INTRODUCING GROUND EFFECT INTO PERSONAL WATERCRAFT

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MARINE DESIGN


Fig. 1

ABSTRACT

This applied design research focuses on the introduction of ground effect into personal watercraft as a way of improving the efficiency and performance of the craft, while also creating a new user experience. Ground effect is an aerodynamic phenomenon experienced by bodies flying in close proximity to a surface and results in a significant increase in the lift to drag ratio. It is used by race boats as a means of improving performance.

The scope of this research will be to investigate how ground effect may be implemented into personal watercraft to help increase their efficiency. This will be used as a framework for designing a revised form of personal watercraft. The opportunity to redesign a craft (from the ground up) provides a product offering a level of market differentiation. As such, all aspects will be assessed for their impact on the efficiency, performance and user experience.

The current paradigm in personal watercraft design is based upon a saddle-style seat, like that of a motorbike. This arrangement does not actively promote a shared user experience, resulting in personal watercraft use being perceived as an anti-social activity. Research conducted into the design of a new general arrangement that promotes more interaction between the driver and passenger while using the product is investigated.

The outcome of this research is a design that has performance comparable to the existing market leaders, while having less impact on the environment. Moreover, it will be a design that confronts the social issues surrounding this adrenalin-inducing pastime.

Fig. 2

Fig. 3

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This project would not have been possible without the help and support of my friends and family. Throughout the project I had many people who lent a hand or offered guidance and support.

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Fig. 4

1.0 INTRODUCTION

Aerodynamic lift is widely used in powerboat racing as a means of reducing the wetted surface of the craft to increase performance. This practice is yet to become popular in the recreational boat market.

The aim of this research project is to create a new, more efficient, class of PWC through the application of aerodynamic lift, an examination of the current PWC paradigm and assessment of possible alternatives to the current designs. This will include alternative general arrangements, aesthetic treatments, user experience, construction processes and hull design.

This thesis documents the research undertaken to satisfy this aim. I will begin by giving a background of the research topics, how they have developed, where they headed and how they affect the scope of this thesis. This section includes a review of the existing literature and an explanation of the research methods and design process within this project and their development toward a variety of solutions. Finally, I will discuss and analyse the results of my research before giving conclusions and recommendations for further research.

In comparing the first Personal Watercraft (PWC), the Sea-Doo, introduced into the market by Bombardier Recreational Products (BRP) in 1968 (fig. 5), with the latest craft (fig. 4,) the similarities are obvious. Little has changed in terms of layout or the way the craft is operated in the 42 years of this category of the craft's existence. However, significant changes have been made in terms of performance, which I will enlarge upon in later sections. Progressing from the initial craft's 32 horsepower engine, manufacturers are now selling craft with 260 horsepower. This has led to promotional videos showing PWC out-running Ferrari sports cars over a quarter mile drag, evidence enough that these are performance-orientated craft, without mentioning the racing circuits set up for them.

It is intriguing, then, that these craft have not yet taken advantage of aerodynamic assistance in their quest for speed when it is prevalent in almost all other powerboat racing circuits, including both inshore and offshore racing classes. This becomes particularly interesting when one considers the relative inefficiency of these craft; a 3.54 metre PWC with 260 horsepower has a top speed of 68mph and a 6.0metre sports boat with 200 horsepower has a top speed of 60mph.

Sea-Doo: A JET SPEEDSTER THAT BRINGS NEW ZOOM AND A NEW BOOM TO BOATING FUN

By DAN FALES, Boating Editor

Photos by Burton McNeely

HERE'S THE FIRST report on the newest and hottest "boat" you'll see this summer. Called Sea-Doo, it's to water what snowmobiles are to snow. In fact, this jet-powered water scooter is produced by Bombardier, Ltd., maker of the popular Ski-Doo snowmobiles.

During a special trip to Florida, I rode a new Sea-Doo. I raced it, jumped it, played tag with it, spun it out. I tried to tip it, to drown it, to foul it on a beach. Verdict: a fun machine that's bound to catch on.

But Sea-Doo's success will not be based on fun alone. There are two other important reasons. First, no propeller. Second, it won't tip over (unless you really **work** at flipping it). Until now, water scooters have been sexy little boats usually powered by outboard motors;

Fig. 5

Fig. 6

2.0 BACKGROUND

In this chapter I analyse the existing theory related to the research areas selected for this project. I begin with a history of personal watercraft that illustrates how they have developed, what the current and past trends have been in terms of technology, features and aesthetics. This leads into an analysis of how aerodynamic assistance has been applied to different styles of racing craft and how they could be applied to this project in particular. As part of this, the principles of ground effect will be introduced and the literature surrounding this will be assessed. This section will conclude with an analysis of the available literature related to stepped-hull design, resulting in the formulation of design guidelines for such a hull form.

2.1 The History and Development of the Personal Watercraft

2.1.1 The Beginning

A PWC is defined by the Personal Watercraft Industry Association (PWIA) as "a vessel which uses an inboard motor powering a water jet pump as its primary source of motive power, and which is designed to be operated by a person sitting, standing, or kneeling on the vessel, rather than the conventional manner of sitting or standing in the vessel."

As previously stated, PWC were introduced by Sea-Doo in 1968. However, due to engine problems all 1500 sold were recalled and the product withdrawn from the market (Horiuchi, 2006). The "craft's turning ability was poor" (Horiuchi, 2006). With a claimed top speed of only 25mph (35mph on the second generation) (Oldseadoos, 2006), it was hardly the performance-orientated device PWC are today. It was not until the early 1970s when Kawasaki Motors Corporation introduced the Jet Ski, a stand up style craft, that the PWC concept became commercially successful (PWIA, 2006).

In 1987 Yamaha Motor Company introduced the Wave Runner (fig. 6), a sit-down style craft similar to the original Sea-Doo, but with more emphasis put on handling (Horiuchi, 2006). This style of craft began the modern era of PWC with only Kawasaki and Yamaha continuing to manufacture stand-up models. Currently there are four main manufacturers: Yamaha, Sea-Doo, Kawasaki, and Honda (PWIA, 2006). Sea-Doo re-entered the market two years after Yamaha, with Honda joining the market in 2002 (PWIA, 2006).

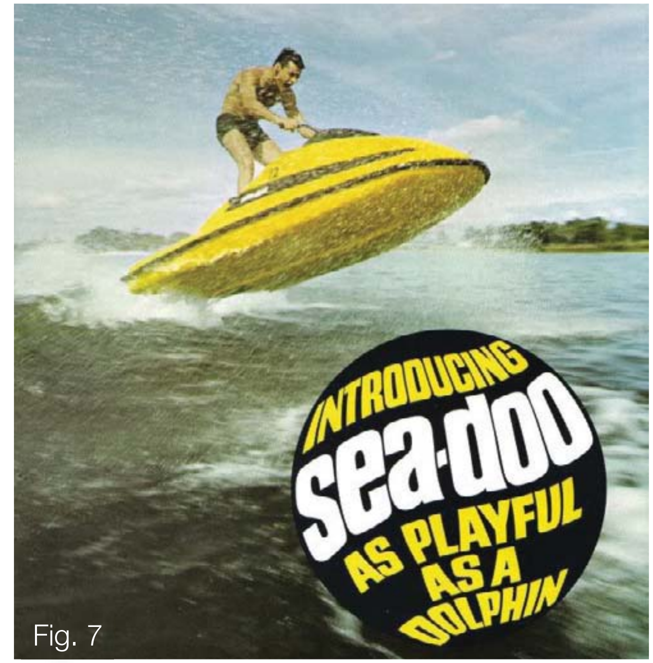


Fig. 7

Fig. 8


Fig. 9

2.1.2 Developments in Technology

PWC are a controversial product, with many marine and shoreline users as well as environmentalists complaining about the noise and pollution that is associated with their operation (Blue Water Network, 2002). The introduction of regulations for new personal watercraft since 1998 have led to significant improvements in the efficiency and sound levels associated with the craft. The PWIA reported reductions in noise levels between 1998 and 2006 of 70%, with evidence on manufacturers' web sites of further reductions.

In the same period, the PWIA also reports a reduction in emissions of 90%, largely attributed to the introduction of four-stroke engines into all sit-down models.

The introduction of the heavier four-stroke engines also corresponds with a trend of larger and heavier PWC than their two-stroke counter parts. When comparing the specifications of the pre-four-stroke craft with those of the current models the difference is clear; both represent the top of the high performance line for Sea-Doo in their respective eras - the 1998 model being smaller in every dimension. A more in-depth look at this is presented in the discussion and analysis chapter.

The modern Sea-Doo in the comparison above uses Sea-Doo's new iS system, making it one of the most technically advanced PWCs ever made. The iS system, introduced in 2009, incorporates the following computer controlled features: braking, reverse, throttle and suspension, and also introduces the first "stepped hull" into the PWC market (fig. 10).

The purpose of the step is not, however, the same as in most stepped hull boats. Where most steps are employed to increase the efficiency of the hull (by reducing wetted surface area), the S3 hull, as Sea-Doo dubs it, tries to do the complete opposite. Sea-Doo uses a small forward sweeping step in line with the water jet intake to create a low pressure zone. This low pressure zone, instead of creating lift, sucks the hull of the boat to the water. I suspect that this is an effort to keep the hull in contact with the water as much as possible to provide as much solid water supply to the impeller as possible. This being said, without testing this hypothesis, it is difficult to tell how effective this system is.

The benefits of other features that Sea-Doo has introduced can more clearly be recognised; the introduction of neutral means that the craft will not start moving forward as soon as the engine is engaged. This is combined with the introduction of a reversing bucket that also doubles as a brake, allowing manoeuvring in marinas and other tight areas, as well as making it easier to dock the craft. When the brake/reverse lever (fig. 12) is pulled, while the craft is travelling at speed, the craft automatically puts itself in neutral, deploys the reversing bucket, and then reapplies power to push against the craft's motion (fig. 13).


Fig. 10

Fig. 11

The introduction of a braking system is another PWC first, but the effectiveness of this feature, however well intentioned, is questionable. Sea-Doo markets the product by saying that it reduces the stopping distance by 100 feet, but neglects to give an indication of the percentage the stopping distance is reduced by or the resulting stopping distance. An independent review by Personalwatercraft.com reported a reduction in stopping distance of between 30-50%, giving a stopping distance of 100ft (or around 30m). Given that it is illegal to operate a craft at more than 5 knots (9.26km/h) within 200m of land or other boats, it is hard to determine a situation where the brake would be necessary - given a PWC's inherently small turning radius.

Sea-Doo has also introduced an intelligent suspension system where the hull moves independently from the upper structure of the vessel. The rider can then adjust how hard or soft the suspension is on the handlebars to suit the riding style and conditions, much like modern suspension in some cars. This will allow a much more comfortable ride at the expense of performance because of the added weight of such a complex structure (fig.14).

Other features included in the Sea-Doo line up include;

• Cruise control

• Automatic retractable mooring ties

• High performance variable trim system (VTS)

• Off-throttle assisted steering

• Tilt steering

• Fold-down re-boarding ladder

• Learning key (limits speed of craft)

• Closed loop cooling system

• Ski tow eye

• Adjustable mirrors

The significant list of features fitted on the new Sea-Doo craft may help to explain the increase in size and weight of the craft described earlier. There seems to be a trend to move away from outright performance towards a more refined craft.

Fig. 12

Fig. 13

Fig. 14

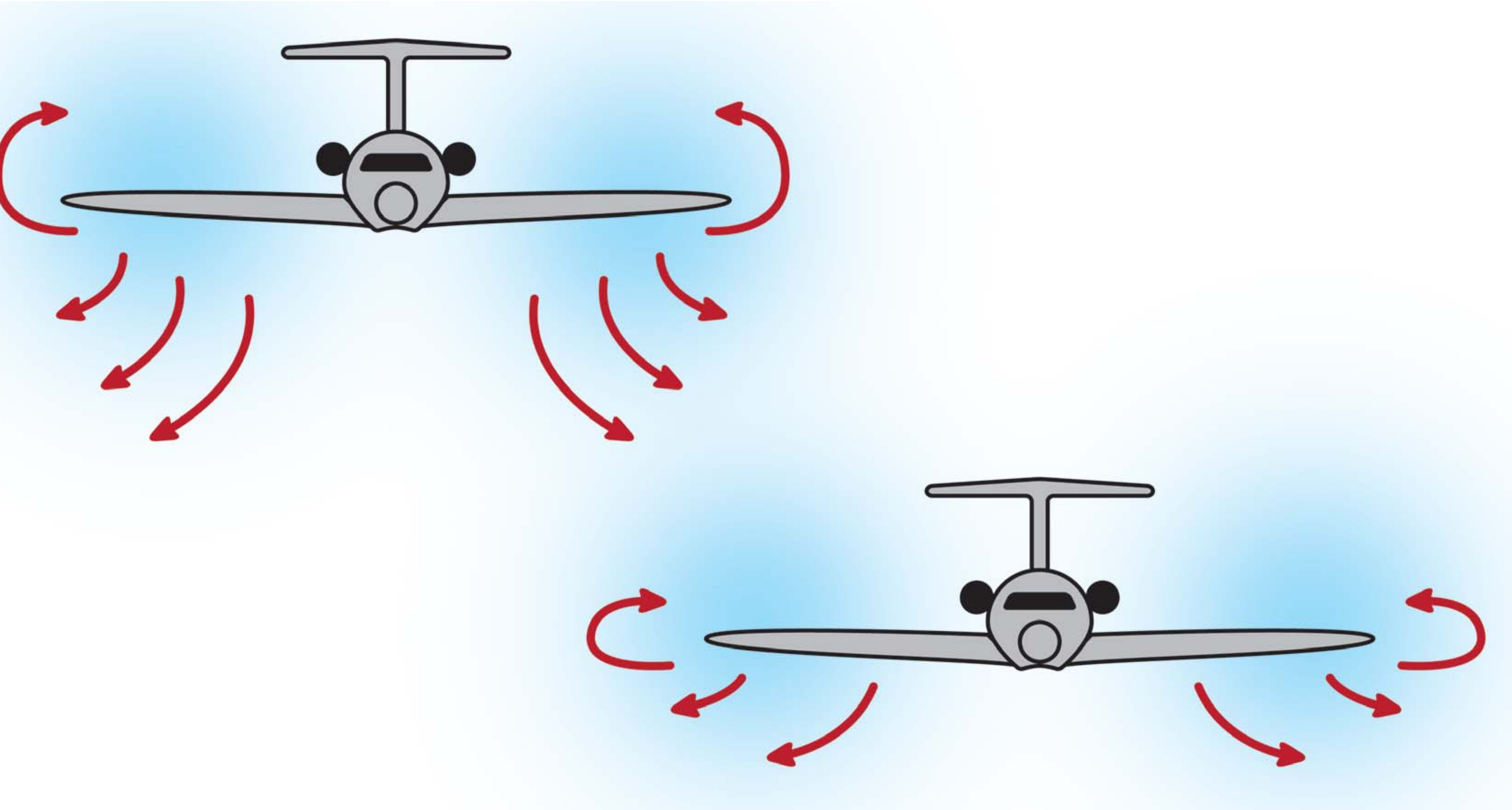


Fig. 15

2.1.3 Personal Watercraft General Arrangement; Implications on Use and User Experience

The current general arrangement for personal watercraft is derived from a motorbike; using a saddle-style seat on which multiple passengers sit one behind the other, and is operated via handlebar controls.

Some of the advantages of this general arrangement are:

- It is familiar through the resemblance to a motorbike or push bike.
- It allows the user to stand when encountering waves to brace themselves.
- It is easily scalable to allow 1, 2, and 3 seated models.
- All of the weight is on the centreline of the craft helping stability.

There are also some disadvantages:

- It is less of a shared experience because the driver cannot see the passenger/s, as such it is harder to communicate.
- It is difficult for the driving to be shared without one person leaving the vessel completely.
- The driver can throw the passenger from the vessel accidentally and on purpose.

2.2 Ground Effect and High Performance Craft

"Ground Effect is an aerodynamic phenomenon that is used by WIG boats to achieve high speed over water with minimum fuel consumption" (Opstal)

When I have previously talked about craft using aerodynamic lift, in actual fact the craft is taking advantage of ground effect; a term given to the effect on air flow over a wing when it flies in close proximity to a surface (fig. 16). In reality there are two forms of ground effect - span dominated ground effect and chord dominated ground effect, I will now briefly explain the effect of each.

Span Dominated Ground Effect

The main component of drag of a wing is the induced drag, i.e. the drag created by lift (Kermode). To create lift the wing has to create a pressure difference between the top and the bottom of the wing (Opstal). At the end of the wing a vortex forms where the high pressure air under the wing spills around the end of the wing (Kermode). When the wing flies close to a surface (i.e. the water) the vortices are suppressed by the lack of room available for them to form, reducing the induced drag of the wing (fig. 15).

Chord Dominated Ground Effect

By flying close to a surface at an angle of attack a "ram wing effect" (Opstal) is created where air is compressed between the wing and the surface. The resulting increase in pressure results in a greater pressure differential between the upper and lower sides of the wing, hence increasing the lift generated by the wing (Opstal).

Fig. 16

Fig. 17

Boats, like planes, are subject to both induced drag and viscous drag. At low speeds induced drag is the greater component of the total drag. However, as the boat's speed increases the viscous, or water friction, drag becomes the major component.

In high speed craft, such as the topic of this research, the viscous drag accounts for "well over 50% of the drag" (Opstal). The best way to reduce the drag is to minimise the wetted surface area of the hull (Russell), this can be achieved by taking advantage of ground effect.

For example, if two identical PWC require 1.5m2 of wetted surface to support them at 100km/h and one of the craft takes advantage of ground effect and reduces its wetted surface to 1.35m2, then there is a reduction in drag of approximately 15%.

Offshore Catamarans, Tunnel Boats, Hydroplanes and more recently Offshore Monohulls all take advantage of the drag reductions associated with supporting a portion of the mass of the craft aerodynamically instead of hydrodynamically.

2.3 Stepped Hulls: Formulating a Design Process

2.3.1 Literature Review

One of the main focuses of this thesis is the introduction of stepped hulls into personal watercraft. In the following section I will give a description and brief history of stepped hulls before I endeavour to formulate a design process for designing a stepped hull.

The concept of stepped hulls was first proposed as early as 1872 by Reverend Rasmus; unfortunately the limitation in engine technology of the time meant that it was not until 1910 that two models were produced by William Fauber (Russell, 2006) (fig. 18 & 20).

Steps are run transversely across the hull (fig. 19) and, like a transom, end a planing surface, this results in a temporary separation of the water surface from the bottom of the hull. Steps only become advantageous in planing craft that travel at over 45 knots (Lord, 1954).

A hull is considered planing when the hydrodynamic forces are greater than the hydrostatic force; that is, when the hull is mainly supported by the forces pushing on the bottom of the hull due to its forward motion.

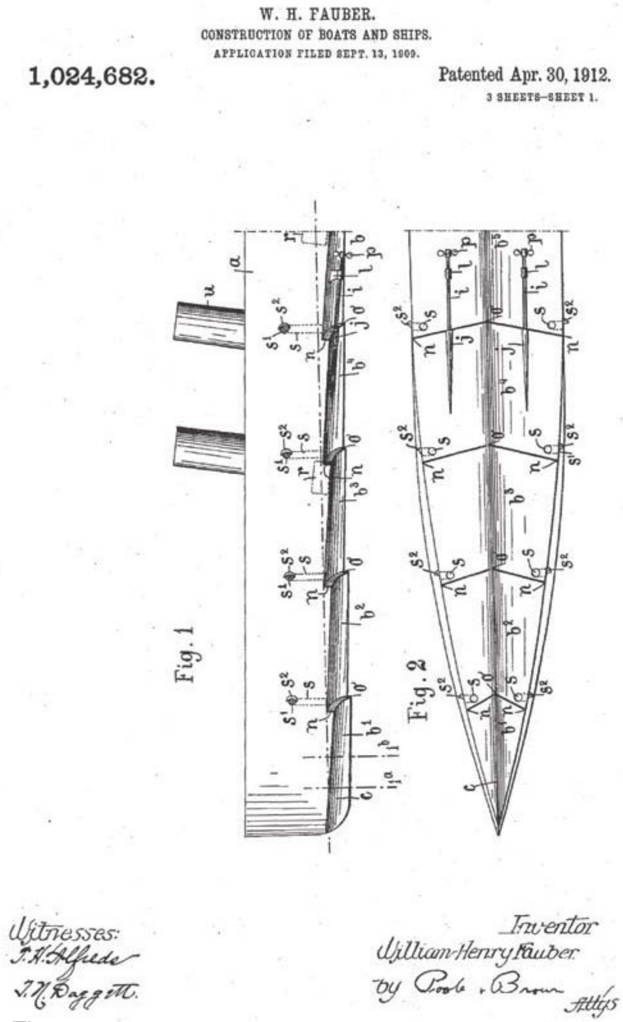


Fig. 18

Fig. 19

The speed at which this occurs is approximately equal to 3.4 times the transom beam of the craft (Akers, 2003a).

Hydrodynamic pressure on the bottom surface of the hull is greatest just behind where the water impacts the hull surface and then falls off towards the stern (Akers, 2003b). This means that a higher aspect ratio (shorter and wider) will produce more lift for a given area than a low aspect (longer and narrower) one. Evidence of this can be seen in aircraft which have high aspect ratio wings to take advantage of the greater lift to drag ratio it gives (Clement). Stepped hulls break the planing surface into shorter segments, effectively increasing the aspect ratio of each surface.

