Retrofitted Jet Ski Stability Assessment

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Abstract

Motivated to tackle pollution problem and promote renewable energy, engineering staffs and students from University of Western Australia started Renewable Energy Vehicle projects with its project's aims oriented around building zero emission vehicles, powered by electricity from renewable sources and make them viable to the market. In 2013, the REVski project was initiated to convert a conventional petrol engine driven Jet Ski to a fully electric powered Jet Ski. Overall aim of the project is to construct an electric Jet Ski that is comparable to a conventional Jet Ski in term of performance but without noise and environmental pollutions that a conventional Jet Ski would create. While pursuing the overall aim of the project, this thesis focus on investigating stability of the REVski due the change in weight distribution after retrofitting and have it assessed against requirements in the relevant standards to check for compliance. Computer aided analysis by MAXsurft Stability and experiments are also done to assist in locating centre of gravity of the REVski.

Acknowledgement

First, I would like to express my gratitude to my project supervisor, Professor Thomas Bräunl, for his advice and guidance throughout the course of the project. I would like to thank Brett Manners from Total Marine Technology for offering his professional advice.

I would also like to extend my thanks to the REVski team members for the wonderful teamwork and experience.

Finally, I would like to thank my wife and family for their continuous support.

Nomenclature

Aft	Toward the stern
B	Centre of buoyancy
Draft	Distance between keel and the waterline
Freeboard	Distance between waterline and the top of the uppermost continuous deck
Forward	Toward the bow
G	Centre of gravity
GM	Metacentric height
GZ	Righting arm
KB	Distance between keel and centre of buoyancy
KG	Distance between keel and centre of gravity
KM	Distance between keel and metacentre
LCB	Longitudinal centre of buoyancy
LCG	Longitudinal centre of gravity
REV	Renewable energy vehicle
Stern	Back end of a watercraft
VCG	Vertical centre of gravity

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1. Introduction

Growing level of pollution impacts and rising fossil fuel prices due to it being a non renewable resource have increase human awareness on seeking ways to reduce fuel consumptions and greenhouse gas emission. With internal combustion engine vehicle being one of the major contributors of urban pollution, it has brought developers to consider alternatives and lead people looking towards electric and hybrid electric vehicle.

Motivated to tackle pollution problem and promote renewable energy, engineering staffs and students from University of Western Australia started Renewable Energy Vehicle (REV) projects with its project's aims oriented around building zero emission vehicles, powered by electricity from renewable sources and make them viable to the market.

REV projects started in 2008 and involve only road vehicles. With the positive outcomes of those projects, REV started the REVski project in 2013 that replaced the internal combustion engine and its original components of a 2008 Sea Doo GTI130 Jet Ski with a 3 phase induction electric motor and various new components. The retrofitted REVski will be tested and compared to a conventional jet ski to determine any further improvements that are required.

While pursuing the overall goal of constructing a electric jet ski that is comparable to a conventional jet ski, the aim of this individual project is to investigate stability of the retrofitted REVski when it goes on water and find its new location of centre of gravity. Due to the increase in amount of overall weight and change in weight distribution, it resulted in the change of location of centre of gravity. With numerous electric components and cables installed across the whole REVski, it is difficult to account for the weights of each individual components and centre of gravity of the individual weights to carry out accurate calculation to obtain the new centre of gravity of the system to provide information for future work or improvement that could be done on the REVski. Location of centre of gravity and buoyancy are important measurements to estimate stability and performance of watercraft. Firstly, stability assessments will be done in accordance to the relevant standards and to ensure that REVski is in compliance and meet the stability requirements. Due to insufficient data available, a computer representation of REVski will be generated and using information available as inputs to obtain a close approximate of the location of centre of gravity and buoyancy of the REVski and location of centre of gravity can be calculated for any weights added or discharged from the system.

2. Literature Review

2.1 Standards

Standards are published documents setting out specifications and procedures designed to ensure products, services and systems are safe, reliable and consistently perform the way they were intended to. They establish a common language which defines quality and safety criteria (Standards Australia 2015). By checking against the relevant standards, reliability and safety of a product can be assessed and improved if needed before it is released to the public. Standards such as National Standard for Commercial Vessels (NSCV), ISO 13590 and Australian Standards 1799 are found and contain the relevant information and requirements in related to stability of a watercraft.

