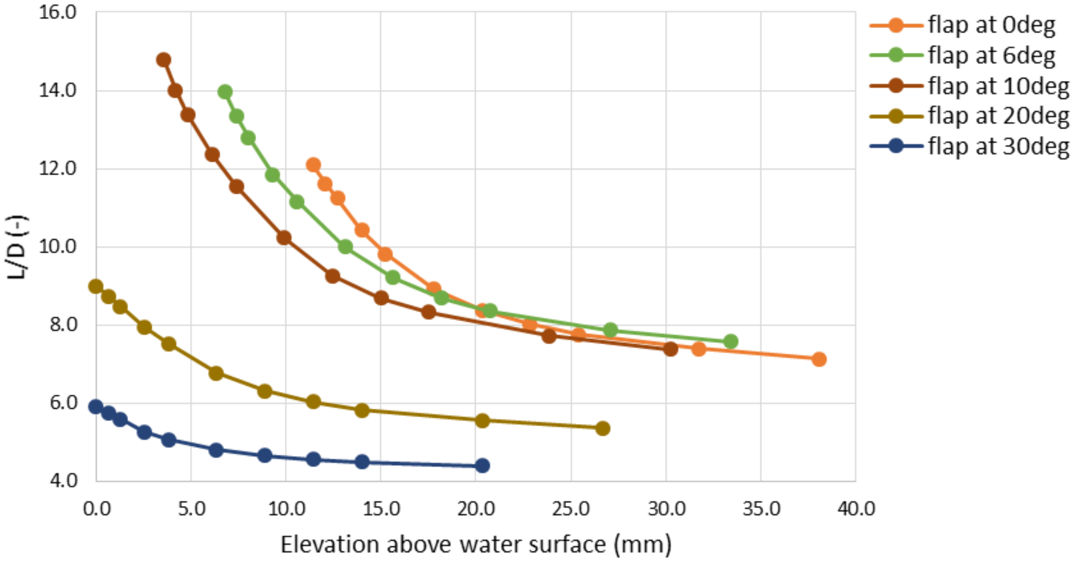

Figure 15: Lift/drag ratio for Sponson B with end plates and flaps down at angles from 0° to 30°

The trailing edge of the flap was even with the bottom of the end plates at 10° downward deflection. At flap angles more than 10° downward (i.e. 20° and 30°) the flap hung below the bottom of the end plates. The flap hanging below the end plates at 30° is shown in Appendix A. When the flap was angled below the bottom of the end plate the drag was greatly increased (Figure 14), thus reducing the lift/drag ratio significantly. Also, as shown in Figure 13, increasing the flap angle past the bottom of the plate (10°) reduced the lift coefficient for small elevations.

The lift/drag ratio at flap angles from 0° to 10° was very similar at elevations above 20 mm (Figure 15). At low separation distances the flap at 0° would likely have produced the greatest lift/drag ratio however this flap angle could not be tested below 11 mm elevation due to the physical constraint of the end plates in contact using the reflection method. Thus the flap at 0° produced the greatest lift/drag ratio above 11 mm. Flaps at 6° downward produced the greatest lift/drag ratio between 7 mm and 11 mm. The 10° downward flap produced the highest lift/drag ratio below 7 mm separation distance. In order to maintain a relatively constant lift/drag ratio in flight, the flap should not be angled below the bottom edge of the end plates, i.e. 10°

4. Conclusions

The goal of creating an aerodynamically neutral sponson was essentially achieved. The new sponson design (Sponson A), in lift and drag, was nearly independent of angle of attack for angles from approximately 0° to 10° in free stream testing. In ground effect, the sponson lift coefficient was found to have some dependence on angle of attack at low heights above the water surface, however the dependence diminished as the sponson approached free stream conditions. An aerodynamically neutral sponson would effectively move the aerodynamic center of the boat towards the aft, increasing boat stability in pitch.

The secondary goal of low drag for sponson A was also accomplished. The drag at all angles of attack was significantly lower than that of the commercially available SGX-45 sponson.

Sponson A was also found to have a negative slope of lift coefficient vs. elevation above the water surface at higher angles of attack. This effect is favorable as it would promote height stability of the sponson, bringing it to a neutral height above the water surface where the lift force matches the weight.

The SGX-45 sponson was found to contribute to the aerodynamic longitudinal instability of a boat in free stream and in ground effect. The sponsons displayed a strong dependence of lift on angle of attack, which would effectively move the aerodynamic center of the boat forward, decreasing pitch stability. The sponson also displayed a positive slope of the lift coefficient as the height above the water surface was increased. This trend leads to an unstable sponson height above the water surface in ground effect.