Initially it was not certain how many steps a hull should have, so as many as twelve were incorporated into some early racing boats (Russell, 2006). Today most hulls incorporate either one or two steps though there is little detailed literature on either the suitability or design of either type of these hulls. There is, however, more information on the limitations and difficulties presented in the design of stepped hulls:

- If steps are put too close together the aft step will be running in the aerated water of the forward step (Akers, 2003b)
- It is difficult to place the centre of gravity on multi-stepped boats as the balance of pressure across the planing surfaces changes as the speed increases (Akers, 2003b)
- “Ventilation of the step is key”(Akers, 2003b), otherwise the suction created by the step will suck the hull to the water and increase, rather than decrease, the drag.
- If the ventilation is cut to the step on one just side of the keel, such as in a seaway or a corner, then just that side will be sucked down resulting in an abrupt turn (Larsson and Eliasson, 2000).
- Stepped hulls have their centre of lateral resistance closer to their longitudinal centre of gravity so are less directionally stable than normal deep-vee hulls and can be prone to spinning out in corners (Akers, 2003b)
- Subtle changes in the position and angle of the steps, the dead rise of the hull or the placement of steps can all dramatically change the handling and behaviour of the craft (Akers, 2003b)

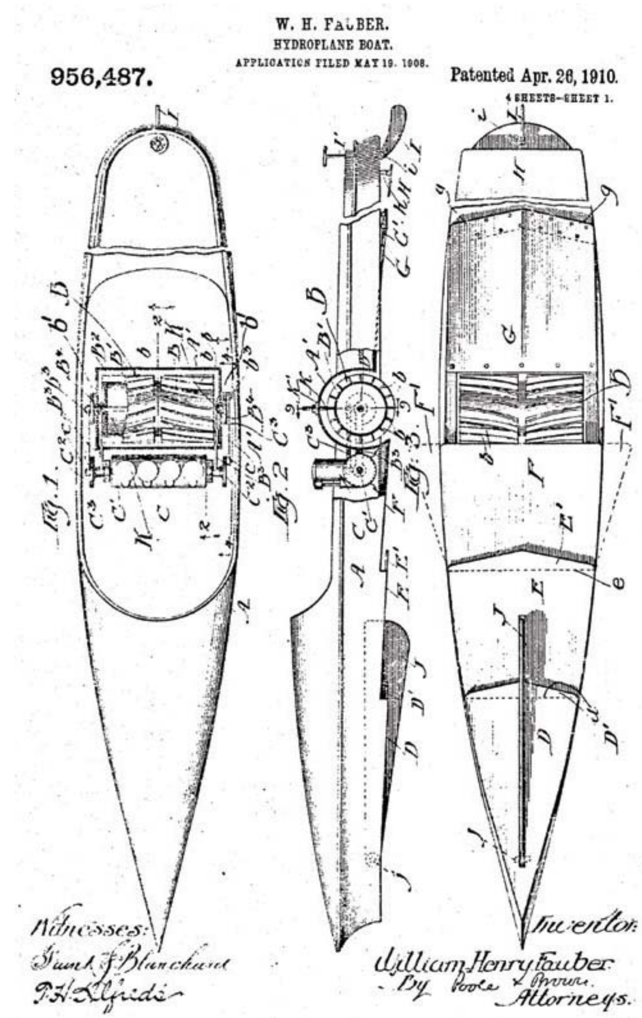


Fig. 20

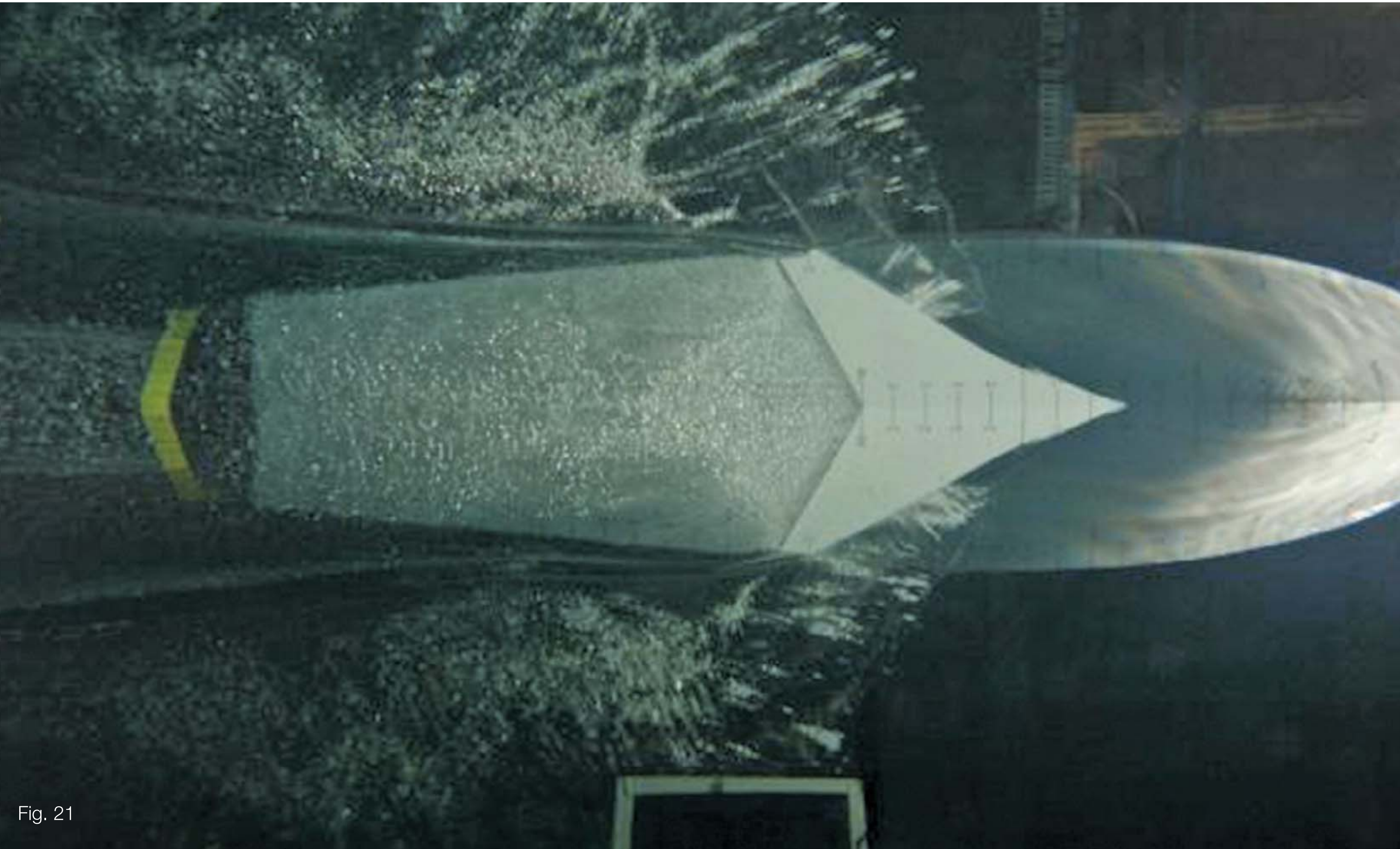


Fig. 21

There is, however, sufficient material available to begin testing a range of stepped hull designs. Eugene Clement, in his papers on stepped hulls, provides design procedures for the design of single stepped hulls with a re-entrant (rearward raking) step.

Clement's work focuses on the Dynaplane configuration, a design featuring a cambered planing surface in front of a re-entrant step (fig. 23). The area of the hull aft of the step runs clear of the water and the trim of the craft is kept constant by an adjustable hydrofoil at the rear of the craft (fig. 21). The benefits of the Dynaplane configuration are clearly outlined in Clement's papers and justified by both tank testing and full-scale prototypes. Unfortunately, the cambered planing of the Dynaplane does not suit the PWC for the following reasons:

- It is not suitable for craft with a dead rise angle greater than 15 degrees.
- It is not suitable for craft that are designed to be fast and light as it will result in an undesirably short wetted length.

However, Clement also presents a design method for re-entrant stepped hulls without a cambered planing surface. The use of a re-entrant step prevents high pressure jets of water exiting over the step and hitting the after body and significantly increasing the drag of the hull (Akers, 2003b), it also allows the negotiation of waves without sharp increases in drag. On a model tested at scale speeds between 60 and 90mph the drag steadily decreased as the speed increased due to the increasing aspect ratio as the hull lifted further out of the water (Clement). As previously discussed, a stepped hull will increase the aspect ratio of a hull. The introduction of a re-entrant step further increases the aspect ratio of the planing surface (Clement), which further increases the efficiency of the hull.

The limitation of the design procedure presented is that it assumes that the planing surface will support 90% of the weight of the hull; this may be fine for single stepped hulls where the centre of gravity is generally 5-10% of the waterline aft of the step. However, in the case of multiple stepped boats the weight of the hull is spread across all surfaces, and so the calculation process will need to be adjusted to meet this requirement.

Although Clement presents a detailed design approach on the design of stepped hulls with re-entrant steps he does not present any information on how to apply

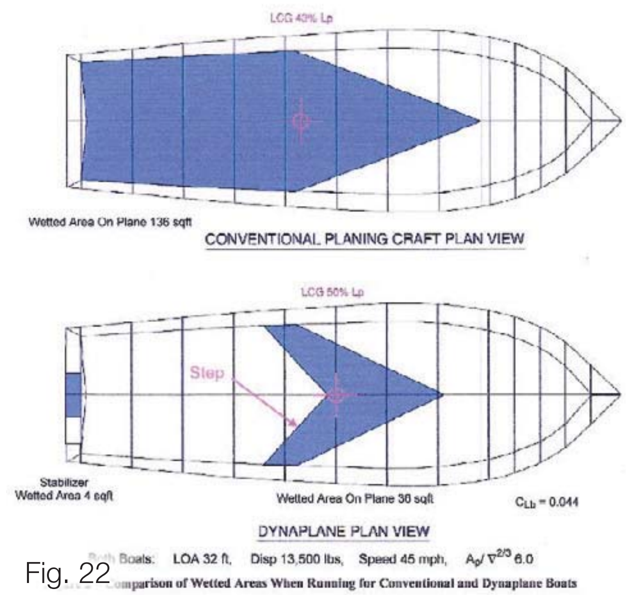


Fig. 22

Fig. 23

Fig. 24

his findings to the design of multiple stepped hulls. I have not currently found a detailed outline on the design of stepped hulls, nevertheless, Akers does give some clues in an article published in Professional Boat Builder Magazine in 2003. These are bullet-pointed below:

- The optimum angle of attack of a multiple stepped hull is 4 degrees; 2 degrees of this should be built into the hull and then the craft run at between 1.5 and 2 degrees of trim.
- The foremost planing surface should have the greatest built-in angle of attack.
- Multiple stepped hulls can be designed to balance on all steps, or to run on just one step at high speed. The latter is easier to design to run over a wider speed range.
- High steps can cause an excessive angle of attack in the trailing planing surface, in which case an 'S' shape should be incorporated into the buttock line.
- Boats with two steps should be loaded such that the longitudinal centre of gravity is located just forward of the aft step.
- Adding a pad or rounding off the keel forward of the first step will stop the hull burying the nose and prevent bow steer.
- Vee hulls perform better when the keel has a radius along its entire length. It is important to maintain a defined keel for directional stability.
- If the pad at the stern produces too much lift it will produce a bow down moment.

2.3.2 Formulating a Design Process

From my review of the existing literature on stepped hull design I formulated the following list of parameters for stepped hull design:

- Number of steps
- Depth of steps
- Angle of attack of planing surfaces
- Sweep angle of steps
- Distance between steps
- Centre of gravity in relation to steps

From this I began trying to formulate a design process. I started with a twin stepped hull as multiple step designs are the most common in contemporary designs, particularly in offshore race leagues.

Fig. 25

Fig. 26

Fig. 27

To start, I looked at a series of designs from Ocke Mannerfelt and Michael Peters (fig. 27), both of which are well known for their stepped hull designs in the offshore powerboat racing scene. From this I found that the positions of their steps were the same proportions in relation to the length of the craft. This equated to a length of 3/8th of the length from the stern for the forward step and 1/5th for the aft step.

From this I reasoned that for the selected running angle of attack the moments generated from the three lifting surfaces had to cancel each other out. A formula for this was generated and embedded in a spreadsheet along with the design process for a swept step as laid out by Clement.

The first page is simply to input the major dimensions of the hull and convert them to imperial for Clement's calculations (fig. 28).

The second page calculates the lift ratios of the positions of the steps and makes sure that the moments generated by the lifting surfaces cancel (fig. 30).

The remaining pages calculate the geometry of the planning surfaces using Clement's process for the first two planing surfaces and Savitsky's formulas for the aft surface (fig. 29).

Basic Dimensions

	Metric	Imperial
Length	3	9.84
Waterline	2.95	9.68
Beam	1.1	3.61
WL Beam	0.5	1.64
Design Weight	215	473.99
Velocity	64	58.33
Deadrise	17.5	17.50
LCG Ration	0.75	
LCG	1.010	3.32

Fig. 28

Forward Planing Surface

Lift

	Input	Output
Step Position	3/8	3.63
Weight	122 1/2	58065.51
Angle of attack	4.5	4.5
Waterline beam	0.35	1.15
$Beam^2$		1.318579
$Velocity^2$		3401.924
C_{lb}		12.94
$1/C_{lb}$		0.08

Sweepback angle	50	
Aspect Ratio	1.6	1.6

l_t/B	0.2
l_r/B	0.99
l_t	0.22966
l_r	1.13681
$l_{1/4}$	0.73491

Drag

	Input
Re	10000000
C_f	0.00293
C_L	20.7113
C_D	1.633087
S	0.824112
D	4578.468
L/D	12.6823

Output Geometry

Root Chord	0.347
Tip Chord	0.070
Median Chord	0.224
Beam/2	0.175
Beam/4	0.088
Sweep Back Angle	50.000
Position	1.11

Fig. 29

Weight Proportions

Planing Surface	Step Position	Step Position	Estimated C.P	Lift estimate	Moments check
Forward (S1)	1.13	0.11	0.34	122.50	41 1/2
Second (S2)	0.67	0.34	0.12	46.24867718	5.53827876
Aft	0	1.01	0.78	46.25	35.93907622
Mean distance (MD)		0.68	0.45	92.50	

Fig. 30

Fig. 31

3.0 RESEARCH DESIGN

This section will cover the research methods and design processes I will employ in this project. I will begin by using the information obtained in the research of the background chapters to formulate my research questions. I will then define potential research methods that could be used to answer my research questions, qualifying the most appropriate for this research project.

Question One

Is wing-in-ground effect a viable method of increasing performance and efficiency of personal watercraft?

Potential Methods

There are two major routes that could be taken to answer this question; through theoretical calculation or through physical testing, or a combination of the two. Below I will describe the methods of both routes before deciding on the right method for this project.

The first stage of the design process is to decide how much of the mass of the craft should be supported aerodynamically based on the implications of the size of the wings on not only top speed and acceleration performance but also cornering ability. Part of this will be working out how much lift can be generated for a certain wing area, this can either be done through calculation or with a wind tunnel.

Research has been conducted on how the lift co-efficient of an aerofoil changes in relation to its height above a surface. The accuracy of this method cannot be measured because not every possible configuration of wing has been tested and so inconsistencies may present themselves.

Wind tunnel testing can represent a more accurate way of testing the actual lift and drag produced by different designs. However, a specialty wing-in-ground effect wind tunnel is needed to simulate real world conditions. Wind tunnel testing is a specialty field in itself and can be very time-consuming to get accurate results.

Once the lift generated is calculated, it can be used to extrapolate the increase in performance given by the reduced wetted surface area. Again, this can be done by either physical testing or theoretical calculation.

Since there are no high speed towing tanks available to physically test the model accurately, the model will need to be either self-propelled using radio control equipment or towed. The problem with physical testing will be the introduction of further inconsistency in results due to ever-changing weather and scaling effects. Physical testing will also only present the final difference in speed or efficiency of the craft. Alternatively, accurate calculations have been formulated by Savitsky so that a more complete set of data, including the reduction in drag, can be calculated.

From the analysis above, using calculations for both stages of the design process will provide the fastest and most straightforward method of answering the research questions, while at the same time providing results accurate enough for the purposes of the project.

Fig. 32

Question Two

Is a stepped hull appropriate for personal watercraft? If so what form would this design take?

Potential Methods

Given the lack of theory surrounding stepped hull design outlined in the previous section it would be unreasonable to try to formulate an entirely calculation-based form of designing and assessing a stepped hull design. Calculation will need to be used for the design so that the size and location of the steps can be determined.

For assessment of the design a scale model of the hull form will need to be developed, this will preferably be a self-propelled radio controlled model rather than a towed model. Having a self-propelled model will allow qualitative assessment of the handling characteristics and stability of the model across the speed range. For the purposes of this research a more conventional PWC hull form will need to be developed to allow direct comparison of results between the two hull forms.

Fig. 33


Fig. 34

Question Three

How can the user experience be improved through the redesign of the general arrangement and controls of personal watercraft? How will this affect the aesthetic treatment of the craft when combined with the research from the previous questions?

Potential Methods

For this question to be answered an analysis of the current general arrangement will need to be carried out, as well as market research into how people use the craft. Possible alternatives will then need to be identified and the advantages and disadvantages of each evaluated against the other concepts. Research must also be conducted into styling of different products that present a similar user experience or are aimed at a similar user group so that a formal aesthetic may be devised.

Analysis of the current general arrangement could either be done through the survey of existing users or by asking a sample of people to test a PWC and then discuss their experience afterwards. The latter method has the advantage of testing people who have never used a PWC before so that initial reactions can be gauged, it may also present more valid results as users can be assessed immediately before and right after using the craft while the experience is still fresh. However, this method may also present a smaller sample size due to the time involved in conducting this survey as well as participating in the research.

A survey of existing users may not present people's initial reactions to the craft but will have the advantages of having a larger sample size with the opportunity to acquire results from a larger range of geographic locations.

From the results of the survey different concepts can be assessed in terms of their suitability to the varied usage patterns of PWC users. Concepts for new general arrangements and controls can be generated through explorative sketching as well as research into others forms of transport that present a similar user experience, appeal to the same market or deal with similar operating conditions.

A formal aesthetic will be arrived upon through the assessment of existing concepts and production vehicles of differing types and styles. Sketches of various concepts will then be generated and an assessment of how different aesthetics suit the differing general arrangement concepts will be carried out. Concepts will be developed until a clear direction is identified. At this time a clay model (fig. 34 & 35) will be created to refine the concept. This will then be 3D scanned so that accurate Computer Aided Design (CAD) modelling of the concept can take place and the concept can be further refined into a final design.

CAD will also be used as a tool for verifying ergonomics and ensuring accurate weight distribution throughout the development stages. Sketching will continue to be used as a development tool alongside clay modelling and CAD stages of refinement.

Fig. 35

Fig. 36

4.0 DISCUSSION AND ANALYSIS

In this section I will address each of the research questions individually. I will begin by outlining the selected methods used in order to answer each research question. I will then present the results of those methods showing how the project developed into the final craft that will be presented at the end of the chapter.

4.1 Question One: Wing-in-Ground Effect

4.1.1 Wing Design

From my own previous research into ground effect (Appendix 1), the centre of gravity of the craft needed to lie on a point 25% of the mean aerodynamic chord. This meant that early on a design with a high angle of aft sweep on the leading edge would be needed to allow a sufficiently large lifting surface without causing excess wing span that would adversely affect the cornering performance of the craft. I also found from previous work that this high angle of aft sweep will also help to produce a design that would be longitudinally stable in flight across a large variance in speed. This conclusion is also backed up by the similar design by Ocke Mannerfelt (2007) (fig. 37), who reports an increase in top speed of approximately 20% on his bat boat designs.

Calculation of the lift co-efficient of the wing in ground effect was done using the formula derived by Abramowski:

$$Cl_{ground} = Cl * (H/C)-0.11 \qquad (1)$$

A figure of 10% was decided upon as a suitable figure for the proportion of the craft's mass to be supported aerodynamically. This decision was based on creating a wing plan form that would not create a craft that was significantly larger than a PWC, while still providing enough lift to achieve a noticeable difference in speed and ride comfort.

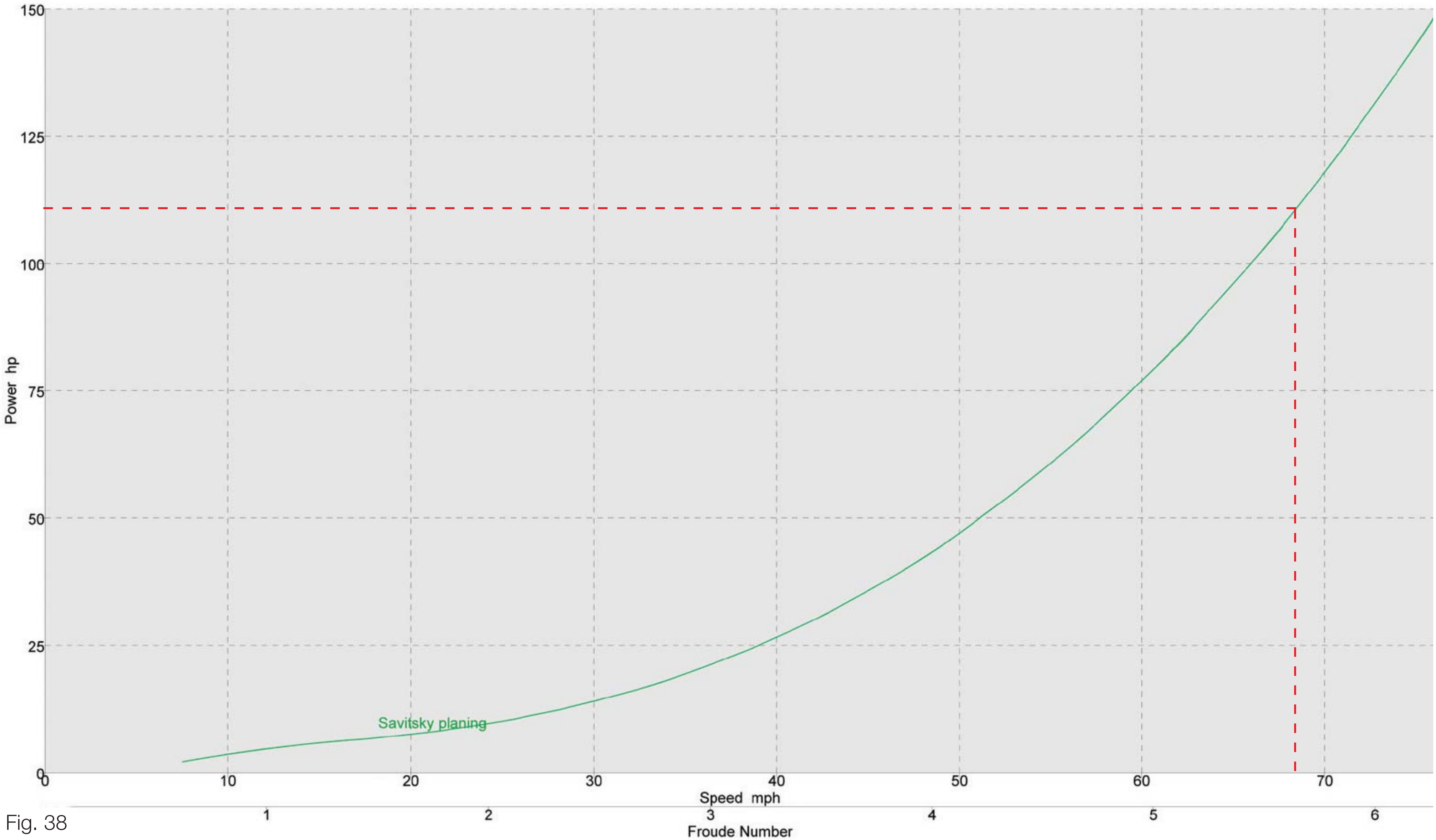
4.1.2 Calculation of Lift of Final Design

The final design has a wing area of 0.569m2 per wing and uses a 0012 NACA aerofoil, meaning that it is a symmetrical foil that has a thickness equal to 12% of the chord. At the running trim of the craft the wings will have an angle of attack of 5 degrees, giving it a lift co-efficient of 0.77.