National Standard for Commercial Vessel

The national standard covers various aspects of vessel that are commercial and non commercial and Part C section 6 of the standard covers stability in particular. A flow chart as shown in Fig 1 is given to assist in finding which section of stability criteria is applicable to a particular vessel through identifying its operational area, conditions and type of vessel. If the vessel involved is considered as a special vessel, it shall be examined according to the relevant sections in Part F of the standard. As the REVski is categories as a leisure craft in general and more specifically, a personal watercraft (pwc). Hence, it is considered to be a Special Vessel and shall refer to NSCV Part F. However, no stability requirement was stated in Part F Section 2 Chapter 10 for personal watercraft. Risk management is the primary objective where operations related factors are addressed to minimise risk to a controllable level.

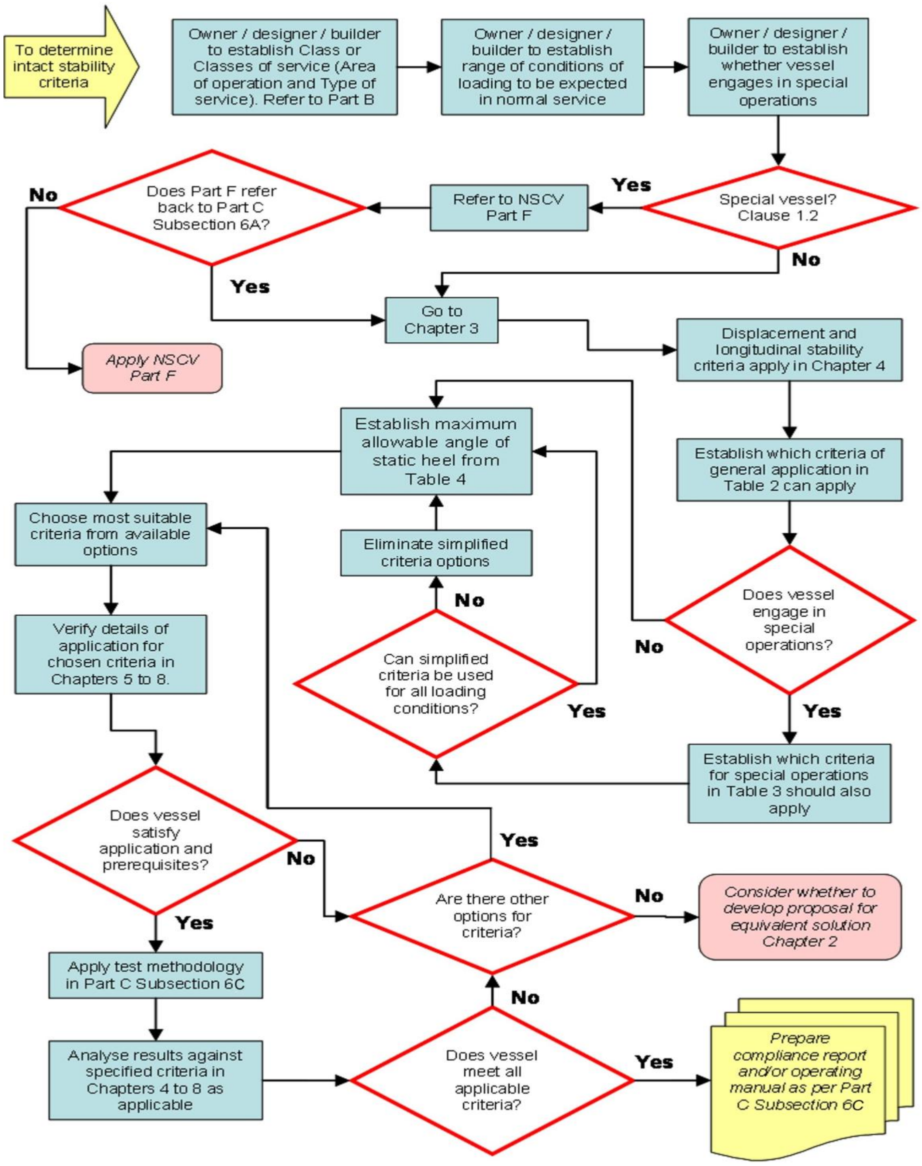

Figure 1. Guidance for determining applicable intact stability criteria (Obtained from National Standard for Commercial Vessels Part C section 6 subsection 6A)

ISO 13590

Stability section within this standard recognizes that a pwc has limited stability when floating in a static condition and emphasize on the ability to recover the pwc if the pwc capsize and facilitation for reboarding. Instead of stability of the pwc, safety of the rider / riders is the main concern. A mean to has to be provided to switch off the engine of the pwc if the rider falls off.