Sponson B was designed with the goal to provide considerable aerodynamic lift in ground effect, but have the lift reduce drastically as the sponson climbed to higher heights. It could then "fly" in a self-regulating fashion a small distance above the water. These goals were achieved. The NACA-4418 airfoil at 5.5° angle of attack showed height stability as the lift decreased with increasing elevation. However, this effect was strong only at a very low elevation above the water surface. Now, addition of large end plates to the airfoil resulted in this property (reduction of lift with increase in elevation) extending to higher elevations. The end plates also greatly increased the lift/drag ratio, especially at low elevations.

5. Future Work

Sponson A appears to have very favorable and predictable behavior. However, for Sponson B a wider range of testing may be desirable. Stability of Sponson B with end plates at negative angles of attack should be tested (or avoided) before this kind of sponson is run on a prototype as some literature suggests they may become unstable at negative angles of attack. Further, smaller end plates could likely be used to obtain a similar height stability effect. More testing would be needed to confirm this.

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Appendix A: Wind Tunnel Testing

A1: Ground Effect Reflection Method

Simply testing an object in a wind tunnel at a distance above a flat plate does not properly simulate ground effects as the plate (ground) is stationary with respect to the object instead of with respect to the wind. To simulate the aerodynamic effects between the water surface and the moving sponson the reflection method was used. The airfoil being measured was connected to the probing equipment and a mirror image model was mounted upside down below the top model. This setup creates a horizontal plane of symmetry between the airfoils that, unaffected by boundary layer effects, continues at the free stream velocity and thus simulating the ground plane. The separation distance between the models is twice the simulated height above the water surface. At high angles of attack the refection method can produce slight errors as the symmetric simulated ground plane is interrupted by vortices; however, it has still been found to be more accurate than a flat plate method [9].

A2: Model Mounting Methods and Data Collection

To test a sponson or airfoil in free stream the model was mounted in the Lehigh University wind tunnel with a 460 mm x 460 mm test section. The model was attached to an Aerolab 3-component internal strain gage force / moment balance, model AEROLAB EWT “Pistol Grip” Sting Balance. A custom probe mounting fixture, with adjustable model angles of attack and a separation distance screw was manufactured and mounted in the wind tunnel as shown in Figure A1.

Figure A1: Sting Probe and model mounting fixture

The data from this probe, when processed through a LabView program, output a lift force and drag force. The lift force and drag force of the model were measured at three different speeds spanning the range of the wind tunnel capability, 14.4 m/s, 21.7 m/s, and 29.3 m/s. The max wind speed was chosen due to vibrations caused at higher speeds. These vibrations were due to the fixture setup and not the stability of the sponsons. The velocity of the wind was calibrated using a pitot tube and a manometer. The angle of attack for sponsons was measured from the bottom running surface of the sponson with respect to the horizontal. For airfoils, the angle of attack was measured between the chord line and the horizontal.

To test a sponson or airfoil in ground effect, the model was mounted using the free stream procedure then a second mirror model was mounted upside down underneath the model being measured. This second model was moved up and down (simulating varying heights above the water surface) using a linear slider on the attachment to the model. Sponson A reflection method testing is shown in Figure A2. Sponson B reflection method testing is shown A3. Sponson B with flaps down reflection method testing is shown in Figure A4.

Figure A2: Sponson A (top) and its mirror image (bottom). Only the top model was mounted to the force balance.

Figure A3: Sponson B (top) and its mirror image (bottom). Only the top model was mounted to the force balance.

Figure A4: Sponson B (top) and its mirror image (bottom) with end plates and flaps deflected down 30° from original chord line

A3: Data Reduction

The lift force and drag force data was reduced to lift coefficient (C_L), total drag area (F_{oT}), and lift/drag ratio (*L/D*). These values were then averaged between the three air velocities for each angle of attack or elevation. The coefficient of lift (C_L) is defined as:

$$C_L = \frac{L}{q * S}$$

where *S* is the projected planform area of the sponson, and *q* is dynamic pressure,

$$q = \tfrac{1}{2}\rho_{\mathrm{air}} v^2$$

where ρ_{air} is air density and *v* is airspeed.

The total drag area (F_{oT}) is defined in this paper as

$$F_{\mathrm{oT}} = \frac{D}{q}$$

where D is total (measured) aerodynamic drag. Note that in this paper F_{oT} is not zero-lift drag area, but total drag area (including induced drag).

Curriculum Vitae

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