The lift co-efficient in ground effect was calculated using the equation given by Abramowski, giving a result of 0.90. This data was used to formulate a spreadsheet to calculate the lift generated at speeds between 0 and 100mph in 1mph increments.

Using a representation of a PWC hull and the performance and physical figures of the Yamaha VX, a craft of the same horsepower as the topic of this thesis, the expected performance gain was formulated.

Fig. 37



150
125
100
75
50
25
0
Power hp
Savitsky planing
0
10
20
30
40
50
60
70
Speed mph
1
2
3
4
5
6
Froude Number

Fig. 38

The program used was Formation Systems Hydromax, prediction software based on the Savitsky formulas. First the basic figures for the VX were set up and the efficiency figure tweaked until the numbers matched up. Then the weight that the wings would support was subtracted from the craft, resulting in a new top speed. This process was repeated until the gains in performance were negligible. This resulted in a top speed gain of 14mph from 54mph to 68mph. The Yamaha VX is Yamaha's entry level PWC, the FZR their top of the line performance craft has a reported top speed of less than 70mph. This means that the addition of the wings equates to an increase in performance that spans the market.

At a speed of 68mph it was found that the wings will support 59kg of the craft's weight.

4.2 Question Two: Stepped Hull

I will now discuss the development of my stepped hull design using the formulas and procedures I outlined earlier. Firstly this will centre on the decision to have only one step instead of two or more. The section will conclude with an explanation of the development process of the design along with the presentation of the results of the testing procedure.

4.2.1 Initial PWC Hull Design

Before designing a stepped hull I first decided to design a hull based on existing PWC hull designs with the intention of using this as a base for comparison and developing the stepped hull design.

Comparing the various designs, I found that much development had occurred which could not be ignored. On comparison of the various current models I also found that the various companies had very different designs.

In particular Sea-Doo (fig. 39) had very peculiar designs when compared to Yamaha's (fig. 40) more traditional hull forms. From my crib sheeting I found that Yamaha achieves a top speed, the same as Sea-Doo, and acceleration from 0-30mph in 1.9 seconds instead of 1.5 seconds achieved by the Sea-Doo, but it does this with only 82% of the horsepower. I also found that both craft are almost identical in weight.

From this I concluded that Yamaha was achieving better efficiency levels than Sea-Doo at the top end of the speed range. This, combined with the more conventional design of the Yamaha hull, led me to use it as the basis for my hull design.

Fig. 39 & 40


Fig. 41

One of the features of the Yamaha hull that sets it apart is the up-turned chine. Generally hulls have a downturn at the chine to maximise lift. This upturn at the chine reduces the lift of this section of the hull, causing the craft to more actively bank into corners without the riders moving their weight. I found that this would fit my concept well since I was considering using bucket seats, making it hard for the users to lean into corners. Getting a PWC to bank into corners is important for handling as this helps the craft to track around the corner rather than spinning out. The use of sponsons (fig. 42) attached to the sides of the craft also helps the craft to track (Bombardier Recreational Products Inc., 2009).

One feature that I omitted from my initial design is the bow steps that are now commonplace in all PWC (fig. 41), and are used to help the craft keep their bow up during cornering by increasing the lift generated by the forward sections of the hull (Bombardier Recreational Products Inc., 2009). This works on the same theory discussed earlier in my research into stepped hull design.

4.2.2 Two Steps or One?

Upon assessment of the current trends in offshore power boat racing, it quickly becomes apparent that the trend is toward having two or more steps in the hull; this trend is prevalent in both multi and mono hull designs. The reason for this is that the effect aspect ratio can be further increased resulting in a more efficient hull form. However, as Clement points out, if the spray root lines exit over the step instead of off the chine then the resulting high pressure spray will wet a portion of the hull aft of the step and cause an increase in drag greater than the drag experienced by a non-stepped planning hull.

It was found that the relatively high beam to length ratio of a PWC, high operating speed and relatively low weight resulted in such a high aspect ratio second lifting surface that it was not foreseeable to create a twin-stepped hull without the spray root lines intersecting the step. This led to the development of the single-stepped design.


Fig. 42

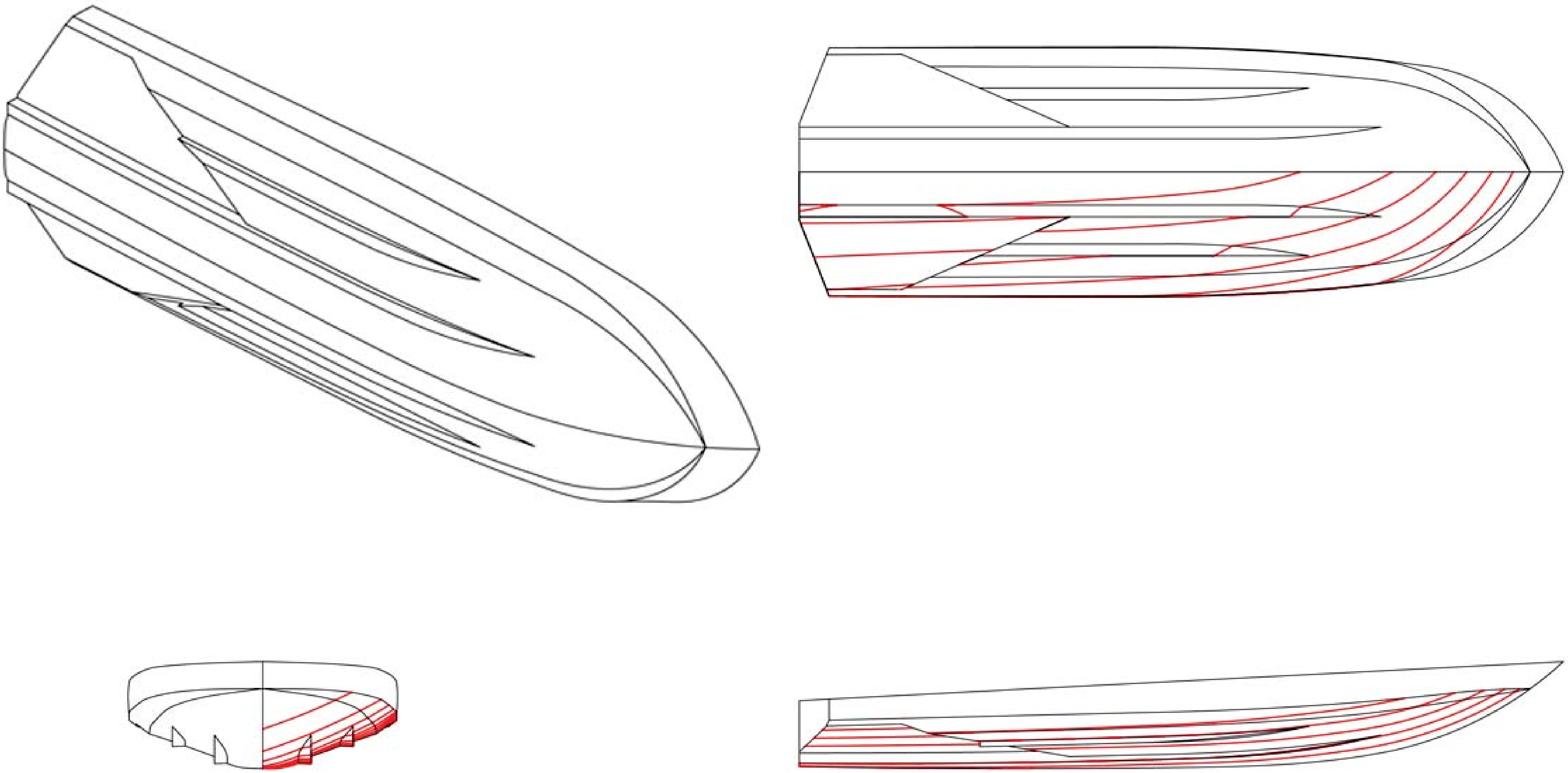


Fig. 43

4.2.3 Development of a Stepped Hull

Early in the project, Richard Karn (refer Appendix 1) pointed out that a stepped hull would not be suitable for water jet propulsion as the step would cause turbulence in the water being fed into the jet unit.

From the spreadsheet I had developed for designing multiple stepped hulls I developed another spreadsheet specifically for single-step hulls. I used this spreadsheet to develop a design that would only be stepped outward of the first planing strake. This would make sure that the water being supplied to the jet unit would be free of any turbulence that might result from the step.

4.3.4 Model Testing

To test the hull designs I built the first design to scale using balsa wood and fibreglass, and fitted it with an electrically powered jet unit. The model was then weighed and lead was added to bring it up to the design weight and position the centre of gravity correctly.

The model was fitted with a data recording system that logged the GPS speed every 0.1 seconds. This was later used to calculate the acceleration the craft.

The purpose of the testing was to compare the two hull designs with the goal of assessing if a stepped hull was suitable for PWC.

I found while testing the first craft that the performance of the model varied considerably with the slightest change in conditions. This is due to the scale of the craft, the slightest ripple on the water equates to a reasonably sized chop at full scale.

This combined with damage sustained to the electric motor during testing meant that it was not a fair playing field for the hulls. When testing the stepped hull the power levels of the motor were noticeably lower and I was unable to record any data.

Nevertheless, I still decided to test the stepped hull for the quantitative aspects of the testing. I would estimate that the craft achieved a top speed ¾ of the original craft. At this speed I noted that the craft did not display any noticeable difference in handling or any of the adverse characteristics that have been attributed to poor stepped hull design in the literature.

For a complete overview of the model construction, equipment used, and testing process please refer to Appendix 5.

Fig. 44

Fig. 45

	Length (mm)	Width (mm)	Dry Weight (kg)	Number of Riders	Engine Type	Engine Displacement (cc)	Engine Power (hp)
1998 XP Limited	2720	1110	370	2	2 Stroke	951	130
210 RXT iS 260	3540	1220	441	3	4 Stroke	1494	260

Fig. 46 & 47

4.3.5 Results ad Conclusions

Even though the testing was inconclusive I still selected the stepped hull due to the quantitative results of the testing combined with the unanimous findings in the literature that the step should lead to increased performance. To continue development I would like to test the designs at full scale so that the handling and performance characteristics of both can be more accurately assessed.

The hull's basic parameters are as follows:

Length	3000
Beam	1150
Waterline	2720
Dead rise	20 degrees

4.3 Question Three: User Experience and Aesthetics

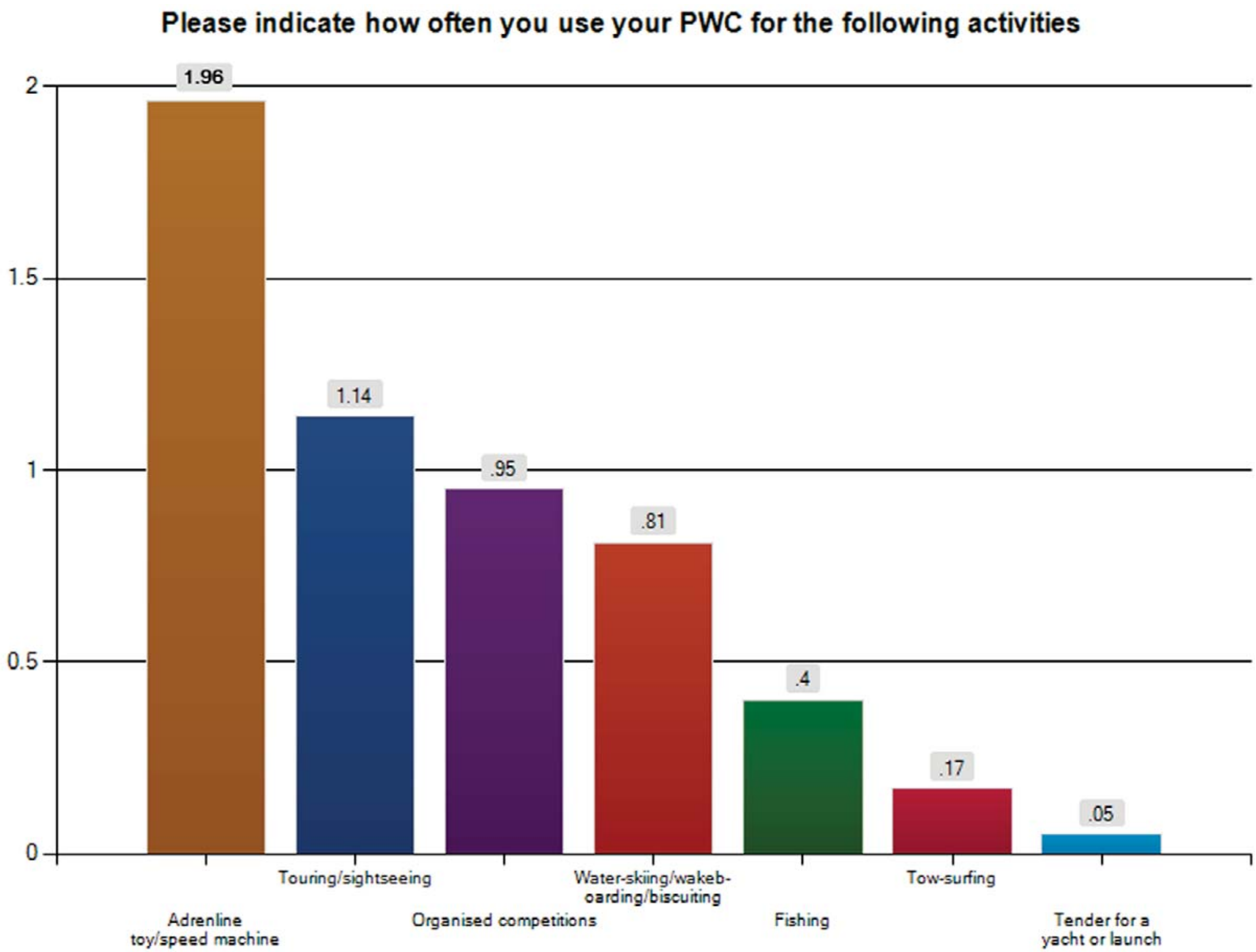
In this section I will cover my development of an aesthetic for the craft I have described in the preceding chapters, while at the same time discuss the creation of a new user experience within the PWC segment. This will begin with an examination of my research into past and present PWC designs as well as other high performance craft with a similar target market. I will then outline my design process before going deeper into each stage of this process to examine some of the decisions and factors that have shaped my design.

4.3.1 Research into PWC and High Performance Craft

For my research into PWC the first thing I did was to produce a crib sheet of all current models on the market. This allowed me get an accurate picture of what was available on the market and what the general parameters were. A comparison of the top models is shown here, the compete crib sheets are available in Appendix 4. At the time the HSR-Benelli PWC had not yet reached the market and was generally excluded from my analysis as it is clearly catering to a different market to the other craft (it also breaks the gentlemen's agreement between manufacturers and the US Coastguard that no production PWC will exceed 65mph). Although other manufacturers are starting to push the limits of this agreement I thought it sensible for product liability reasons not to exceed the current paradigm of performance.

As part of my research I also looked at past PWC models to get an indication of where they have developed from and what changes have been made. I found that since 1998 all PWC manufacturers have introduced 4 stroke engines into all sit-down models (PWIA, 2006). This has been to conform to environmental Protection Agency (EPA) standards on emissions. This had led to a 90% reduction in emissions and a 70% reduction in noise when compared to pre 1998 models (PWIA, 2006). I conducted my own comparison of the physical parameters of current craft and pre 1998 craft. The two craft shown here represent the top of Sea-Doo's high performance PWC in their respective years; the yellow craft is from 1998 and the red one from 2010. It is interesting to note that the introduction of 4 stroke engines has coincided with an increase in the overall dimensions and weight of the craft.

As part of my research into PWC I conducted an online survey of 66 PWC users from around New Zealand. A detailed account of how this survey was carried out and a presentation of the complete results are available in Appendix 4.



Please indicate how often you use your PWC for the following activities
2
1.5
1
0.5
0
1.96
1.14
.95
.81
.4
.17
.05
Adrenline toy/speed machine
Touring/sightseeing
Organised competitions
Water-skiing/wakeb-oarding/biscuiting
Fishing
Tow-surfing
Tender for a yacht or launch

Fig. 48

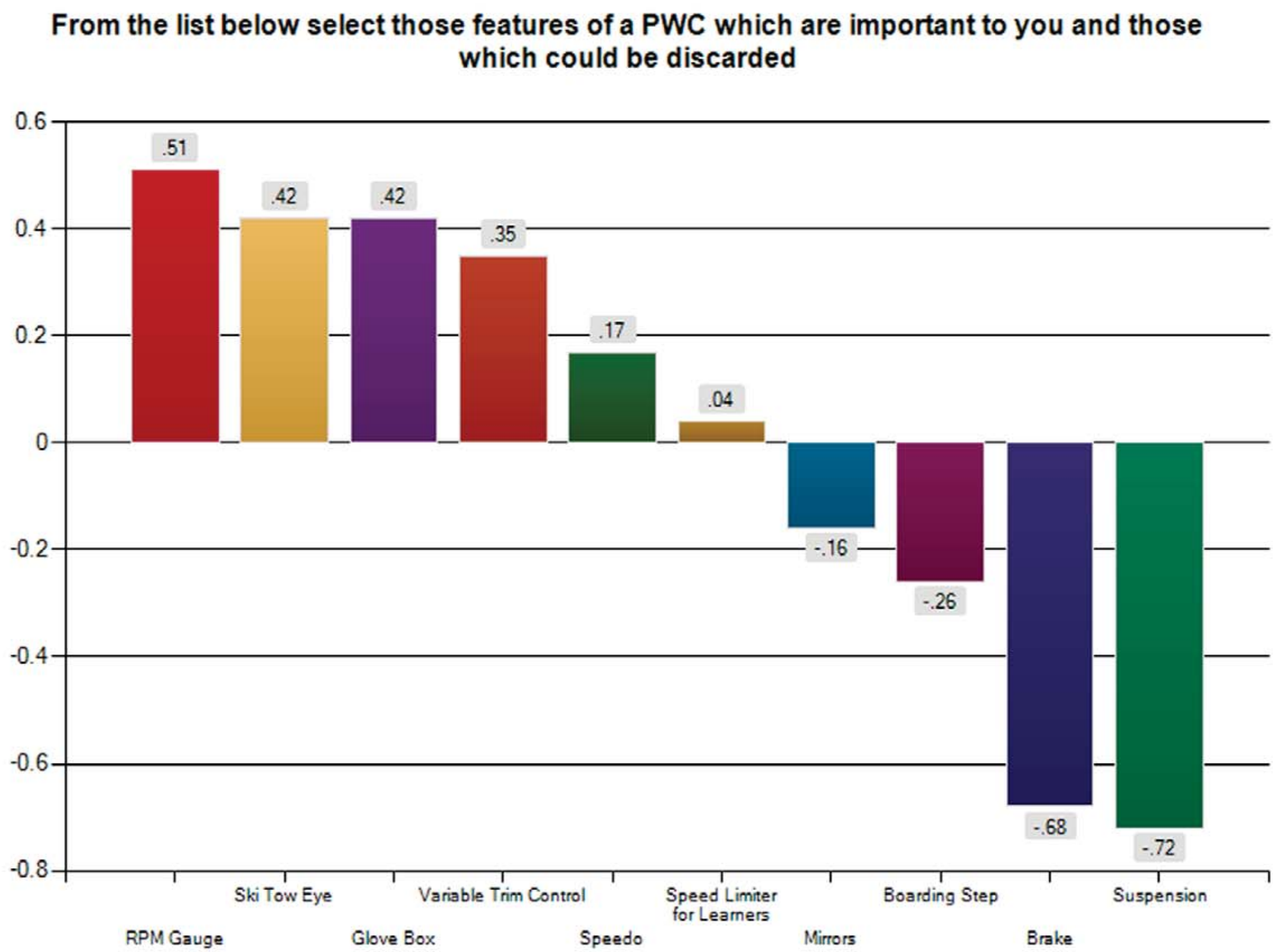

From the list below select those features of a PWC which are important to you and those which could be discarded
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
.51
.42
.42
.35
.17
.04
-.16
-.26
-.68
-.72
RPM Gauge
Ski Tow Eye
Glove Box
Variable Trim Control
Speedo
Speed Limiter for Learners
Mirrors
Boarding Step
Brake
Suspension

Fig. 49

Fig. 50

From the survey it was found that the main use of PWC is as an "adrenaline toy or speed machine" (fig. 48). This confirmed my approach to the project of putting an emphasis on the performance of the craft. I also found that the additional features that have been added to the craft and that contribute to the extra weight of the craft are not very important to the end users (fig. 49). From these findings I decided to develop a craft based on the same design principles of the lighter and nimbler 1998 models while still maintaining the emission and noise levels of the modern craft.

4.3.2 Creation of a New User Experience

In this section I will discuss the need for this craft to offer a new user experience. I will also cover what the influences on the user experience have been. As I have already discussed the current user experience of PWC is very motorcycle orientated. In this project I looked to create a new user experience within the PWC market. This was needed so that the design would not be looked at as just a PWC with wings attached.

Also when changing the direction of my project, as I outline in Appendix 1, from a one person flying machine to a two person waterborne craft, the reasons for doing this led to a project with a focus on creating a better shared user experience.

"PWC operators are commonly viewed by other coastal stakeholders in a negative light" (Whitfield and Roche, 2007), I wanted to create a new class of PWC that was more socially acceptable. "Most models are designed to accommodate two or three riders, but results of a PWC survey indicate that 68% of PWC riding is done alone" (National Transportation Safety Board, 1998). From this I wanted to develop a design that promoted use by more than one person to help change the perception of PWC as antisocial.