AS 1799

In AS1799 Small Craft, it sets out various requirements for watercrafts up to 15m that are used for leisure purposes. It provides method of calculating maximum load capacity and stability requirements for watercraft of different types, sizes and operational areas. The relevant sections shall be used after establishing the REVski's type of motor installation and its area of operation.

2.2 Archimedes' principle

A watercraft's stability from capsizing is a major concern from the safety of life standpoint when goes on water. How a watercraft remains afloat and in static equilibrium state involves a fundamental physical law. The fundamental physical law controlling the static behaviour of a body wholly or partially immersed in a fluid is known as Archimedes' Principle which, as normally expressed, states that a body immersed in a fluid that is buoyed up by a force that equals the weight of the displaced fluid (Lewis 1988). This force is known as the buoyancy force. If a ship floats freely, the buoyancy is equal to the weight of the ship. The force of buoyancy acts at the centre of buoyancy (B), which is the centre of gravity of the underwater volume of the ship (Stokoe 2003). A typical vessel's centre of gravity (G) is higher than its centre of buoyancy (Benford 2006) where both buoyancy and weight are in the same vertical line but act in the opposite direction, as in Fig 2. In the event where weight distribution is significantly uneven, listing or trimming will occur. These are inclinations due to the internal weight that is distributed more to one part of the watercraft.

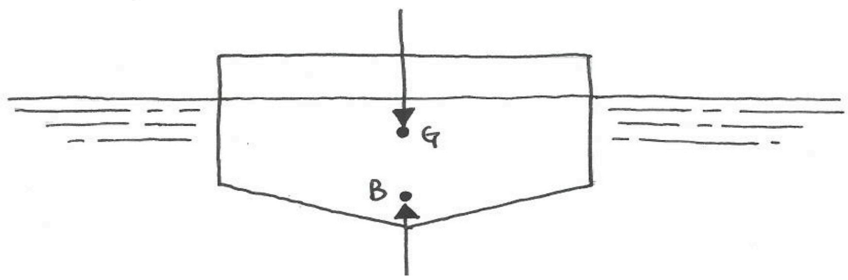

Figure 2. Equilibrium State

2.3 States of Equilibrium

Static equilibrium conditions are classified into three states of equilibrium, depending in how the body reacts when it is displaced slightly by an external disturbance, which changes the forces acting on it (Zubaly 1996). A watercraft is considered to be stable when it remain upright when at rest in calm water and able to return to its initial position if it is heeled temporarily to either side by some external force. For a watercraft that is unstable, it will continue to heel and either come to rest at a different position or consequently capsize if disturbed. A watercraft is considered to be in neutral equilibrium if it remains in the new position after the disturbance. For a floating watercraft, rotation about the x-axis is known as heeling whereas rotation about the y-axis is known as trimming (see Fig 3).

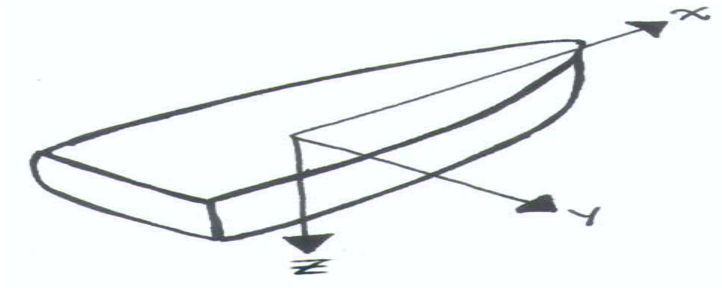

Figure 3. Rotation about x axis and y axis

2.4 Transverse metacentre and Metacentric height for stability at small angles

When a watercraft is inclined to a small angle θ by an external force, position of centre of buoyancy will shift to the more deeply immersed side. As shown in Fig 4, in this inclined condition, a horizontal line is drawn between G and intersects the line of action of B_1 at Z. This distance between G and Z is the righting arm (GZ). As the forces no longer coincide, a moment known the righting moment is formed. This righting moment will returns the watercraft to its original position as soon as external force is removed. Point M, known as the metacentre, is located on the intersection between vertical line of action of B from upright position and the vertical line of action of B_1 in the inclined position. GM is the metacentric height and it contributes to the magnitude of righting moment. Thus, metacentric height is a useful indication of a watercraft's initial stability. GM is considered to be positive when M is located above G and negative when M is located below G. The greater the initial GM, the greater the stiffness of watercraft will be as a greater heeling moment is needed to incline the watercraft from its equilibrium state. A large GM should be avoided for the following reasons (Rhodes 2003):

- The ship will return to the upright very quickly whereby the motion will be jerky causing excessive strain on cargo lashings and possible cargo shift
- Loose gear will be flown about

- It is uncomfortable for crew and injury may result from the ship's quick motion
- Structural damage to the ship may occur due to racking

However, for the REVski, it may be desired to have large GM to make the watercraft stiffer and harder to flip over when traveling at a fast speed.