This led me to the design of a craft with a transverse seating arrangement, the development of which I will cover later in the chapter. This allows the users to see each other and converse much more easily while operating the craft, leading to a more social experience. Having the ability for the users to more quickly and easily swap roles between driver and passenger also helps to encourage use by more than one person.

This is not the first time that a PWC has been designed with a transverse seating arrangement, though I did not realise this until after I had settled on this arrangement.

In 1991 Kawasaki introduced the Sport Cruiser (fig. 51) more commonly known as the SC (Kawasaki Motors), featuring a bench style seat and a steering wheel that could be changed from one side to the other or located in the middle for single person use.

Although by today's standards the SC's styling is not representative of a performance craft, it is on par with the styling of Kawasaki's other craft of the time (fig. 52 & 53). This cannot, then, be the reason that the craft was only produced for four years.

Fig. 51

Fig. 52 & 53

Instead if a comparison of the performance figures of the SC to Kawasaki's other craft of the time (fig. 54) is made, it is noticeable that the SC was 14.5% slower (Group K, 1998), the wide flat bottom of the SC would have also led to poorer handling than competing craft. I attribute this lack of performance to the demise of the SC. This cemented the idea that I had to create a craft that equalled the performance of existing PWC if it was to be seen as an alternative rather than a compromise.

4.3.3 Propulsion

One of the things I considered in my evaluation of current PWC is the propulsion method, a water jet powered by a gasoline engine.

In a water jet, "water is taken up into a tunnel in the hull and accelerated" (Marshall, 2002) by an impeller. It is this "acceleration of the water that creates the force, so it does not matter whether the water is ejected above or below the water surface." (Larsson and Eliasson, 2000) (fig. 55)

"To optimise propulsion, as much water as possible should be accelerated but the speed increase should be as small as possible," (Larsson and Eliasson, 2000) This suggests itself to a large propeller spinning at low RPM. Unfortunately due to the impeller being located inside the hull this is hard to achieve in a jet unit, leading to lower efficiency levels than more traditional forms of propulsion. Expect to lose "30 percent efficiency" (Marshall, 2002) compared to an outboard.

This figure is not entirely accurate due to efficiency levels changing with variations in speed. Jet units have gained in popularity in high speed craft since they have no external appendages which account for an increasing proportion of the total drag as speed increases (Larsson and Eliasson, 2000).

Another advantage of the jet unit is that there is no external propeller (fig. 57) making them safer on craft operating around people or when the craft may roll.

The above led me to continue with the use of a jet unit for propulsion although my initial inclination had been towards a more efficient outboard.

Fig. 54

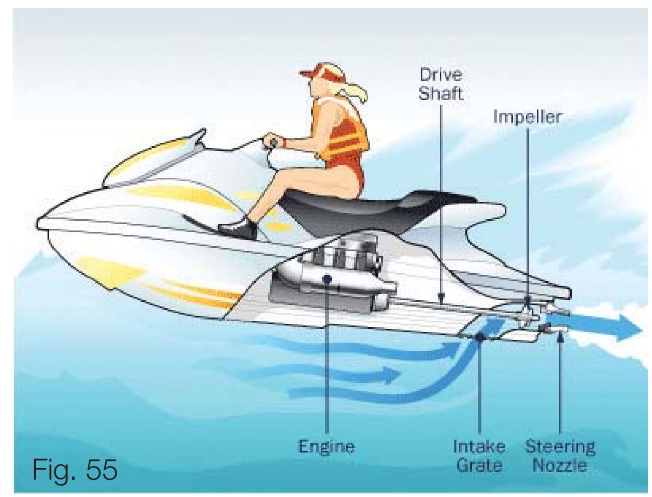


Fig. 55

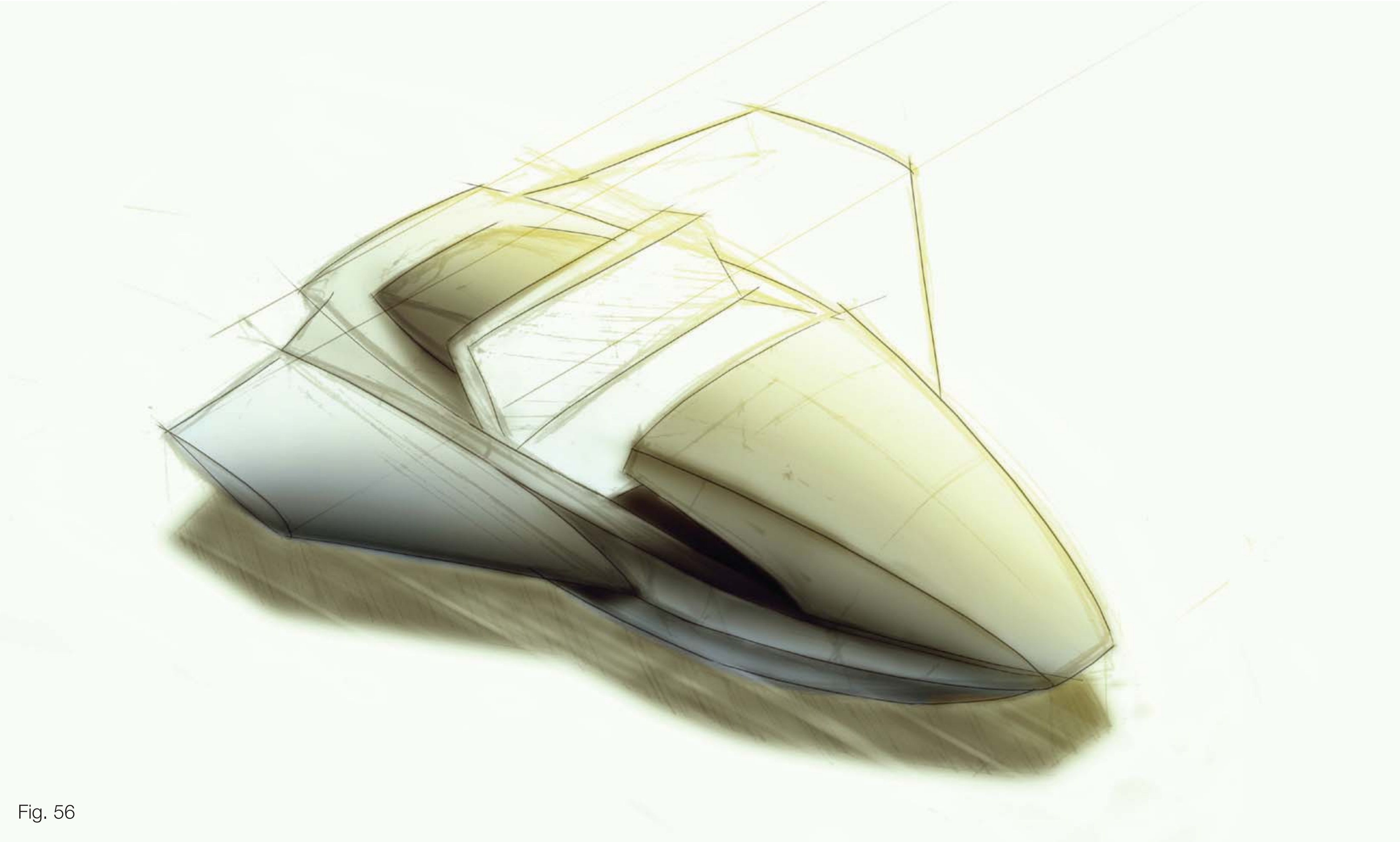


Fig. 56

I also investigated the possibility of using an electric propulsion mechanism. Research was conducted into current battery technology and an Ultralife battery cell selected for representation.

The cells specs are as follows:

Nominal voltage	3.7v
Capacity	58maH
Energy	2.2wh
Energy Density	147wh/kg
Mass	15g

(Ultralife Corporation, 2009)

Assuming the craft had a 110 horsepower (82Kw) motor, which, given the usage pattern of PWC, needs to run at wide open throttle for a minimum of 2 hours, requiring 164kw/h of battery power. Dividing this by the number of kilowatts per kilogram gives a battery weight of 558kg, when current PWCs weigh approximately 350kg. It is clear that this is not acceptable.

Instead the industry standard 4–stroke engine was chosen to power the jet unit.

4.3.4 Development Process and Design Features

This section will cover the development process of my design. I will begin by giving a brief overview of this process before discussing each of the steps in detail.

My design process was based largely on the processes used in the automotive industry. I began by producing loose sketches to allow me to experiment with form and proportion freely. I then started developing my general arrangement using CAD using print outs from this to underlay my sketching. Furthermore, CAD was used alongside this process to verify the geometry I had drawn and to allow me to start producing weight calculations. From here a clay model was produced to refine the form. The clay was then scanned and used as an underlay to model my CAD model over the top of. The detail design work was carried out during the CAD process.

Towards the end of the CAD process a full scale ergonomic mock up was constructed to verify the ergonomics. The design process was concluded with the creation of a quarter scale design model.

Loose Sketches

I began sketching from day one of the project, before I had conducted any background research. I did this to allow myself to experiment with form before I became restricted by the results of my research. I continued to sketch without any reference of scale or proportion to continue this, the sketch shown is a result of this process (fig. 56). It was not until I settled on the use of a side-by-side seating arrangement and stability issues had to be assessed that I produced general arrangements using 3D CAD software.

Fig. 57

Fig. 58

Additive Inspiration

As my focus on performance grew due to the results of my market research I decided to move away from the couch seating idea as the connotations that go with a couch would be very different to the craft I was trying to create. Instead I returned to the idea of having two individual bucket seats to help create a more purposeful looking aesthetic.

This started me down the path of taking an additive approach to the styling of the craft. This type of styling is component driven, where instead of the design looking like one continuous form it is instead made up from many individual components similar to the aesthetic of a motorcycle. This type of styling has gained acceptance in high performance automotive design but has not yet been widely applied in marine design. Examples of this type of styling can be seen in the Ariel Atom (fig. 59), KTM X-Bow (fig. 61 & 61), and BMW Vision (fig. 58).

Since, due to anthropometric considerations, the seats would be relatively large in comparison to the rest of the craft I decided to develop their aesthetic first and then use that as a basis for the rest of the craft.

Fig. 59

Fig. 59

Fig. 60

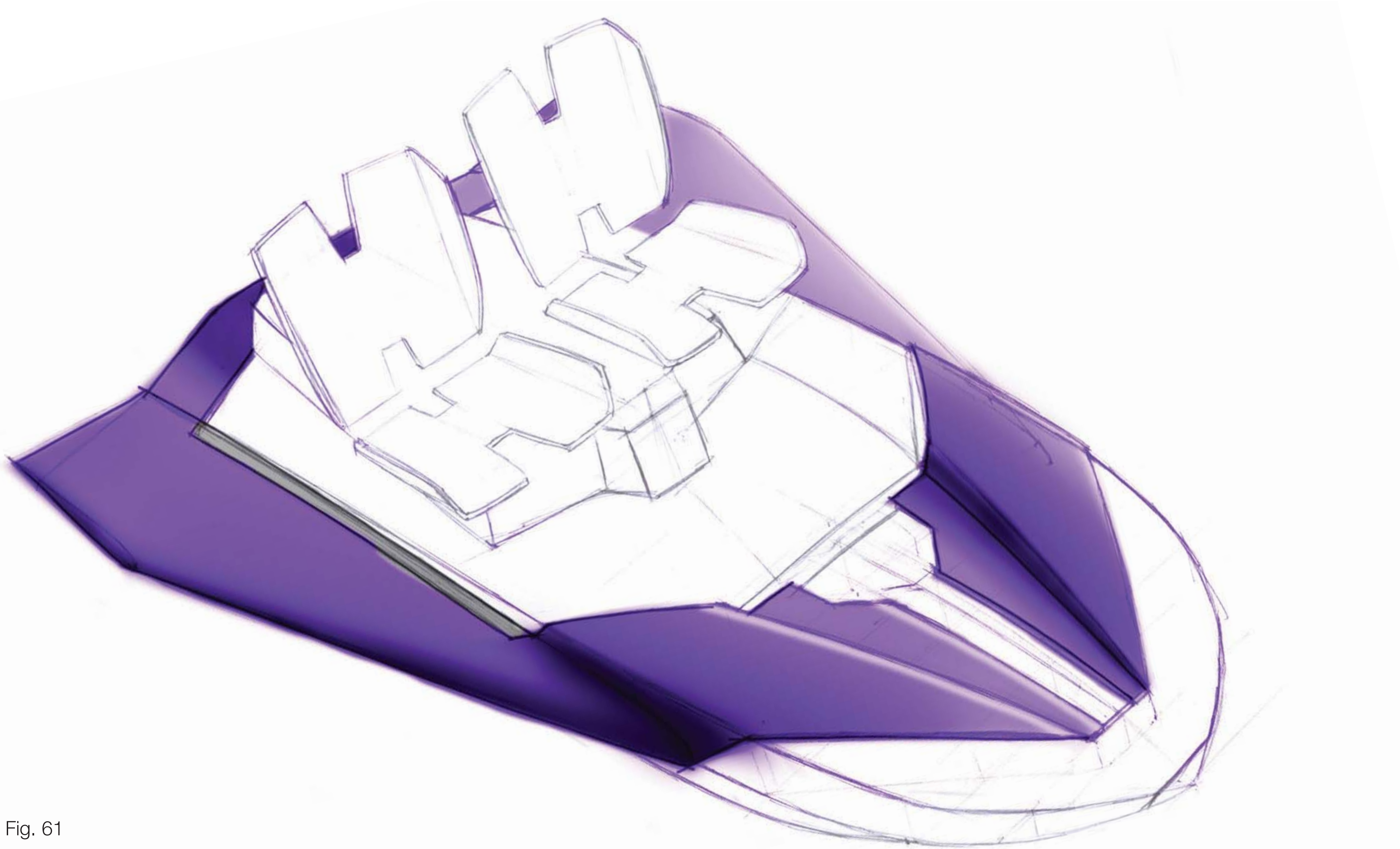


Fig. 61

Two sketches from the development of the seat are reproduced here, showing the diversity of the concepts that were considered. The H style design was further developed in CAD to be used as part of my 3D general arrangement.

CAD Underlays

From this point I used printouts of this CAD model as templates to my sketching (fig. 67). This allowed me to more accurately replicate the general arrangement I had created.

My initial general arrangement looked like figure 61 with a high central seating position over the top of the engine. This is similar to the current PWC arrangement in that the occupants sit on top of the engine. Unfortunately, this arrangement had several problems. The first was the difficulty of boarding the craft, the high location of the seats combined with only a small gap between them meant that one of the seats would have to be moved for boarding and that the users would have to stand on top of the engine, leading to a high centre of gravity which would cause instability. The advantage of this general arrangement was the ability to have the two seats back to back so that one person would face aft while water skiing, this also presented a convenient way to store the extra seat when only one person was using the craft.

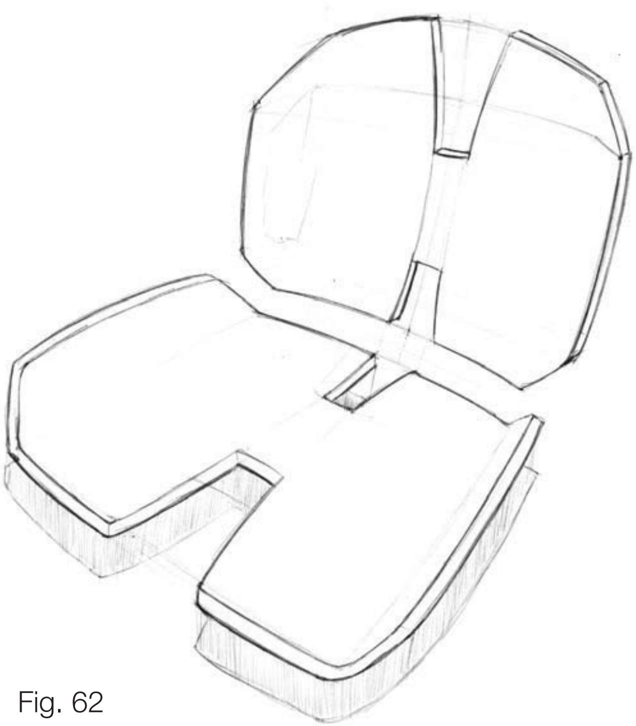


Fig. 62

Fig. 63

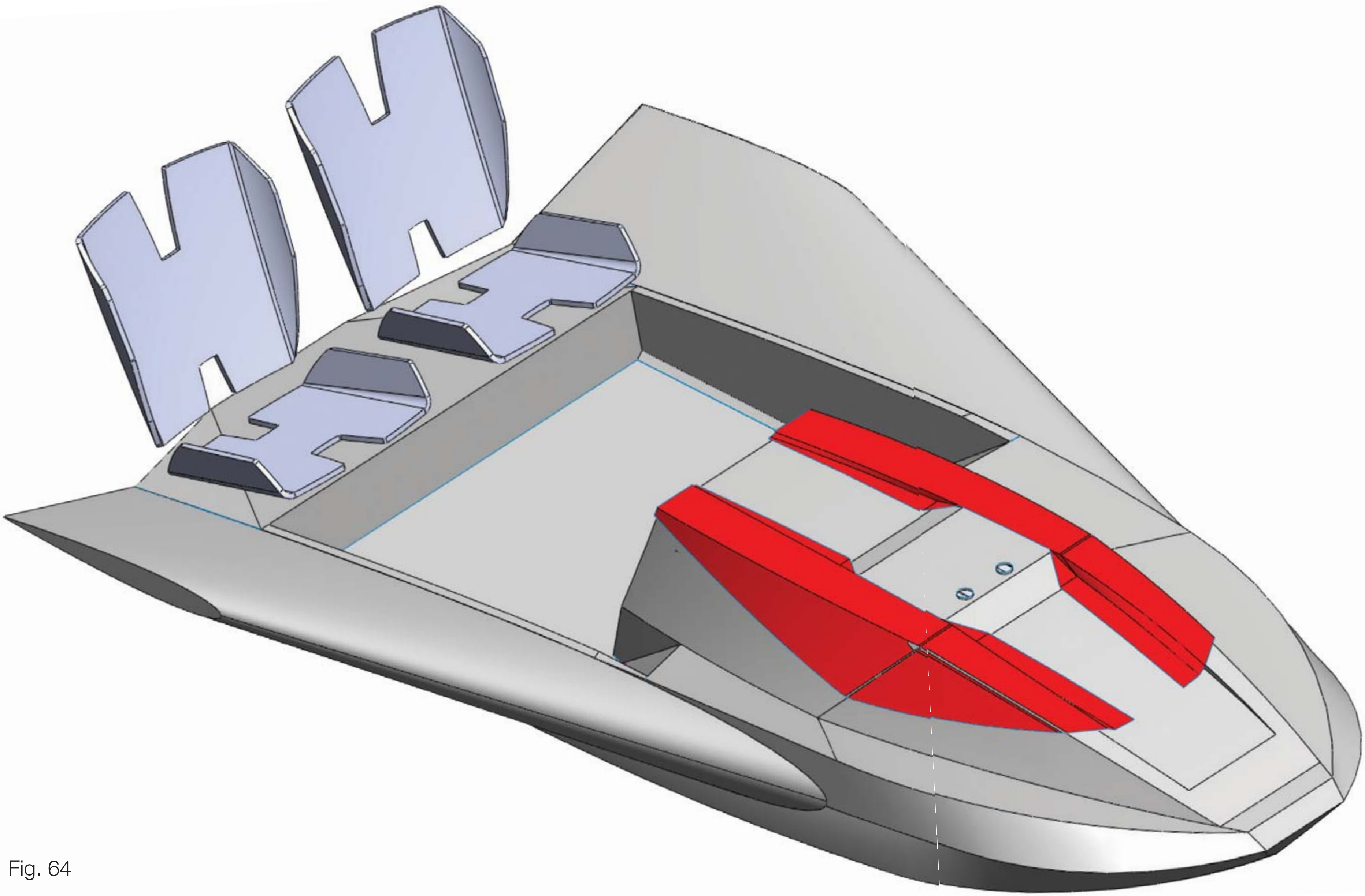


Fig. 64

To help improve the stability of the craft and make it easier to board I decided to adopt a general arrangement similar to the Sea-Doo 3D (fig. 65). This also allowed me to move the seats closer to the water which would help to increase the user's sense of speed, heightening the adrenaline rush.

When adopting this general arrangement I wanted to push it to the extreme by suspending the seats off the craft. This further removed the user experience from what is currently available. Due to the light weight of the craft in comparison to the people on board the weight distribution would not allow this. The seats are pushed as far aft as possible; this shift in weight is offset by moving the engine and fuel further forward in the craft. My basic general arrangement is shown in figure 67. It has been kept as simple as possible to allow more freedom in my sketching.

CAD Aesthetic Mock Up

Once I felt that I was getting close to the basic overall form the craft would take I began to create a basic mock up of the design in CAD to verify the geometry I had drawn. This was an iterative process requiring me to go back and forth between CAD and sketching.

Figures 64 and 66 show the result of this process; the sketch and the 3D CAD model. At this stage I am treating the wings as an individual component with a hole cut right through to allow the users to see through to the water. The idea was to allow the users to see through to the water and prevent them being feeling cut off from the water by the wings. Unfortunately the wings were so deep in comparison to the width of the hole that it would not have been possible for the users to see through to the water without making the holes bigger, which would have rendered the wings redundant.

Fig. 65

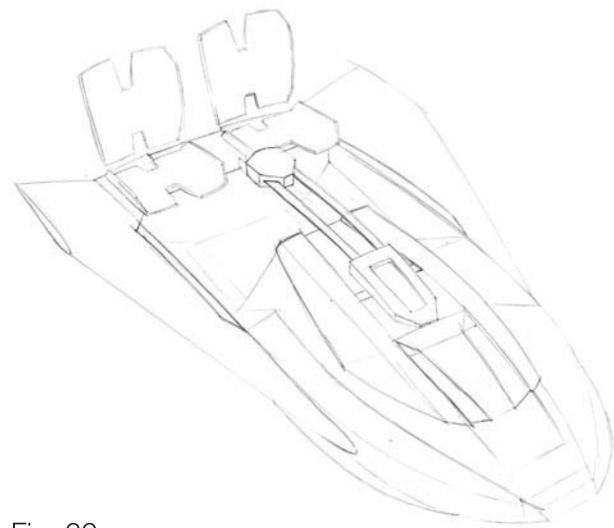


Fig. 66

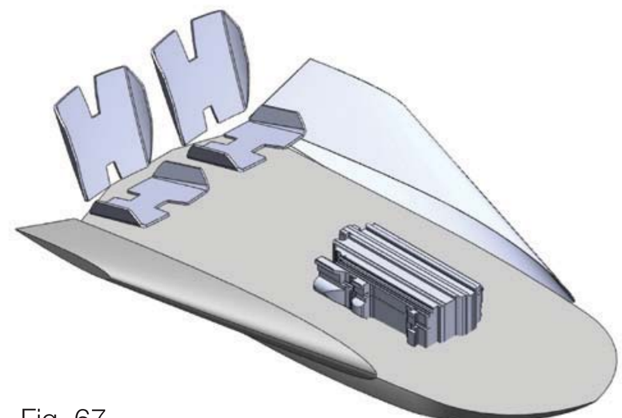


Fig. 67

Fig. 68

Clay Modelling

Once at the stage shown in the previous images, I began to translate the design into a clay model. Since I would not be using the clay model for display purposes I decided to save time by creating a half model of the design and use a mirror to give an impression of the overall form.

Figure 69 shows the beginning of the process where I have merely transformed the geometry of my current design to clay.

I first began developing my ideas using a series of tapes to map out my ideas for how to treat the styling of the floating surfaces. Figure 70 shows a natural progression of the surfaces I had drawn in the previous step of my development process. This design still lacks unity and needs something to tie it all together rather than making a feature of the engine compartment.

To help me develop ideas more rapidly, I continued to use sketching alongside the clay modelling process. In this rendering (fig. 68), I was experimenting with bridging the surfaces down to the wing. This was done to help unite the engine compartment with the rest of the design.


Fig. 69


Fig. 70

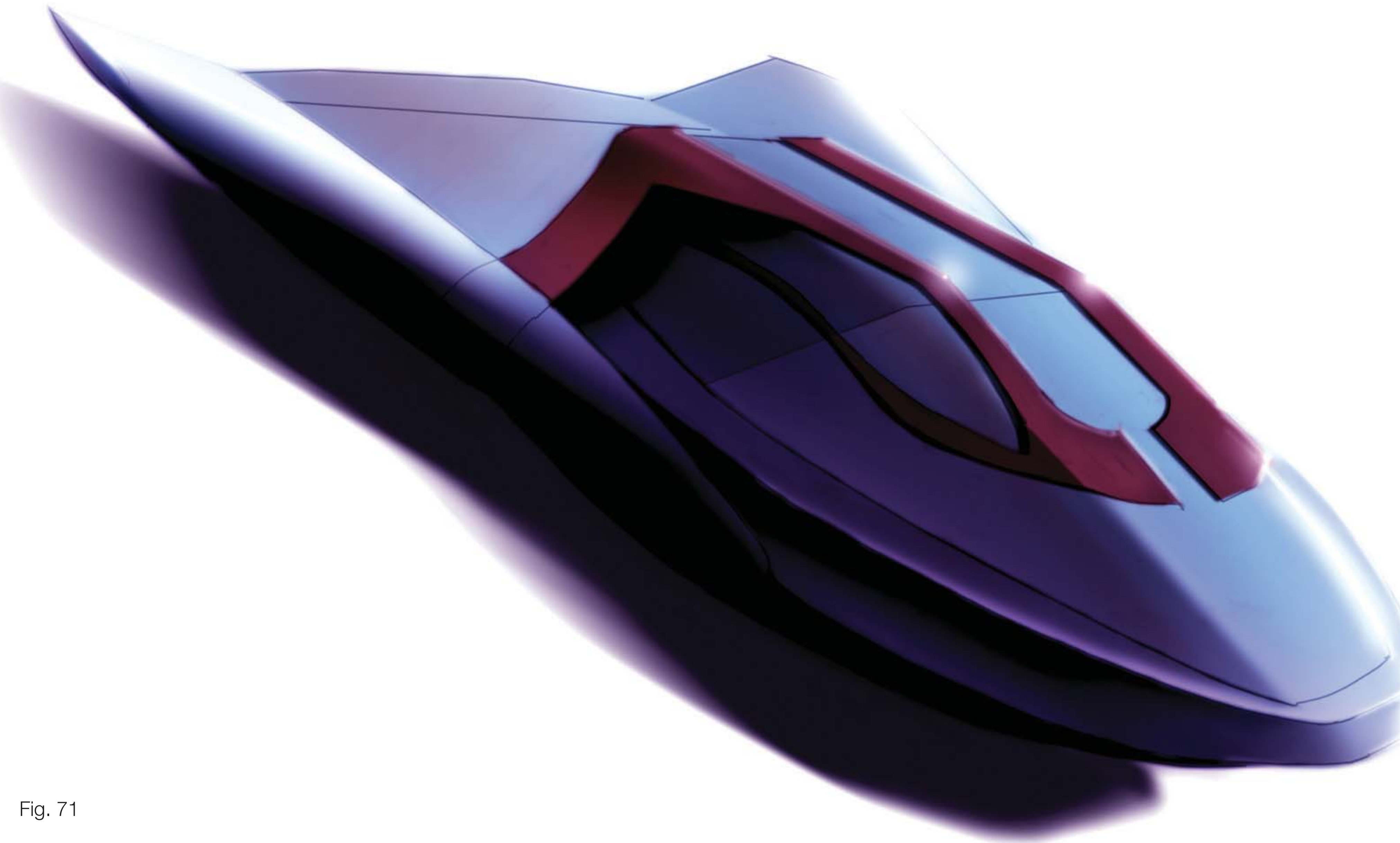


Fig. 71

Returning to the clay model, I found using a series of paper cutouts an effective way of developing and testing the geometry of the floating surfaces. I often combined these with tapes; in this photo I am trying to integrate the floating surfaces with the rest of the design (fig. 72).

I felt that the thinner surfaces of figure 71 did not create enough presence, nor were they assertive enough to communicate the performance of the craft.

Figure 73 shows the blending of the wing into the main surface making them part of the same component as the hull, after it was realised that the gap between the hull and the wing would not achieve its goal.

Instead I decided to create a part line in the wing which would break up the large top surface of the wing while also helping to integrate the floating surfaces (fig. 74).

The recess in the top of the engine compartment was run all the way to the back of the surface to help create the impression that the offset distance of the floating surfaces was greater (fig. 75).

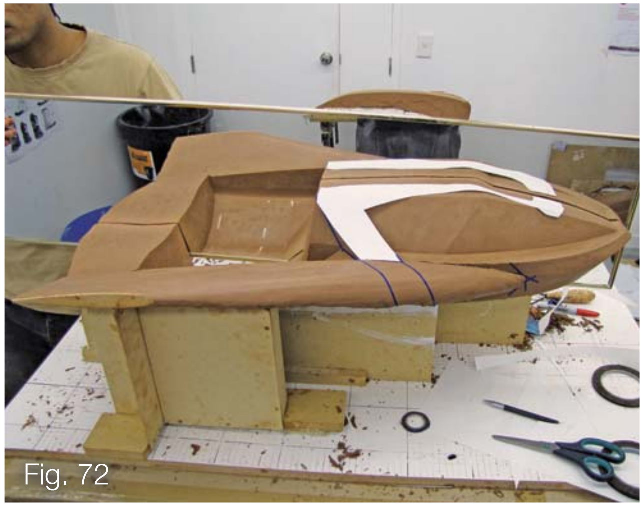


Fig. 72


Fig. 74


Fig. 73


Fig. 75

Fig. 76

The top surface of the wing was extended inboard to create the illusion that the hull is tapering towards the stern (fig. 78). This was inspired by 1960s motorboat styling (fig. 77) and was used to help create a more sporting and elegant aesthetic.

Figure 79 shows the design of the floating surfaces reaching maturity. A block model of the seat was created to give the model a sense of scale while also allowing me to better integrate them with the rest of the design. A concept for the treatment of the stern of the craft has been taped out where the floating surfaces will continue from the wings under the seats. Also, the cockpit floor has been raised to improve ergonomics for smaller users and is now above the waterline.

Figure 80 is a concept where the floating surfaces form the mounting mechanism for the seats; unfortunately they contradicted my direction of having flat hard lined surfaces contrasting with a more curvaceous and sculptured form underneath. The design of the stern has been refined and the central cut made thinner so that it flows on better from the cut on the engine compartment (fig. 81).


Fig. 77

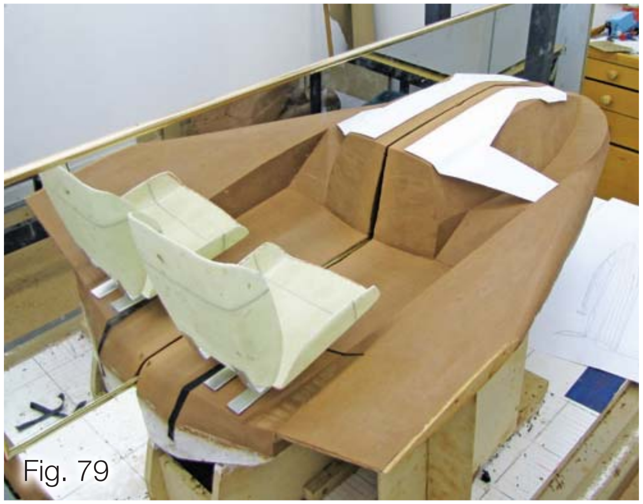


Fig. 79

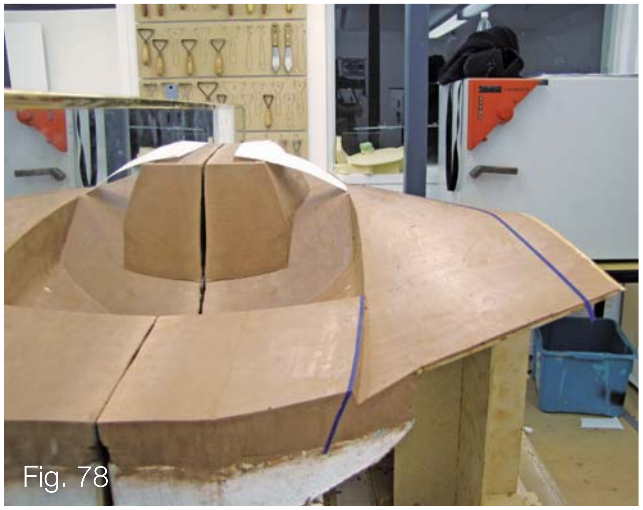


Fig. 78


Fig. 80

Fig. 81

A concave surface was added to the side of the engine compartment to help break up the surfaces and further create a more sculptured look (fig. 76).

Figures 81 and 82 are photos of the final clay model. Note the final iteration of the stern development, where the floating surfaces now join to form a step when boarding the craft.

The final step in the clay modelling process was having the model scanned. This gave me an accurate representation to create my CAD model over.

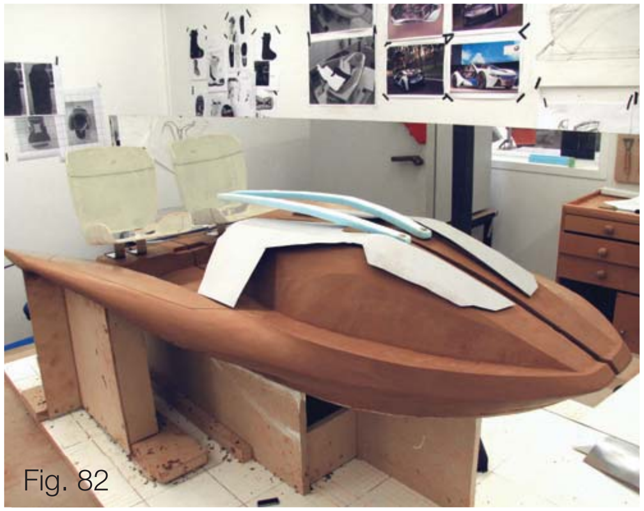


Fig. 82

Fig. 83

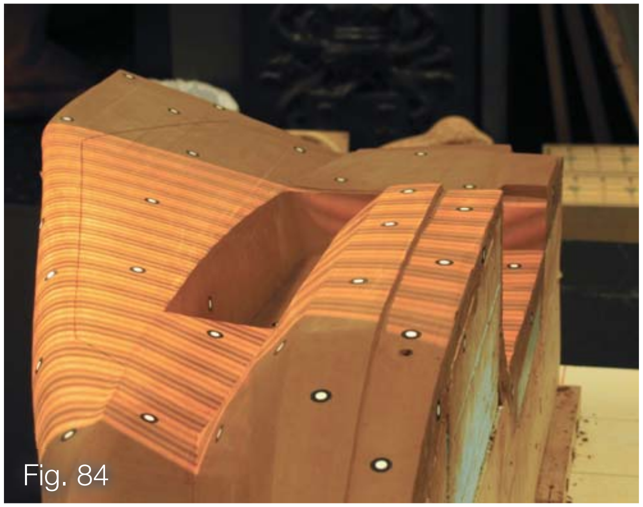


Fig. 84

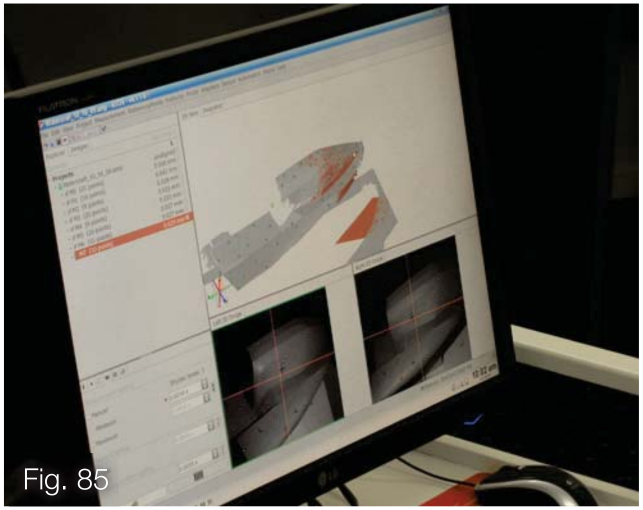


Fig. 85

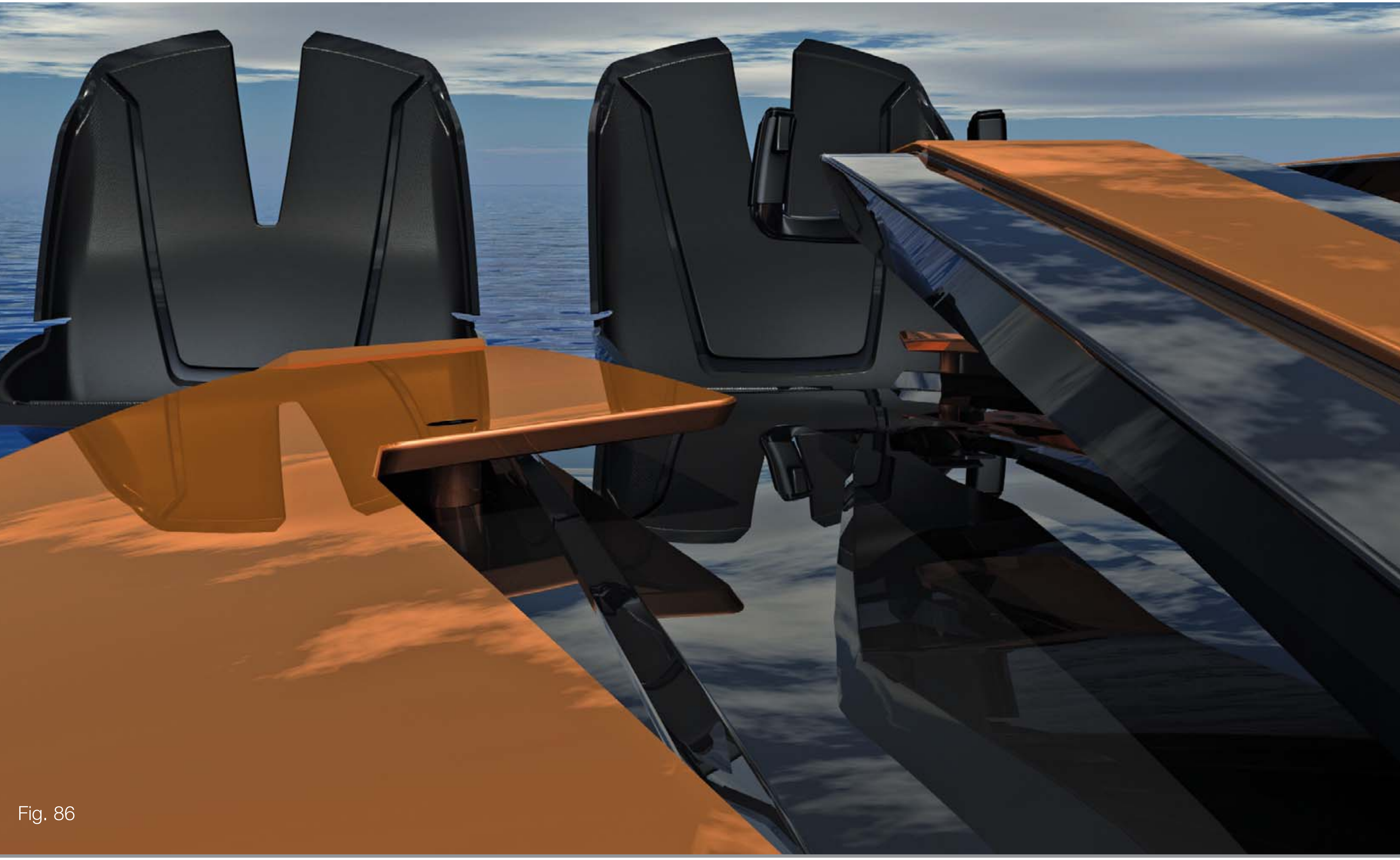


Fig. 86

CAD Modelling

I spent eight weeks building the CAD model of my design, most of this time was dedicated to design development and detail design.

The first step in the process was importing the STL file that resulted from scanning my clay model. This included zeroing the model, nesting the hull file, and checking the dimensions against the CAD mock up that resulted from my sketching process. I found that I had to lift the wing slightly to give sufficient clearance from the water, which altered the sheer line slightly but the rest of the major dimensions lined up well to the existing hull design.

From this I began re-creating the surfaces of the model using the STL file as a template (fig. 87). Once the main body of the design was complete I began adding the other components, starting with the floating surfaces. Until this point I had only designed the floating surfaces as a sheet part with no thickness, I liked this look and so to preserve it I added an undercutting chamfer to all of the sides to create the illusion of a super thin surface (fig. 86).

The seats received a major redesign during this process. Throughout the creation of my CAD model I returned to sketching to develop my ideas. The development of the seat was one of these times. Because I found it difficult to get the proportions of the seat right in my sketches, once I had a fair idea of the direction I wanted go I returned to CAD to get the proportions right and finalise the details.

I wanted the seat to be supportive without the users feeling claustrophobic, to do this I made the seats deep around the hips but toned back the side supports on the seat back. This makes sure that the users are held firmly in place but still allow them to move their upper body during cornering. I also wanted it to look purposeful without being intimidating. To do this I used a seat back that is only 590mm high instead of a full bucket seat which may have made the design less approachable to families.

The seat sizes were based on of a 95th percentile male and 1st percentile female. I went smaller than the accepted norm of a 5th percentile female to help account for families with younger children using the craft.

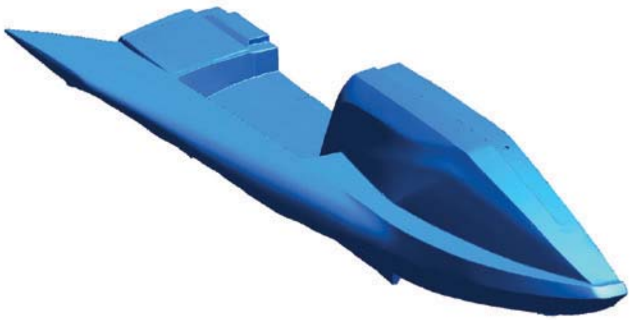


Fig. 87 & 88

Fig. 89

The final seat was designed as a single piece moulded design to ensure that it would be rigid and supportive enough when operating in choppy water at high speeds. This gave the seat an inherently organic form to which I added a series of hard cut lines so that it would fit with the aesthetic of the craft. The cuts were sized so that they would not reduce the comfort of the seats; the seat back cut has a maximum width of 89mm while the base cut is a maximum of 82mm.

Cuts were also made through the cushion layer to help break up the surface area of the seat cushion. The cut on the seat back part of the cushion was mirrored to the outside of the seat to help add some detail to the large surface. This not only helped to break up this large outward facing surface but also it helped to improve the rigidity and strength of the seat back.

Each seat is cantilevered above the craft using a ‘U’ shaped mount. This was done so that from the stern they have the appearance that they are floating above the craft, creating a cleaner look. The arms on the mounts were also made wider so that their profile thickness could be minimized, resulting in a less block-like form (fig. 90).

The seat mounts slide into cavities in the rear wall of the cockpit, or if there is only one person on board, under the bridge in the middle of the craft as illustrated.

The seats can also be removed from the mounts, making them easier to store or stack. When removed from the craft, the seats can be used as a beach chair. This was considered important to the concept to maintain a level of equality between the users: if only one person is using the craft then at least the other user can sit and relax in comfort. Extensions on the bottom of the seat reduced the recline angle by 12 degrees when they are used on the ground, to ensure that the ergonomics are correct in both situations.

Like the seat supports mentioned earlier, the steering arms were made wider so that their profile thickness could be reduced, as I wanted them to be visually light to stop them from looking clumsy or bulky. To help this I took styling cues from the floating surfaces, adding an under-cutting chamfer to the sides of the arms (fig. 89).

The floating surfaces are mimicked on the top of the steering arms to help integrate the arms with the rest of the design. This also serves as a way to add detail and interest to the flat upward facing surfaces.

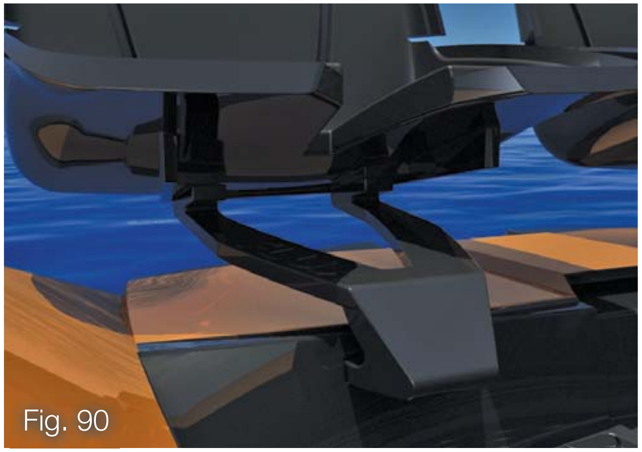


Fig. 90

Fig. 91

Fig. 92

Effort was made to keep the same aesthetic treatments throughout the design. This included the U bar steering which uses a series of twisting and curved surfaces as the base but also has a series of planar surfaces to link back to the floating surfaces (fig. 91).