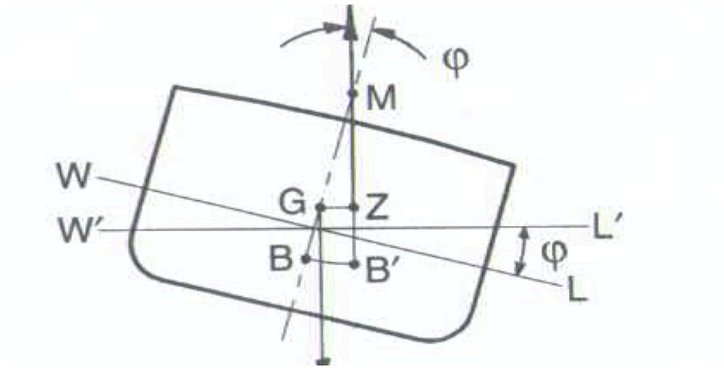

Figure 4. Stability ar small angles (Obtained from Zubaly 1996)

Metacentric height is often used as an index of stability when preparation of stability curves for large angles has not been made. Its use is based on the assumption that adequate GM, in conjunction with adequate freeboard, will assure that adequate righting moments will exist at both small and large angles of heel (Lewis 1988). While GM itself can be used as indication of stability, no information on range of GM that pwc should have could be found.

2.5 Obtaining transverse metacentric Height

The positions of B and M have been seen to depend only upon the geometry of the ship and the draughts at which it is floating (Tupper 2004). In other words, positions of B and M are dependent on the submerged volume of the hull. As a result, height of metacentre above centre of buoyancy (BM) can be calculated through dividing moment of inertia of water plane about the centreline by the volume of displacement. By using Eqn (1), height of metacentre above keel (KM) can be obtained if height of the centre of buoyancy above the keel (KB) is also known. Also, if position of vertical centre of gravity from keel (KG) is known, GM can be obtained using Eqn (2).

$$\mathbf{KM} = \mathbf{KB} + \mathbf{BM} \tag{1}$$

$$\mathbf{KM} = \mathbf{GM} + \mathbf{KG} \tag{2}$$

Calculations to be done to obtain moment of inertia can be very tedious for watercraft with complex geometrical forms and are mostly done by computer to achieve better accuracy and to avoid unwanted mistake that may occur if done by manual calculations. Also, provided that position of B and G are known, then only GM can be calculated. Method is needed to obtain GM if positions of B and G are unknown. Direct determination of GM can be done through heeling the watercraft to small angles by moving weights on board. Method known as the inclining experiment can be done. Lewis (1988) wrote that an inclining experiment is also conducted after a ship has been converted if the conversion is extensive enough to preclude a reliable estimate of the effect of the conversion on weight and centre of gravity or after extended service if it is felt that the weight or centre of gravity may have been affected significantly by the accumulation of many minor changes. The purposes of the inclining experiment are to determine the displacement and the position of the centre of gravity of the ship in an accurately known condition (Rawson & Tupper 1968). A general set up of the experiment is by placing two sets of weights, each of *w* on each side of the watercraft h distance apart at about the watercraft's centreline. One set of the weights is moved across distance *h* and placed on the other set of weights. As the watercraft is inclined, G moves to a new position G_1 and B to B_1 (see Fig 5). The inclined angles can be measured by using a pendulum. Assuming that *d* and *l* are the distance and length of a pendulum, it follows that tan φ = *d* / *l*.