I used drive-by-wire technology for the controls as this is becoming common in PWC and allowed me much more freedom in the styling aspects. This also allowed me to reduce the bulk of the steering mechanism, while also reducing the physical strain on the driver. After testing the Surfango motorised kayaks and talking with the retailers I found that the throttle finger can get very tired during prolonged use. By using drive-by-wire, the force needed to operate the throttle can be reduced.

The two pads on the top of the craft control the vertical trim of the jet nozzle and two trim tabs at the rear of the craft. This allows the driver to trim the pitch and roll of the craft; particularly important when towing water skiers or if one user is significantly heavier than the other.

The start/stop buttons have been positioned where they can easily be accessed and a safety lanyard would need to be attached to the underside of the U bars for the craft to operate.

A small LCD information panel is located in front of the steering mechanism. This will communicate the following to the driver: speed, rpm, jet nozzle trim setting, and fuel and oil warnings (fig. 93).

I constructed a full scale ergonomic mock up of the design and found that having the arms heading off at an angle to the driver was disorientating as there was little else to give a sense of direction. To combat this, a façade was added to the steering mount that always faces directly forward. I also found that the steering would need to be adjusted vertically to suit different users. To achieve this the steering arms will pivot around their mounting point. This will be operated using a small lever on the underside of one of the arms, the other arm will have a similar lever which will lock the arms horizontally. Having the arms locked in place while in motion will increase the handling of the craft, as well as provide some bracing for the driver.

The cockpit was given a rubber floor to make it more comfortable and to give the users some traction. It was decided that the rubber grip should be recessed as it gave the craft a more refined look. The cockpit also features a glove box on each side for storing drink bottles, sun block, first aid kits and other personal items.

Fig. 93

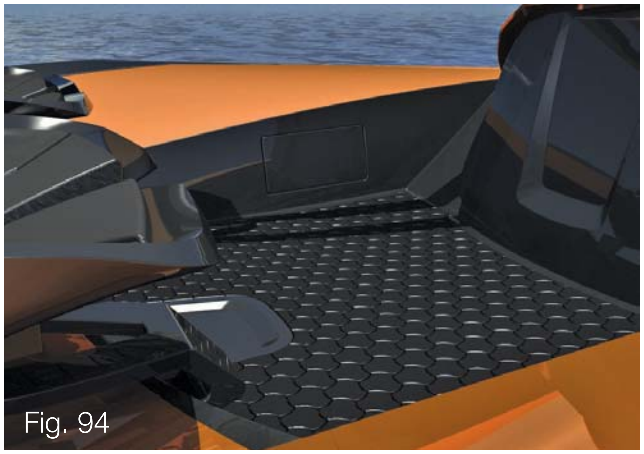


Fig. 94

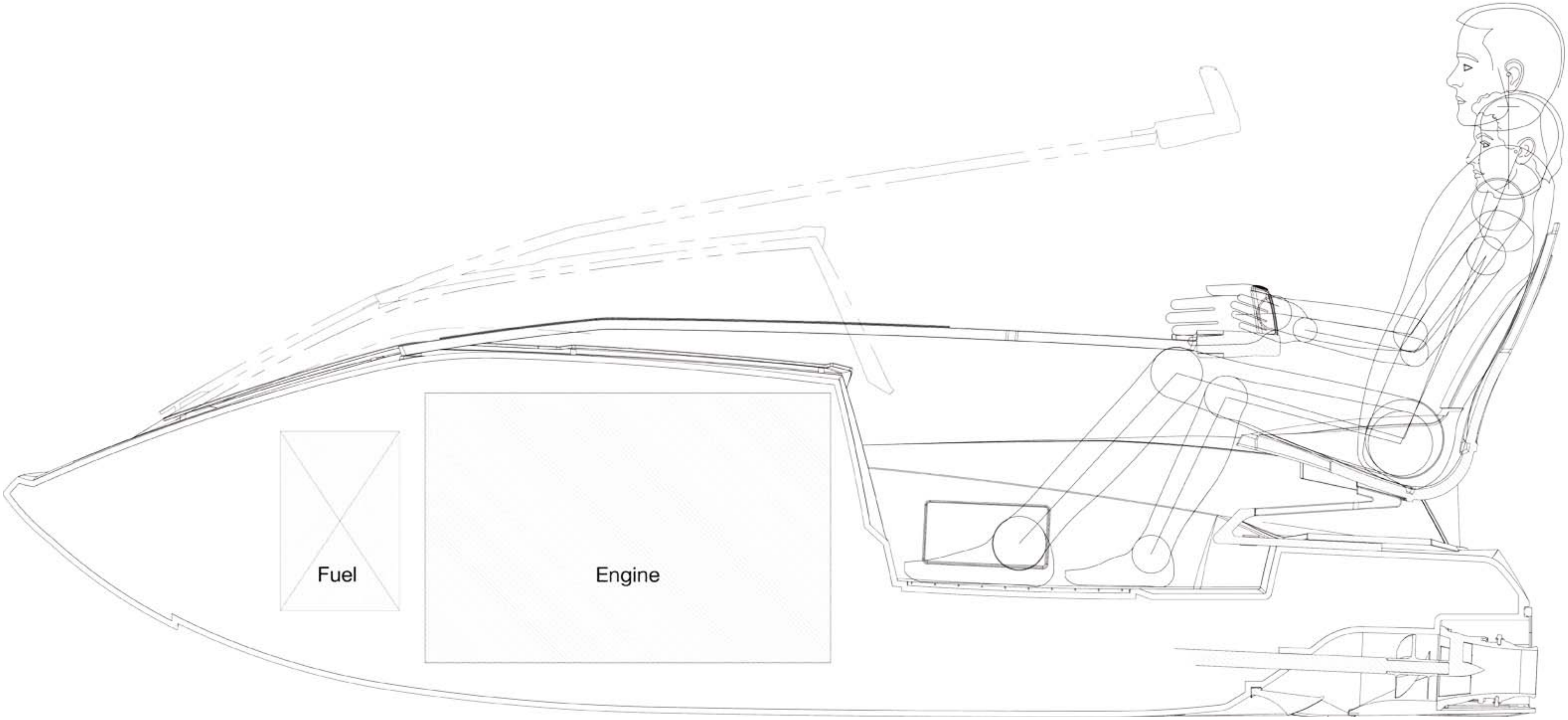


Fig. 95

Two fuel caps were added to keep the design symmetrical. Their position was chosen as this area of the craft was lacking detail compared to the rest of the craft. The small detail that runs forward from the fuel cap was added to integrate it with the surface (fig. 96). It has not been decided what the secondary cap will be used for at this stage. If possible, it could be used to check the oil level without having to open the engine hatch.

The engine hatch opens as shown in the image. This creates a large opening for accessing the engine, making maintenance less problematic. Due to the saddle style seat, current PWC access to the engine is limited and the engine cannot be removed from the craft without the engine being dismantled first.

The engine bay is supplied with air via two NACA ducts tucked under the front of the floating surfaces (fig. 97). Air vents have been hidden from view to keep a more elegant aesthetic and to help it to remain approachable. Having the ducts hidden also helps to keep water out of the inside of the craft, though a baffle system will also be used to stop water ingress should the craft be upturned. The air in-vents are located on a forward slanting surface to make sure they are in a high pressure zone, similarly the upturn at the rear of the floating surfaces will create a low pressure zone, helping to suck air out of the vents (fig. 98).

Though boarding the craft is envisioned to generally be from the beach or wharf, a fold-down step ladder has been incorporated into the stern of the craft (fig. 98). This is in direct opposition to the results of my survey where users said that a step ladder was not necessary,


Fig. 96

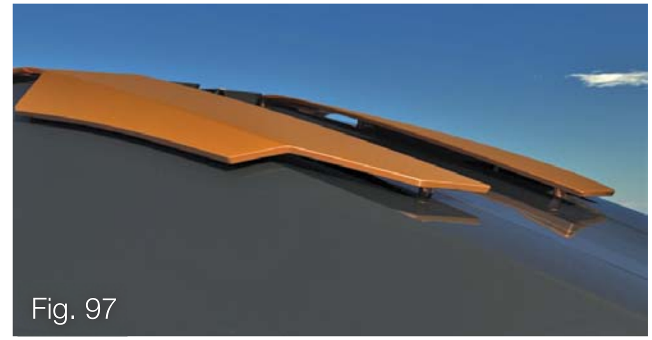


Fig. 97

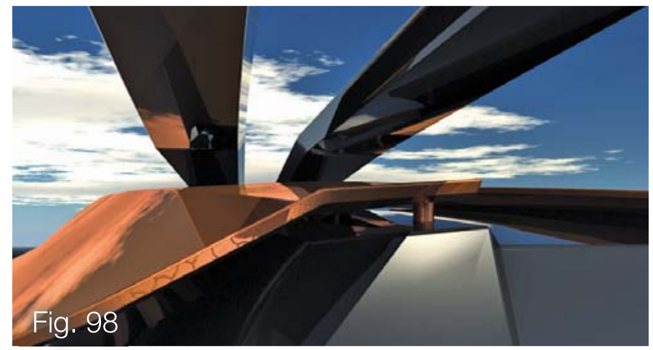


Fig. 98


Fig. 99

Fig. 100

however, because the gap between the seats is relatively small I found that a place to stand was required.

Lastly, a quick aesthetic mock up of a jet unit and the surrounding parts were added for display purposes. The technical aspects of this part of the design still need to be considered.

4.3.5 Colour Scheme

I will now discuss the selected colour scheme of the design and how I arrived at this solution.

Having designed the craft to be more elegant than aggressive, I began by looking at both classic and sporting colour schemes. The result was two competing schemes, one blue and white, the other red and dark gray (fig. 101).

Eventually I chose to go with the more classic blue and white colour scheme and began producing CAD renderings of the design. However, on re-examination of these renders it was decided that the selected colour scheme was too safe and boring choice for an original concept (fig. 102).

Instead I decided a darker hull colour was needed as this had become symbolic of performance in the PWC industry. Both Sea-Doo and Yamaha use black hulls for their performance models and white for their recreation models. I felt it particularly important to make this visual link with this design since it could easily be mistaken for a lower performance ski due to the lower horsepower used.

In light of this I returned to the dark gray base colour, and began looking for a colour for the floating surfaces. I settled on a metallic copper as this had a high level of contrast with the grey and was not a standard colour so would draw attention to the concept.

I then began producing all of the visual presentation material for the project, only to decide that this colour scheme was also still too safe and that the dark colour made it too aggressive looking (fig. 100).

I started looking for a lighter grey colour but ended up liking how a grey blue metallic went with the copper. This was an unconventional colour choice that would add impact to my design and make it stand out. Unfortunately, it was too late in the project to change the renderings I had already completed so I had to keep them the same grey colour but instead painted the model in the final colour scheme.

Fig. 101

Fig. 102


Fig. 103

4.3.6 Design Model

When I changed my project I liked the thought of producing a full scale model of my design. Since it would only be 3 metres long I thought this achievable. Then Atomix Boats became involved in the project and we began looking at the possibility of producing a full-scale working prototype. Unfortunately, this arrangement fell through (my arrangements with Atomix Boats are detailed in Appendix 2).

At this stage I decided that by only doing a scale model I would allow myself much more time to work on the other components of my project. This would also be a more practical solution and I felt that a scale model would have sufficient detail to effectively communicate the design.

The model was machined out of ABS plastic as this was more cost-effective and durable than rapid prototyping. ABS also allowed a high level of detail and for thin sections such as the wing tips to be machined. All additive parts were rapid prototyped as this provided a high level of detail that matched up to the detail in the CAD model.

Fig. 104


Fig. 105

Fig. 106

Fig. 107

Fig. 108

Fig. 109

5.0 CONCLUSION

The aim of this project was to create a new, more efficient class of PWC through the application of aerodynamic lift, an examination of the current PWC paradigm and the assessment of possible alternatives to the current designs.

Formal research had been carried out first through publications, physical testing and a user survey, and then through the design of a craft that incorporated the above features.

In assessing the current PWC paradigm it was found that there is little variation in design and that in comparison to other craft they exhibit poor efficiency levels. It was hoped that this poor efficiency would be reduced by removing some of the heavier features that are not considered important by current PWC owners. Further reductions were made by employing modern manufacturing techniques that still minimise labour costs.

I discovered that PWC are currently viewed as being anti-social and that the current general arrangement did not encourage a shared user experience. From this a new general arrangement was developed one that uses a transverse seating arrangement, allowing more user interaction during operation of the craft while also allowing the roles of driver and passenger to be switched quickly and easily.

I found that the main use of PWC is as a recreational adrenalin toy and, as such, a large focus of the project has been on creating a craft with performance that rivals the market leaders. This was considered important to the project so that consumers would view the craft as an alternative rather than a compromise or a gimmick.

The use of ground effect has helped achieve these performance goals. Research was conducted into current mono-hull designs that use ground effect, resulting in a wing design similar to Ocke Mannerfelt's design to ensure that the craft remains stable. It was calculated that if wings of the same size were fitted to Yamaha's entry level PWC, the VX, it would achieve a top speed equal to their top of the line ski. This result justified the research.

Research was conducted into stepped hulls as another means of improving efficiency and performance. A literature review was conducted, resulting in a design process for single and multiple-step hull designs. From this it was found that a single step design was the most suitable for the craft. Research was also conducted into current PWC hull forms from which a non-stepped hull design was developed before having the step added. This resulted in two comparable designs being developed, the only difference being the step.

The two designs were tested at scale using radio control so that both qualitative and quantitative characteristics could be assessed. Model testing was inconclusive in terms of performance gain due to damage caused to the motor during testing. The testing that was completed did suggest that handling would not be affected, though further testing at full scale is needed to confirm this and produce more reliable results.

The results of testing, combined with the findings of the literature review implies that step hulls may find a new application in PWC.

Overall, the project has been a success, resulting in Flux: a new class of personal watercraft based on the implementation of ground effect and a stepped hull to increase performance. The craft places a heavy emphasis on providing a shared user experience through the use of a transverse seating arrangement and controls that can easily be changed from one side to the other.

Fig. 110

FLUX'S SPECIFICATIONS

Length	3000mm
Beam	2500mm
Height	956mm
Waterline	2720mm
Waterline Beam	1150mm
Capacity	2 adults (160kg)
Light Displacement	220kg
Engine	1050cc four stroke
Power	110hp
Construction	Hand laid fibreglass


Fig. 111

Fig. 112

Fig. 113

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Fig. 114

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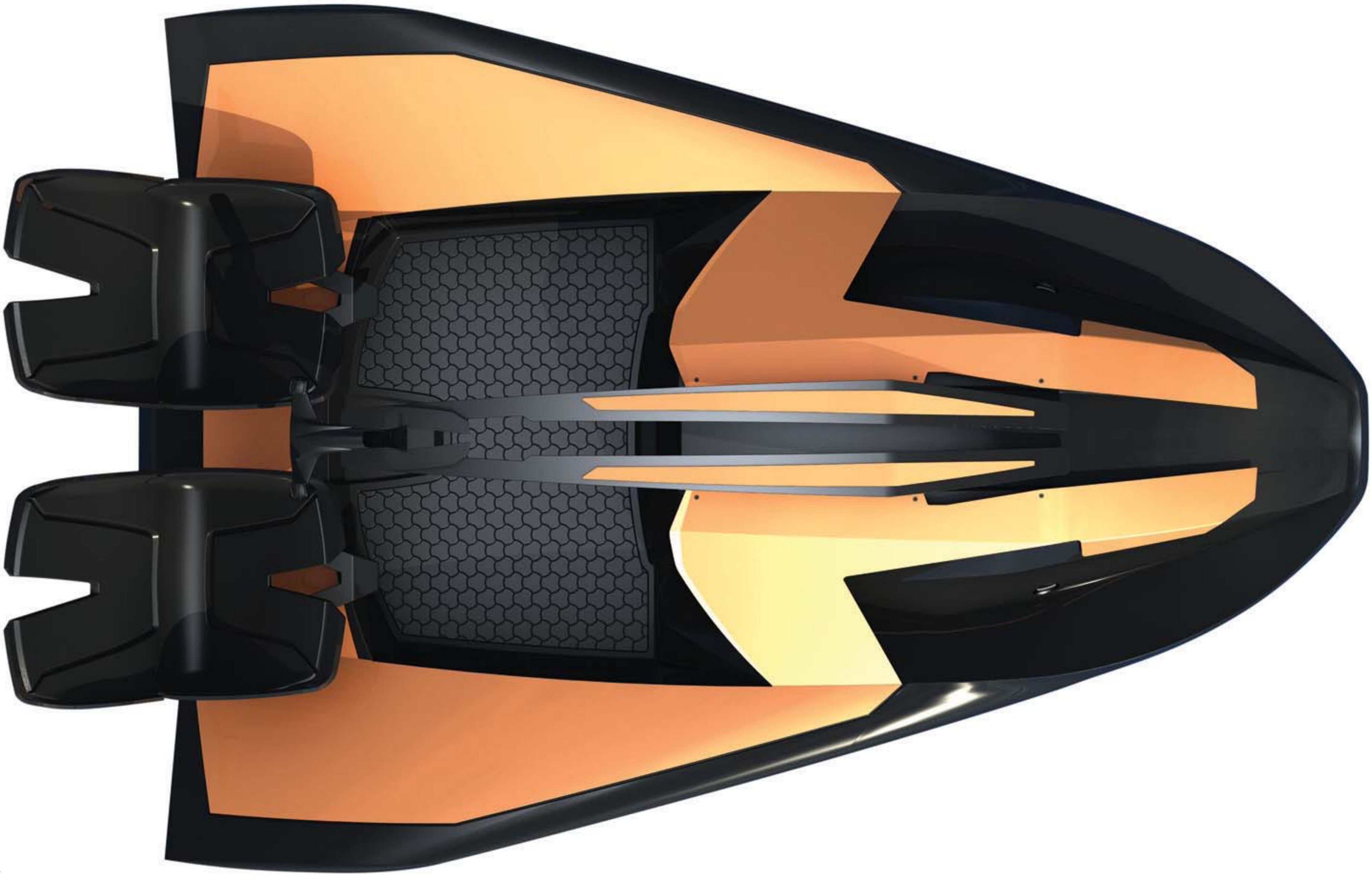

Fig. 115

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Fig. 116

APPENDIX 1 - PREVIOUS WING IN GROUND EFFECT RESEARCH AND PROJECT ORIGINS

As part of my undergraduate degree I completed a major final year project over two semesters. The brief for this project was to design a wing in ground effect craft to act as a tender to a large super yacht with the aim of providing a fast, efficient, and comfortable transport that was able to access remote and shallow areas out of the reach of the slow and large super yacht.

The concept is capable of carrying four passengers and incorporates a 4.8m rear deck that promotes interaction with the marine environment, with two built in sun loungers that convert to a dining area.

Propulsion is supplied by two electric ducted fans helping to keep the noise of the craft to a minimum, giving the craft a more refined and social user experience since ambient noise in the cabin will be reduced to a level where casual conversation can take place.

Throughout the project I had a mentor, Bruno deMichelis, who is currently developing his own wing in ground effect craft and who also developed a craft for the Italian Military while in college. Bruno helped me to interpret the results of model testing I carried out during the first half of the project.

I tested a range of models under Bruno's guidance in the development of my final configuration. Models were built out of styrene foam, plywood, and balsa wood with lead being added to position the centre of gravity and bring the model up to scale weight. The models were then propelled using a 10m long piece of bungee to give a smooth acceleration, the aim of this was to find a design that would fly stably in ground effect. In the end my final configuration weighed 850g and flew over 50m stably in ground effect, this was in line with results achieved by Bruno in his testing program.

I began my Master's project looking to develop this configuration and apply it to the personal watercraft market with the aim of increasing the accessibility of this unique user experience. Unfortunately, after a month into the project I realised that I would not be able to achieve this goal due to the poor load carrying capability of the craft. At a size of 4.5m long and 4m long the craft would still only be able to carry one person. Due to scaling laws I would be closer to the 9.8m long craft from my previous project before I could carry the extra person, clearly this was not acceptable for a personal watercraft that was meant to increase accessibility and compete with 3.5m long personal watercraft.

I came up with an alternative concept centred on the introduction of ground effect into personal watercraft to increase the efficiency of the craft while still providing a new user experience. I compared the two concepts on several key aspects and sent the results to some experts for comment. The comparison and responses are noted in full below.

My Comparison:

I started my Master's three weeks ago but am now having second thoughts about my project and am considering changing the focus. I have included my thoughts on this below. I would be grateful, if you have time, if you would have a read through and let me know what you think:

I started out this year with the intention of designing a wing in ground effect craft for the personal watercraft (PWC) market. However, after initial research and estimates I am finding that perhaps this is not a suitable application for this technology and so am proposing to change the craft to being constantly waterborne but still aerodynamically assisted, I am picturing something similar to a bat boat (see the attached image).

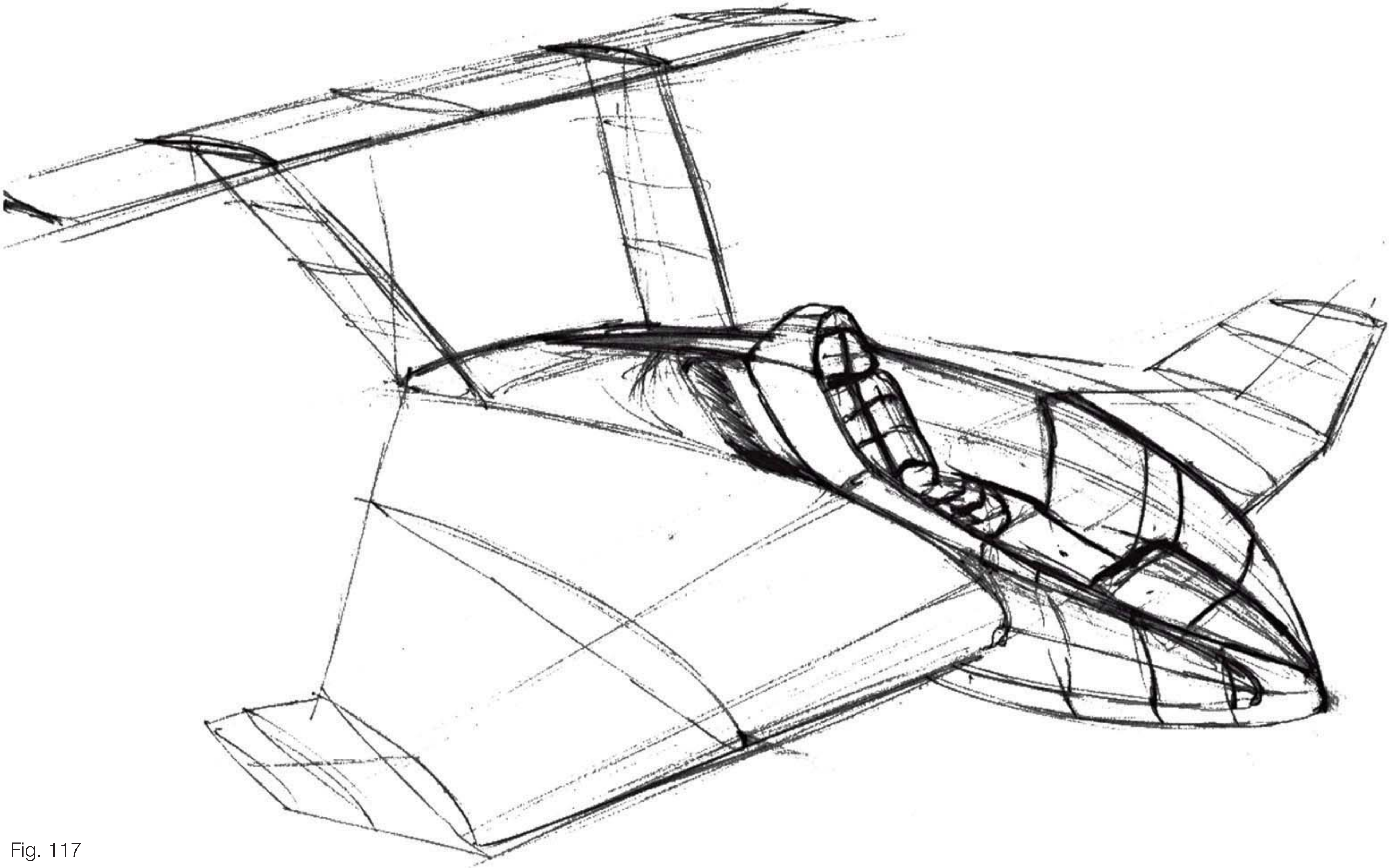

Fig. 117

My reasons for this are summarised below;

1. My main concern with the WIG concept is the lack of load carrying capacity; although large WIGs are known for their efficiency and ability to carry large loads this does not equate for a smaller craft due to scaling effects.

   In the absolute best-case scenario my initial estimates point to a craft that will be in excess of 3.5x4m and only able to carry one person with no cargo. I think it is unacceptable to have a craft for only one person to use due to the lack of ability for people to share the experience, which would make it more appealing to couples and families. It also raises the issue of how to teach someone to drive the craft when it cannot be demonstrated by being on board the craft with them.

2. This brings me to my next point: that the WIG, by nature, will have much steeper learning curve than the waterborne craft (HSC). This is due to the WIG having four primary controls (roll, pitch, yaw and throttle) as opposed to the HSC only having two primary controls (throttle and yaw).

   Given the above it is reasonable to assume that a much wider range of people will be capable of operating the HSC compared to the WIG.

3. In terms of comfort, because the WIG is operating clear of the water surface it should be more comfortable in operation; the HSC on the other hand will be subjected to the impacts and vibrations associated with operating in waves. However, the smaller wings of the HSC will have a cushioning effect and will make the craft more comfortable than a competitor product like a jet ski.

4. The HSC will also be suitable for a wider range of applications. One of these is waterskiing; the 2002 National (America) Recreational Boating Survey found that 44.55% of people use their PWC for waterskiing and that for 21.7% of people, this was that primary use for the craft. To me this is too big a segment of the market to ignore.

5. In terms of market and marketability I think the two craft are at opposite ends of the spectrum, the WIG would be looking at creating a niche market for itself and would be more likely to create new customers for the PWC market from an aeronautical background than to convert a significant number of people from the dominant jet ski style craft.

   The HSC on the other hand would be in more direct competition with jet skis. This may open up an opportunity to look at the project as a redesign of the jet ski, taking it back to first principles and designing from scratch.

   From my investigation I concluded that the WIG is a more radical and unique concept (though I have seen two or three concepts for WIGs of this size) when compared to the HSC and existing products in the PWC market. But I also found that the limitations and complexity of the craft may limit its appeal and usability.

The Projects

I have also been thinking about the two concepts in terms of individual projects and what they might contribute to my portfolio. I feel that I already have one WIG in my portfolio and though this provides a nice base for me from which to start my Masters' I am scared of my portfolio becoming too specialised in one area.

Also, in my opinion, I think the HSC will give me more options in terms of styling compared to the WIG due to a (slightly) lower importance of aerodynamics.

Fig. 118

Responses:

Bruno deMichelis, mentor for final year project and WIG designer.

I have read your email and I agree that if you intend to look at the recreational market you should deepen your knowledge about HSCs and SEPPS, which I believe to be more viable and important that HSCs at the present stage. Good luck and keep in touch.

Richard Karn, New Zealand America's Cup Teams 1987-2000

If your WIG project was aimed at the PWC market, then your commentary makes sense.

By the way, what does HSC stand for ?

The batboat is not as stable as I thought it would be. I saw one race here recently, and it bounced and bucked its way around the course. It still had a tendency to chine walk something shocking. (see pic)

It certainly wasn't as stable as the big offshore powerboats with those big wings on top of them.

To get any decent aero forces you need either wing area or boat speed (or both). It sounds like you will be in the big wing area box.

Are you interested in doing an inflatable, hang glider type wing to give much greater area, for minimal weight, along with robustness. Modern sail-kites use cheap, low tech materials in an ingenious way to provide very rigid, controllable flying canopies. They weigh peanuts, develop mountains of lift and are very tough, unless you puncture a bladder.

I can imagine a jet-pump powered PWC with an 8sqm inflated rib wing, developing about 50kg of lift at a boatspeed of 20 knots. This would give the craft an airey feel, and you would be able to bounce it off waves going into a head wind and maybe make small gliding passages. If the wing is a soft structure it should be safe, even at the hands of fearless, generation Y kids.

From these responses I decided to continue with the water based concept and abandon the full wing in ground effect craft.

Fig. 119

APPENDIX 2 - ATOMIX BOATS

In May, while conducting my research into stepped hull design, I met with Brett Bakewell-White, a local designer responsible for the design of the Sleep Head offshore racing catamaran. During the meeting he suggested that he had a client that might be interested in my project as they had recently approached them about designing a PWC for them.

The company was Atomix Boats, "production based boat builders of a wide range of sports boats, fishing boats, RHIBs, tenders, PWC for the international market," based in Glenfield with production facilities in China.

I met Richard Cains, the sales and distribution manager, on the 3rd of June to discuss the possibility of us working together. He was positive about my project and was keen for me to keep the creative control as well as ownership of any intellectual property. The plan was to apply for a grant through Enterprise North Shore for the materials to build the prototype; Atomix would be responsible for supplying the engine, jet unit, and electric for the prototype.

We got as far as discussing a 2% commission on any craft that the company sold, and Richard said that the gear for the craft had left China with their latest shipment of boats. This was sometime during July. I was due to meet the owner of the company, William, in early October to finalise the agreement and sign the contracts. This was already later than I had anticipated. William had to postpone our meeting twice due to being held up in Australia, after that I never heard from him or Richard again. At this point I had formed the opinion that it would not be such a bad thing if I did not complete the full size prototype as it would allow me to concentrate on the designing the details of the design.

Though nothing came to fruition from my dealings with Atomix, it did have a significant impact on my project, mainly because by the time they pulled out of the project I was in the final stages of my clay model. One of the main things that came out of my dealings with Atomix was the engine I used. This was because they had already developed an engine and jet unit, which they supplied the drawings of. If the project was to continue I would look at different powering option and possibly upgrading to a 130hp engine in order to match the acceleration levels that the existing top of the line PWC are achieving.

The Sea-Doo 3D I mention in the main body of the text was originally released with a 110hp engine that was then upgraded to 130hp, so it is foreseeable that I can do the same with my design without making any design changes. Even with this upgrade the craft will have exactly half of the horsepower of the 2010 Sea-Doo RXP-X.

Fig. 120

APPENDIX 3 - ENGINEERING

While still assuming that I would be building a full scale prototype for Atomix Boats, I worked with Formula Cruisers, a local builder of sports fishing boats, to specify the fibreglass laminates for the craft. The following is a series of spreadsheets specifying the different laminates, estimating the weight of the hull structure, and estimating the cost of producing the prototype.

Prototype Cost Estimate

Item	
CNC Machining	$ 5,000.00
Paint job	$ 2,500.00
Building Materials	$ 3,286.24
Presentation Materials	$ 1,000.00
Mechanical Parts	$ 600.00
Seat Upholstery	$ 300.00
total	$ 12,686.24

Fig. 121

Laminate Specifications

A Bottom

No	Description	Fibre wt%	Thickness (mm)	Reinf kg/m^2	Resin kg/m^2
1	300gm Boat Cloth	0.500		0.300	0.300
2	900gm Double Bias	0.500		0.900	0.900
3	300gm Kevlar	0.440		0.300	0.382
4	900gm Double Bias	0.500		0.900	2.000
5	300gm Boat Cloth	0.500		0.300	0.300
	Totals		0.00	2.700	3.882
	Total Laminate Weight				6.582
	Total Laminate Area				1.841

B Top Sides

No	Description	Fibre wt%	Thickness (mm)	Reinf kg/m^2	Resin kg/m^2
1	300gm Boat Cloth	0.500		0.300	0.300
2	400gm Double Bias	0.500	0.46	0.300	0.300
3	4mm Coremat		4.00	0.163	2.000
4	400gm Double Bias	0.500	0.46	0.300	0.300
5	300gm Boat Cloth	0.500		0.300	0.300
	Totals		4.92	1.363	3.200
	Total Laminate Weight				4.563
	Total Laminate Area				9.23

C Seat Laminate

No	Description	Fibre wt%	Thickness (mm)	Reinf kg/m^2	Resin kg/m^2
1	FFGC061M	0.5		0.200	0.200
2	FDB420	0.5		0.420	0.420
3	Divinycell H60 10mm			0.600	0.7
4	FDB420	0.5		0.420	0.420
5	FFGC061M	0.5		0.200	0.200
	Totals		0.00	1.840	1.940
	Total Laminate Weight				3.780
	Total Laminate Area				0.996

D Floating Panel Laminate

No	Description	Fibre wt%	Thickness (mm)	Reinf kg/m^2	Resin kg/m^2
1	300gm Boat Cloth	0.5		0.300	0.300
2	Divinycell H60 10mm			0.600	0.7
3	300gm Boat Cloth	0.5		0.300	0.300
	Totals		0.00	1.200	1.300
	Total Laminate Weight				2.500
	Total Laminate Area				1.258

Fig. 122

Composite Weight

Item	# Items	Panel Type	Tapping Type	Area per Item m^2	Area m^2	Tapping Length m	Panel Weight kg/m^2	Tapping Weight kg/m	Tapping kg	Panel kg	Fill, Paint kg	Total kg	
Totals	61.000				14.091							72.741	48.509
Hull Panels													
Hull Bottom	2	Bottom	None	1.168	2.336		6.582			15.37513		15.37513	
Strake 1	2	Bottom	None	0.106	0.212		6.582			1.395345		1.395345	
Strake 1 side	2	Bottom	None	0.042	0.084		6.582			0.552873		0.552873	
Strake 2	2	Bottom	None	0.090	0.180		6.582			1.184727		1.184727	
Strake 2 side	2	Bottom	None	0.090	0.180		6.582			1.184727		1.184727	
Chine	2	Bottom	None	0.266	0.532		6.582			3.501527		3.501527	
Top sides	2	Top Sides	Join	0.327	0.654		4.563			2.984202		2.984202	
Central stern	1	Top Sides	Join	0.111	0.111		4.563			0.506493		0.506493	
Side Stern	2	Top Sides	Join	0.079	0.158		4.563			0.720954		0.720954	
Bow	1	Bottom	Join	0.079	0.079		6.582			0.519964		0.519964	
Sub Total	18				4.526							27.92594	17.10828
Deck													
Sides	2	Top Sides		0.339	0.678		4.563			3.093714		3.093714	
Rear Deck	1	Top Sides		0.539	0.539		4.563			2.459457		2.459457	
Cockpit Aft	1	Top Sides		0.157	0.157		4.563			0.716391		0.716391	
Cockpit floor	1	Top Sides		0.883	0.883		4.563			4.029129		4.029129	
Cockpit wall	2	Top Sides			0.000		4.563			0		0	
Foot rests	2	Top Sides		0.085	0.170		4.563			0.77571		0.77571	
Fore Deck	2	Top Sides		0.245	0.490		4.563			2.23587		2.23587	
Bow top	1	Top Sides		0.013	0.013		4.563			0.059319		0.059319	
Reverse bow	1	Top Sides		0.016	0.016		4.563			0.073008		0.073008	
Engine side	2	Top Sides		0.288	0.576		4.563			2.628288		2.628288	
Engine top	1	Top Sides		0.753	0.753		4.563			3.435939		3.435939	
Engine Aft	1	Top Sides		0.2	0.200		4.563			0.9126		0.9126	
Sub Total	17				4.475							20.41943	16.9155
Wings													
Top	2	Top Sides		0.6	1.200		4.563			5.4756		5.4756	
Bottom	2	Top Sides		0.658	1.316		4.563			6.004908		6.004908	
End Plate	2	Top Sides		0.658	1.316		4.563			6.004908		6.004908	
Sub Total	6.000				3.832							17.485	14.48496
Seat													
Base	2	Seat Laminate		0.248	0.496		3.78			1.87488		1.87488	
Back	2	Seat Laminate		0.25	0.500		3.78			1.89		1.89	
Sub Total	14				0.996							3.76488	0
Floating Panel													
Panel	2	Foating Panel		0.629	1.258		2.5			3.145		3.145	
Sub Total	20				1.258							3.145	0

Fig. 123

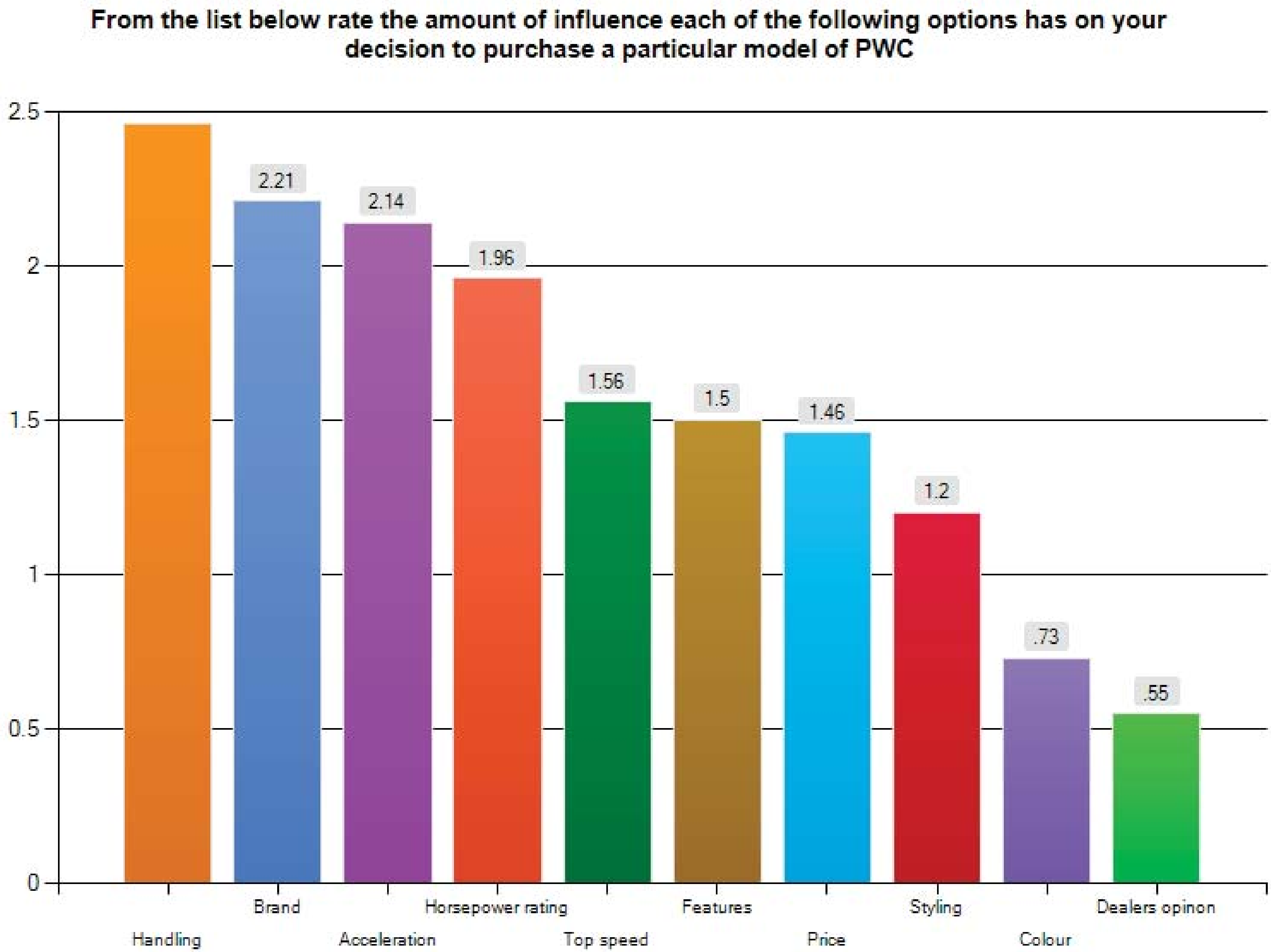
From the list below rate the amount of influence each of the following options has on your decision to purchase a particular model of PWC
2.5
2
1.5
1
0.5
0
2.21
2.14
1.96
1.56
1.5
1.46
1.2
.73
.55
Handling
Brand
Acceleration
Horsepower rating
Top speed
Features
Price
Styling
Colour
Dealers opinon

Fig. 124

APPENDIX 4 - MARKET RESEARCH

An online survey was conducted of personal watercraft users from around New Zealand to assess trends in the uses and the preferences of the users of personal watercraft. In total 66 responses were collected with 59 of those answering every question.

The survey was designed following the methods described by Kolb in her book; Marketing Research: A Practical Approach. This allowed me to gain meaningful data on all but a few of my questions. Kolb (2008) also presents methods on how to code multiple choice answers to allow me quantitatively assess the results and give more credibility to the results.

The following is a presentation of the survey; the questions that were asked and the results of these, where appropriate graphs have been included along with the raw results.

The first step in the process was to identify the aims of the research, these were:

- Assess preferences new PWC buyers.
- Gain insight into the consumers' decision making and buying habits.
- Learn what features people look for and are most concerned with when purchasing a new PWC.
- To establish the primary uses people have for PWC.
- Discover the motivations of the consumer to purchase a PWC (intended use) and to compare this to the outcomes of the purchase (or the actual use).

1. The first question simply identified the sex of the respondent. Not surprisingly it was male dominated. What was surprising was the extent, with 97% of respondents being male.
2. The second question looked to establish the age of the market. I already had results from an American survey which suggested that the average PWC

2. What age are you?		**Response Percent**	**Response Count**
<20		7.6%	5
20-29		27.3%	18
30-39		**39.4%**	**26**
40-49		18.2%	12
50-59		7.6%	5
60+		0.0%	0
	answered question		**66**
	skipped question		**0**

Fig. 125

7. Please indicate how often you use your PWC for the following activities						
	Never	**Occasionally**	**Regularly**	**This is all I use it for**	**Rating Average**	**Response Count**
Organised competitions	**44.1% (26)**	20.3% (12)	32.2% (19)	3.4% (2)	0.95	59
Adrenline toy/speed machine	3.5% (2)	17.5% (10)	**57.9% (33)**	21.1% (12)	1.96	57
Water-skiing/wakeboarding/biscuiting	**42.1% (24)**	36.8% (21)	19.3% (11)	1.8% (1)	0.81	57
Tow-surfing	**86.5% (45)**	9.6% (5)	3.8% (2)	0.0% (0)	0.17	52
Tender for a yacht or launch	**96.4% (53)**	1.8% (1)	1.8% (1)	0.0% (0)	0.05	55
Fishing	**70.9% (39)**	20.0% (11)	7.3% (4)	1.8% (1)	0.40	55
Touring/sightseeing	24.1% (14)	**39.7% (23)**	34.5% (20)	1.7% (1)	1.14	58
					answered question	**61**
					skipped question	**5**

Fig. 126

user was over 40 (PWIA), but needed this question to give meaning to the rest of my results. Of the 66 respondents who answered this question 39.4% were aged 30-39 years and 18.2% were 40-49. This suggests an older market base than one might expect from this type of recreational vehicle, but this may have something to do with the price of the craft.