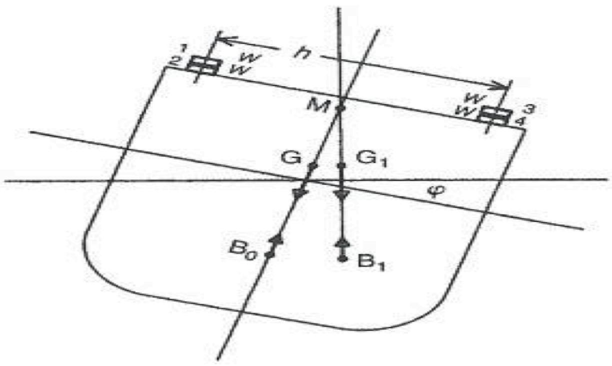

Figure 5. Inclining experiment (Obtained from Tupper 2004)

The heeling moment that results from moving the weights is equal to the watercraft's righting moment to obtain the watercraft's GM as follows by Eqn (3).

$$\mathbf{W\,.\,GM\,\sin\varphi = \mathit{w}.\mathit{h}\cos\varphi} \quad (3)$$

If KG is obtained after knowing GM of the inclining condition, vertical centre of gravity (VCG) can be calculated for any loading conditions providing that amount of weight and distance between VCG and the weight loaded or unloaded are known. The same method can be applied to calculate for longitudinal centre of gravity (LCG).
The change in G can calculated by the following equations:

For weight added, the shift in G is

$$\frac{\boldsymbol{d} \times \boldsymbol{w}}{\boldsymbol{W} + \boldsymbol{w}} = \boldsymbol{\Delta G} \qquad (4)$$

For weight taken off, the shift in G is

$$\frac{\boldsymbol{d} \times (-\boldsymbol{w})}{\boldsymbol{W} - \boldsymbol{w}} = \boldsymbol{\Delta G} \qquad (5)$$

where
d = distance of G of weight from G of watercraft
w = weight added to or taken off the watercraft
W = weight of watercraft

From equations shown, it can be observed that G of the REVski will move towards weight added whereas G would move away from a weight taken off.

Alternative method to determine GM could be done by mean of rolling periods tests. Rhodes (2003) states that it can be shown that the roll period is very much a function of the ship's beam and the formulae (Eqn 6) used for the rolling period test is:

$$\mathbf{T} = \frac{\boldsymbol{f} \times \boldsymbol{Beam}}{\sqrt{\boldsymbol{GM}}} \qquad (6)$$

where f is a factor for the rolling period known as the rolling coefficient. This rolling coefficient is typically obtained through conducting test on that particular watercraft. Even though there are few ways of obtaining GM, without information such as KM, GM itself is not sufficient to tell the positions of G and B.

2.6 Reverse Engineering of Shapes

Reverse engineering provides a means of obtaining quick and accurate digital representation of a real object in a fully surfaced 3D computer model when a CAD file of an object is unavailable. This is done through measuring points along surface of the object. Each point has an x, y and z coordinate locating the point in 3-D space (Page, Koschan and Abidi n.d.). The commonly used 3D measuring technique used for reverse engineering include mechanical contact and various non-contact measuring techniques (Venuvinod & Ma 2004). No one technique can be considered as the best. The choice of a methodology rather than another depends on several factors (object size, required accuracy, kind of analysis to be performed, budget, time execution, etc), which have to be clearly defined by the customer when the survey is commissioned (Troisi & Menna 2010). Tools to be considered to assist in getting shape of the hull are 2D scanner and laser distance measurer.

2.7 Computer Software

Improvement in computer and software capabilities has resulted in multiple software being created to simulate real conditions to help obtain more information for design and data collections. To help obtain hydrostatic data of the REVski, MAXsurf Stability is selected to analyse 3D model of the hull due to availability. By utilising the specified conditions analysis available in the software, hydrostatic parameters of the watercraft at a particular loading condition can be obtained by specifying the values of heel, trim and immersion. These values could be obtained by placing the REVski on water and obtain draft values at various positions of the REVski.

3. Approaches

3.1 Stability Requirements

With no method of stability test provided for pwc by NSCV and ISO 13590, stability of REVski is tested according to requirements stated in section 2 and 5 of AS1799. With operating environment area of the REVski identified to be sheltered waters and smooth waters, REVski shall be assessed according to the stability requirements for protected water.