3. This question looked to establish how many craft people were likely to own, 50% of respondents owned one PWC with no one owning more than five craft. This suggests that people were unlikely to buy a secondary craft so I could not design mine as such, it had to be able to compete with existing craft and be viewed as an alternative and not a compromise.
4. This question looked to establish if there were any particular models or years that were particularly popular among respondents. The results were varied, suggesting plenty of variety in the models people purchased.
5. In this question I was looking to see how many respondents bought their craft brand new, the purpose of this was to gauge the size of the new craft market. It was found that over

6. How many years have you been regularly riding PWC

	Response Percent	Response Count
1	1.6%	1
2	16.4%	10
3	18.0%	11
4	11.5%	7
5	6.6%	4
6	4.9%	3
7	1.6%	1
8	6.6%	4
9	1.6%	1
10 or more	**31.1%**	**19**
	answered question	**61**
	skipped question	**5**

Fig. 127

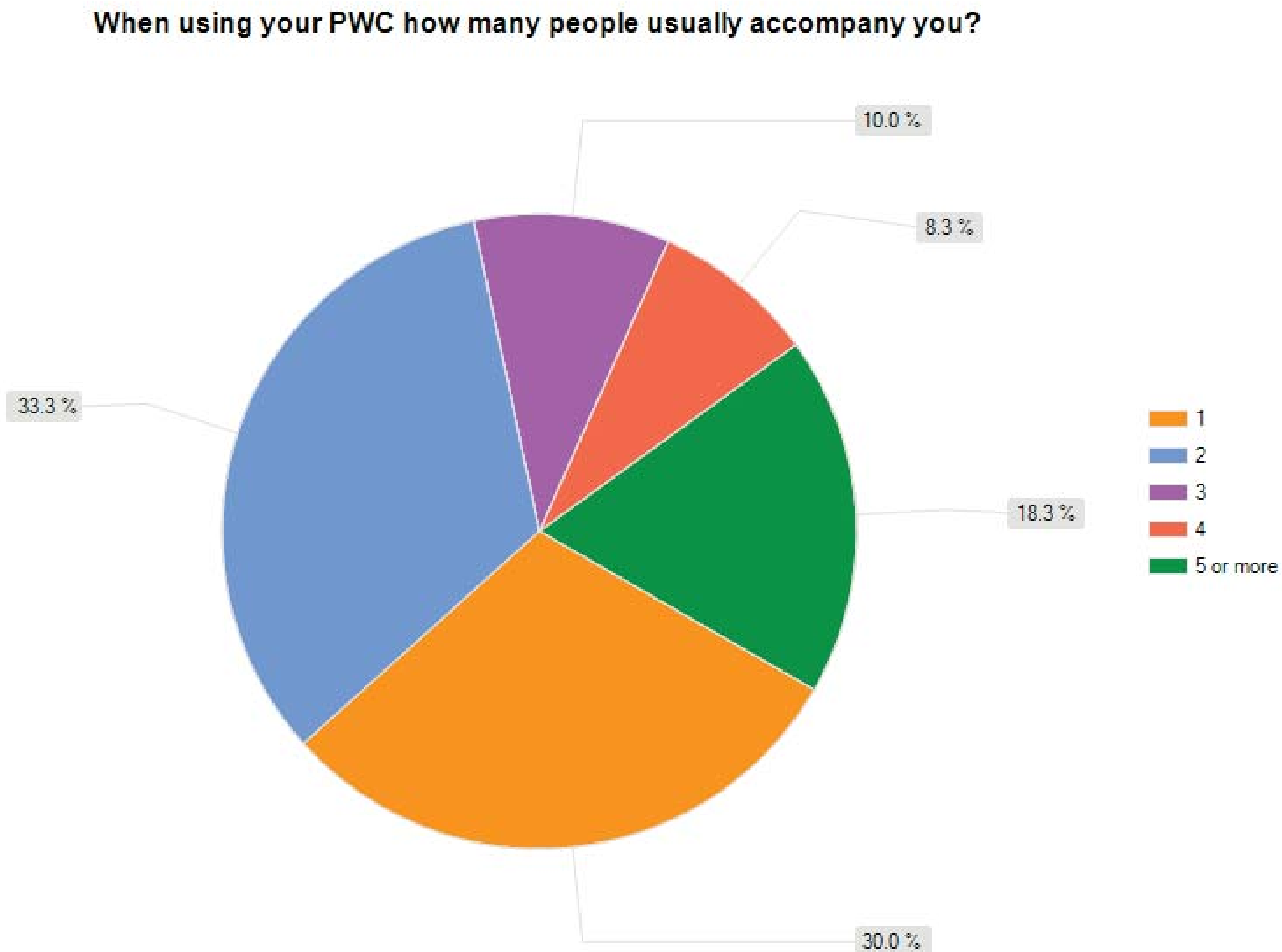
When using your PWC how many people usually accompany you?
10.0 %
8.3 %
33.3 %
18.3 %
30.0 %
1
2
3
4
5 or more

Fig. 128

half (55.7%) bought their craft second hand. In reality not a lot of insight was gained from this question but it is an interesting statistic nonetheless.

6. This question asked the respondents how many years they had been regularly riding PWC. It was surprising that there was a trough between people who had been riding for more than 10 years and those who had only been riding for 2 or 3 years.
7. This was one of the most important and fruitful questions of the survey, the aim of this question was to identify what people were using their PWC for. Answers were given a point scale ranging from 0 for never, to 3 if that was all they ever used it for with the means being graphed. The results of this made me focus on the use of the craft as a recreational adrenaline toy.
8. A major effect on the design is the conditions in which it will be used. I found that the most common location was on a lake. Surf was also popular due to the number of respondents who were pole ski riders. The results of this question were reasonably spread suggesting that the craft would likely encounter a large variety of conditions.
9. The aim of this question was to quantify the number of people using a single PWC at one time. However, I failed to specify this is in the question, making the results of this question reasonably redundant.
10. This question did not have any significant impact on my design.
11. The aim of this question was to find out what people were looking for when they purchase a PWC. Again a point scale was used ranging from 0 to 3, with the mean answers being graphed.

I was at first surprised that handling was more important than acceleration or top speed, but considering the large number of aftermarket bolt-on parts to help these and the difficulty in changing the handling characteristics of a poorly designed hull this is not that surprising. The fact that the horsepower rating is valued so highly is one of the reasons for this project. Consumers should be putting more focus on what they get out of the craft not the size of the engine that goes into it.

8. In which areas do you use your PWC regularly

	Response Percent	Response Count
Coastal Bays and Inlets	50.8%	31
Surf	63.9%	39
Lakes	**70.5%**	**43**
Rivers	50.8%	31
Open ocean	45.9%	28
answered question		61
skipped question		5

Fig. 129

14. From the list below select those features of a PWC which are important to you and those which could be discarded

	Important	Could be discarded	N/A	Rating Average	Response Count
Suspension	9.1% (5)	**56.4% (31)**	34.5% (19)	-0.72	55
Brake	10.9% (6)	**56.4% (31)**	32.7% (18)	-0.68	55
Speedo	**48.2% (27)**	33.9% (19)	17.9% (10)	0.17	56
RPM Gauge	**63.0% (34)**	20.4% (11)	16.7% (9)	0.51	54
Variable Trim Control	**58.9% (33)**	28.6% (16)	12.5% (7)	0.35	56
Mirrors	32.1% (18)	**44.6% (25)**	23.2% (13)	-0.16	56
Ski Tow Eye	**61.8% (34)**	25.5% (14)	12.7% (7)	0.42	55
Glove Box	**58.2% (32)**	23.6% (13)	18.2% (10)	0.42	55
Speed Limiter for Learners	**43.6% (24)**	40.0% (22)	16.4% (9)	0.04	55
Boarding Step	29.1% (16)	**49.1% (27)**	21.8% (12)	-0.26	55
				Other (please specify)	16
				answered question	**57**
				skipped question	**9**

Fig. 130

12. This question looked to see if there was a dominant brand in the market. The results were not that surprising.

13. The reasons people were loyal to particular brands was varied and but reasonably standard. There was no one thing that seemed to have more importance than anything else.

14. This was another one of the more significant and insightful questions of the survey. The goal of this question was to assess which feature users thought were important and those that were not needed. It also looked at gauging the overall importance consumers placed on the additional features of their craft. Overall I found that there was not a high importance placed on the additional features, particularly the heavier, more recently added, features.

15. The aim of this question was to assess if there was a current model that was significantly more popular than anything else, and why that was. Results were widespread, but with no conclusive results showing that any particular model was more popular than the rest.

12. Do you have a loyalty or preference towards one of the following brands?

	Response Percent	Response Count
Kawasaki	14.0%	8
Sea-Doo	29.8%	17
Yamaha	**42.1%**	**24**
Honda	1.8%	1
HSR-Benelli	0.0%	0
No	12.3%	7
Other (please specify)		5
answered question		**57**
skipped question		**9**

Fig. 131

Fig. 132

APPENDIX 5 - MODEL TESTING

The aim of the model testing was to assess the performance of a stepped hull design in comparison to a conventional PWC hull. Radio control was selected so that qualitative aspects, such as handling, could be assessed as well as outright performance.

Research was conducted into radio control equipment to ensure that the target speed was achievable. This resulted in an electric motor, lithium polymer batteries, miniature jet unit, and data recorder being purchased.

The data recorder consisted of a central recording unit with plug-in modules that measured the RPM of the motor, throttle level, GPS location and speed, and the charge of the batteries.

The test site was an adequately large pond beside Lake Pupuke in Takapuna, Auckland. The pond is flanked by a large cliff on one side allowing for sheltered conditions for testing. A pond was selected as it did not add any inconsistency into the result from currents or tides. A pool was also considered but access to a pool large enough for the model was not available.

A scale of 2/9th was selected based on selecting a scale weight that would allow the model to reach the target scale speed. The model was constructed from balsa wood and sealed with fiberglass and epoxy, this gave a strong, water tight structure that was cost effective and provided a reasonably accurate representation of the intended hull form. The electronics were then installed into the hull, the model was bought up to the scale weight and the centre of gravity tweaked using strips of lead.

Testing of the model consisted of a series of straight line drags as well as testing the cornering and handling characteristics. Data from the GPS was then collected and entered into a spreadsheet so that the acceleration of the model could be calculated.

During testing of the initial model I noticed significant variance in the performance figures between tests. This was attributed to slight variances in the surface conditions of the pond. Because of the scale of the model the smallest ripples on the surface of the pond would lead to significant speed.

I pushed on with the testing hoping to get results in ideal conditions with both models. It was decided to modify the original model to incorporate the step to eliminate any variance in results arising from differences in the handmade hulls.

During testing of the first model the electronics were completely submerged in water, at first this had no effect on the performance of the model. However, after leaving the model to sit the motor seized. I was able to free it but the performance was not the same. This cancelled out any comparison of acceleration or speed between the two craft.

From this point I decided to cancel any further testing, as it was not a pivotal point of my research and I had already spent more time on it than I had originally allowed for in my timeline. The testing was not a complete failure. Even though I cannot quantify the results I can report that the stepped hull design did not display any of the adverse characteristics that have been associated with poor design in the literature. This, combined with the literature unanimously reporting that a stepped hull will display better performance than a non stepped hull, made me decide to use the stepped hull in my final concept.

From here I would like to construct a full scale prototype to eliminate scaling factors, it is foreseeable to construct a hull that could easily be changed from a stepped hull to a more traditional hull shape.

Representative Models Cribsheet

Basic								
Make	**Seadoo**	**Seadoo**	**Yamaha**	**Yamaha**	**Kawasaki**	**Kawasaki**	**Honda**	**HSR-Benelli**
Model	RXT-X	GTX Limited IS	FZR	FX SHO	Ultra 250X	Ultra 260X	Aquatrax F-15X	Series R Race ed
Style	Musclecraft	Luxury Perform				Muscle craft	Muscle craft	Muscle craft
Price (US$)	$13,699.00	$16,499.00	$12,599.00	$12,599.00	$11,699.00	$11,999.00	$13,999.00	$26,335.00
Dimensions								
Length (m)	3.31	3.54	3.37	3.37	3.37	3.37	3.40	3.23
Width (m)	1.22	1.22	1.23	1.23	1.19	1.19	1.25	1.20
Height (m)	1.20	1.28	1.16	1.16	1.15	1.15	1.08	1.03
Displacement (kg)	365	430	366	376	416	416	436	328
Rider Capacaity	3	3	2	3	3	3	3	3
Fuel Capacity (l)	60	70	70	70	93.6	93.6	84	87
Storage Capacity (l)	112.1	62	80.6	100	240	240	10	
Engine								
Horsepower	255	255	210	210	250	260	197	342
Displacement	1493.8	1493.8	1812	1812	1498	1498	1470	2260
Induction	supercharged	supercharged	supercharged		supercharged	supercharged	turbocharged	
Stroke	4	4	4	4	4	4	4	V6 4 stroke
Power/Weight	0.70	0.59	0.57	0.56	0.60	0.63	65.00	1.04
Drive Unit								
Impeller dia.	155	155	155	155	155	155	155	155
Impeller material	S/S 3 blade	S/S 3 blade	S/S 3 blade	S/S 3 blade	3 Blade S/S	3 Blade S/S	S/S 3 blade	S/S 3 blade
Performance								
Top Speed (MPH)	68.3		68	67.4	>65	69	65	90
Acceleration (0-30)	1.5		1.9	>2	<2	1.8		

Fig. 133

APPENDIX 6 - CRIB SHEETS

2009 Sea-Doo Models

Basic													
Make	Seadoo	Seadoo	Seadoo	Seadoo	Seadoo	Seadoo	Seadoo	Seadoo	Seadoo	Seadoo	Seadoo	Seadoo	Seadoo
Model	GTX Limited IS	GTX 215	GTX 155	RXT IS	RXT-X	RXT	RXP-X	RXP	GTI SE 155	GTI SE 130	GTI 130	Wake Pro 215	Wake 155
Style	Luxury Performance	Luxury Performance	Luxury Performance	Musclecraft	Musclecraft	Musclecraft	Musclecraft	Musclecraft	Recreational	Recreational	Recreational	Sport	Sport
Price (US$)	$16,499.00	$11,999.00	$10,699.00	$14,999.00	$13,699.00	$11,999.00	$13,399.00	$11,999.00	$9,699.00	$8,699.00	$7,799.00	$12,999.00	$9,999.00
Dimensions													
Length (m)	3.535	3.31	3.31	3.535	3.31	3.31	3.07	3.07	3.225	3.225	3.225	3.31	3.225
Width (m)	1.224	1.22	1.22	1.224	1.22	1.22	1.22	1.22	1.245	1.245	1.245	1.22	124.5
Height (m)	1.277	1.2	1.2	1.277	1.2	1.2	1.16	1.18	1.17	1.17	1.17	1.2	1.17
Displacement (kg)	430	364	355	430	365	366	351	353	338	338	333	384	339
Rider Capacaity	3	3	3	3	3	3	2	2	3	3	3	3	3
Fuel Capacity (l)	70	60	60	70	60	60	60	60	60	60	60	60	60
Storage Capacity (l)	62	129.8	129.8	62	112.1	118.9	40.3	40.3	46.8	46.8	46.8	129.8	46.8
Engine													
Horsepower	255	215	155	255	255	215	255	215	155	130	130	215	155
Displacement	1493.8	1493.8	1493.8	1493.8	1493.8	1493.8	1493.8	1493.8	1493.8	1493.8	1493.8	1493.8	1493.8
Induction	supercharged	supercharged	Normally Aspirated	supercharged	supercharged	supercharged	supercharged	supercharged	Normally Aspirated	Normally Aspirated	Normally Aspirated	supercharged	Normally Aspirated
Stroke	4	4	4	4	4	4	4	4	4	4	4	4	4
Power/Weight	0.593023256	0.590659341	0.436619718	0.593023256	0.698630137	0.587431694	0.726495726	0.609065156	0.458579882	0.384615385	0.39039039	0.559895833	0.457227139
Drive Unit													
Impeller dia.													
Impeller material	Stainless Steel	Stainless Steel	Stainless Steel	Stainless Steel	Stainless Steel	Stainless Steel	Stainless Steel	Stainless Steel	Stainless Steel	Stainless Steel	Stainless Steel	Stainless Steel	Stainless Steel
Performance													
Top Speed (MPH)				65	68.3		65						
Acceleration					0-30MPH in 1.5secs								

Fig. 134

2009 Yamaha Models

Basic												
Make	Yamaha	Yamaha	Yamaha	Yamaha	Yamaha	Yamaha	Yamaha	Yamaha	Yamaha	Yamaha	Yamaha	Yamaha
Model	FZR	FX Cruiser HO	FX Cruiser SHO	FX HO	FX SHO	FZS	VX	VX Cruiser	VX Deluxe	VX Sport	VX700	Superjet
Style												
Price (US$)	$12,599.00	$11,899.00	$13,199.00	$11,399.00	$12,599.00	$12,899.00	$7,699.00	$8,699.00	$8,299.00	$7,899.00		$7,199.00
Dimensions												
Length (m)	3.37	3.34	3.37	3.37	3.37	3.37	3.22	3.22	3.22	3.22	3.22	2.24
Width (m)	1.23	1.23	1.23	1.23	1.23	1.23	1.17	1.17	1.17	1.17	1.17	0.68
Height (m)	1.16	1.24	1.24	1.16	1.16	1.16	1.15	1.15	1.15	1.15	1.15	0.66
Displacement (kg)	366	365	381	360	376	369	319	323	322	319	283	132
Rider Capacaity	2	3	3	3	3	3	3	3	3	3	3	1
Fuel Capacity (l)	70	70	70	70	70	70	60	60	60	60	50	18
Storage Capacity (l)	80.6	100	100	100	100	80.6	70.8	70.8	70.8	70.8	70.5	
Engine												
Horsepower	210						110				73	73
Displacement	1812	1812	1812	1812	1812	1812	1052	1052	1052	1052	700	700
Induction	Super charged										N/A	N/A
Stroke	4	4	4	4	4	4	4	4	4	4	2	2
Power/Weight	0.57	0.00	0.00	0.00	0.00	0.00	0.34	0.00	0.00	0.00	0.26	0.55
Drive Unit												
Impeller dia.	155	155	155	155	155	155	155	155	155	155	155	144
Impeller material	S/S 3 blade	S/S 3 blade	S/S 3 blade	S/S 3 blade	S/S 3 blade	S/S 3 blade	S/S 3 blade	S/S 3 blade	S/S 3 blade	S/S 3 blade	S/S 3 blade	S/S 3 blade
Performance												
Top Speed	<70			62	67.4							
Acceleration					0-30 in >2							

Fig. 135

2009 Kawasaki Models

Basic					
Make	Kawasaki	Kawasaki	Kawasaki	Kawasaki	Kawasaki
Model	Ultra 250X	Ultra 260LX	Ultra 260X	Ultra LX	SX-R
Style					
Price (US$)	$11,699.00	$12,299.00	$11,999.00	$10,099.00	
Dimensions					
Length (m)	3.371	3.371	3.371	3.371	2.28
Width (m)	1.194	1.194	1.194	1.194	0.75
Height (m)	1.15	1.15	1.15	1.15	0.7
Displacement (kg)	415.93	415.93	415.93	377.27	159
Rider Capacaity	3	3	3	3	1
Fuel Capacity (l)	93.6	93.6	93.6	93.6	18
Storage Capacity (l)	240	240	240	240	0
Engine					
Horsepower	250	260	260		80
Displacement	1498	1498	1498	1498	800
Induction	Supercharger	Supercharger	Supercharger	Natural Aspiration	N/A
Stroke	4	4	4	4	2
Power/Weight	0.601062679	0.625105186	0.625105186	0	0.503145
Drive Unit					
Impeller dia.	155	155	155	155	
Impeller material	3 Blade S/S	3 Blade S/S	3 Blade S/S	3 Blade S/S	
Performance					
Top Speed (MPH)	>65		69		
Acceleration	0-30 in <2		0-30 in 1.8		

Fig. 136

2009 Honda Models

Basic		
Make	Honda	Honda
Model	AquaTrax F-15	Aquatrax F-15X
Style		
Price (US$)	$12,999.00	$13,999.00
Dimensions		
Length (m)	3.4	3.4
Width (m)	1.245	1.245
Height (m)	1.08	1.08
Displacement (kg)	423	436
Rider Capacaity		
Fuel Capacity (l)	84	84
Storage Capacity (l)	105	10
Engine		
Horsepower	153	197
Displacement	1470	1470
Induction	Natural Aspiration	Turbo Charged
Stroke	4	4
Power/Weight	0.361702128	0.451834862
Drive Unit		
Impeller dia.	155	155
Impeller material		
Performance		
Top Speed	57	65
Acceleration		

2009 HSR-Benelli Models

Basic			
Make	HSR-Benelli	HSR-Benelli	HSR-Benelli
Model	Series R Race ed	Series R Prestige	Series R Pro ed
Style	Muscle craft	Muscle craft	Muscle craft
Price (US$)	$26,335.00	$21,000.00	$15,750.00
Dimensions			
Length (m)	3.23	3.23	3.23
Width (m)	1.2	1.2	1.2
Height (m)	1.03	1.03	1.03
Displacement (kg)	328	328	263
Rider Capacaity	3	3	3
Fuel Capacity (l)	87	87	70
Storage Capacity (l)			
Engine			
Horsepower	342	278	172
Displacement	2260	2260	1130
Induction			Natural Aspiration
Stroke	V6 4 stroke	V6 4 stroke	3 cylinder 4 stroke
Power/Weight	1.042682927	0.847560976	0.653992395
Drive Unit			
Impeller dia.			
Impeller material			
Performance			
Top Speed (MPH)	90		
Acceleration			

Fig. 137

2009 Surfango Models

Basic				
Make	Surfango	Surfango	Surfango	Surfango
Model	Adventurer	Hawaii	Hawaii GT	Hawaii GTXL
Style	Sit in Kayak	Sit on Kayak	Sit on Kayak	Sit on Kayak
Price (US$)	$3,800.00	$3,500.00	$4,100.00	$4,400.00
Dimensions				
Length (m)	3.08	2.65	2.91	3.05
Width (m)	0.7	0.7	0.77	0.77
Height (m)				
Displacement (kg)	53	58	63	68
Rider Capacaity	1	1	1	1
Fuel Capacity (l)	8	8	8	8
Storage Capacity (l)				
Engine				
Horsepower	9.5	9.5	9.5	9.5
Displacement	150	150	150	150
Induction	N/A	N/A	N/A	N/A
Stroke	4	4	4	4
Power/Weight	0.179245283	0.1637931	0.150793651	0.139705882
Drive Unit				
Impeller dia.				
Impeller material				
Performance				
Top Speed (MPH)	27	24	24	27
Acceleration				

Fig. 138

APPENDIX 7 - DECLARATION

Written Assignment Originality Declaration

Student ID:	04177371
Surname:	Burrough
First Name:	Isaac
Paper Number:	197 800
Paper Title:	Design Thesis
Assignment Title:	Introducing ground effect into personal watercraft

Declaration

- I declare that this is an original assignment and is entirely my own work.
- Where I have made use of the ideas of other writers, I have acknowledged (referenced) the sources in every instance.
- Where I have made use any diagrams or visuals, I have acknowledged (referenced) the sources in every instance.
- This assignment has been prepared exclusively for this paper and has not been and will not be submitted as assessed work in any other academic courses.
- I am aware of the penalties for plagiarism as laid down by Massey University.

A copy of the Assessment and Examination Regulations can be found under the Statutes and Regulations section on the Massey University website (http://calendar.massey.ac.nz/)

Massey University
COLLEGE OF CREATIVE ARTS

Student signature:

Isaac Burrough 18 November 2010