Protected water requirements for boats under 3.75m

Prior to conducting the stability assessment, maximum load capacity and maximum persons capacity needs to be first determined according section 2 Maximum Capacities and Buoyancy of the AS 1799. Maximum load capacity of the hull was determined by adding the wet weight of pre modified jet ski and its persons capacity. This method was selected over the method of manual calculations of the volume of the hull provided by AS1799 due to the reasons that there may be errors introduced when the measurements of the hull are taken and during calculations. Also, maximum load capacity is unobtainable through manual calculation method as the weight of the hull is unknown. By taking the difference between maximum load capacity and the current weight of REVski, and dividing that difference by 90kg, the lower whole number of the remainder is the maximum persons capacity. Then, stability assessment is conducted according to section 5. Stability of the REVski under static condition has to comply with the requirement of Clause 5.2. It is required that REVski shall not ship water when it is loaded in following way in smooth water as stated below (Standards Australia 2009):

1. A mass equivalent to the mass of the largest engine for which the boat is rated, including fuel tanks and fuel is located in the normal position.
2. All on board equipment supplied with the boat is aboard.
3. An allowance of 10kg per person for ancillary equipment and gear is located in the normal stowage areas.
4. A mass equivalent to 50% of the maximum persons capacity (in kilograms) calculated at 80 kg per person is located on the centreline of the boat (see Appendix A).
5. A mass equivalent to 50% of the maximum persons capacity (in kilograms) is distributed as far to one side as possible in the space for, and in the normal positions of, persons (see Appendix A).

As it is hard to secure 40kg of weights when placed on different positions on the REVski, it is decided that the team member with the lightest weight will sit at different positions to simulate the loading condition for the stability assessment of the REVski. Weight of the team member is approximately 62kg. Figure 6 shows an example of the loading done.

Figure 6. Weight distributed as far to one side as possible at amidships

3.2 Reverse engineering hull shape of REVski

As the position of B and M are dependent on geometry of the hull of a watercraft and no hydrostatic data obtainable as the manufacturer holds the proprietary rights to the data, reconstructing 3D computer model is the ideal solution to obtain more information. As the construction of the 3D model will be mainly used for calculation, only shapes at a number of stations along the length of REVski need to be defined. These shapes do not have to be perfectly fair because all calculation programs for hydrostatic and stability and resistance are not sensitive to the smoothness of the hull (Hollister n.d.). Error within three per cent is considered to be acceptable. To generate the shape of the hull at different stations, a table of offsets needs to be created. Due to limited working space for measurements, as the REVski has to stay on the trailer for ongoing installation work at the time scheduled for measurements to be taken, a Bosch 15m digital laser distance measurer was chosen to assist with measuring. The offsets table was obtained by measuring distances to hull from a datum point on ground at the stern of REVski in the x, y and z axis as shown in Figure 7 at multiple stations along the length of the REVski. Yellow lines in figure 8 illustrate the approximate positions of each station with station 0 starting from the stern of the REVski.

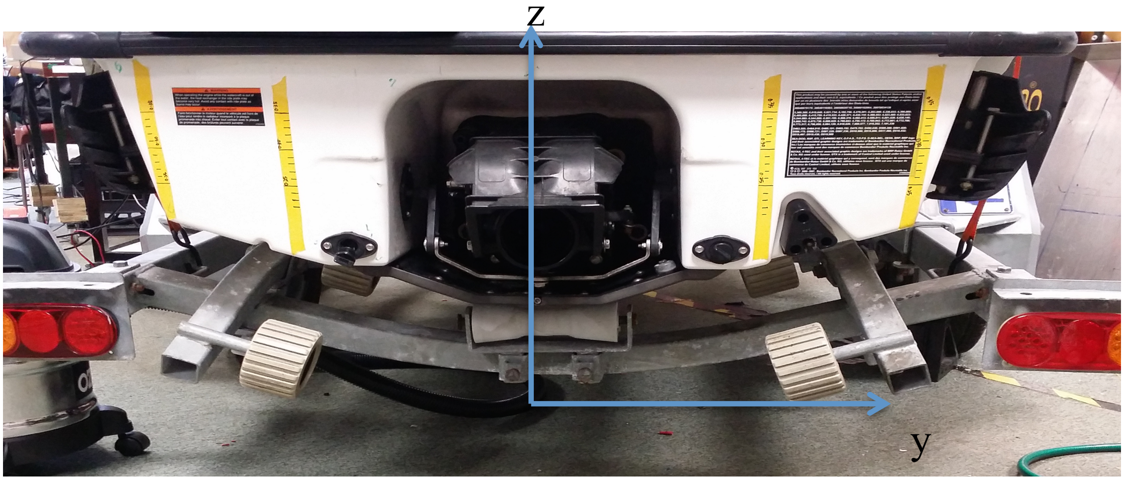

Figure 7. Datum point from stern of REVski (x axis into the page)

Figure 8. Approximate positions of stations

As the hull is symmetrical, only half breaths are measured. These measurements (see Appendix B) obtained are then used to create the body plan on AutoCAD (see Fig 9). Each curve represents a station along the length of the REVski.

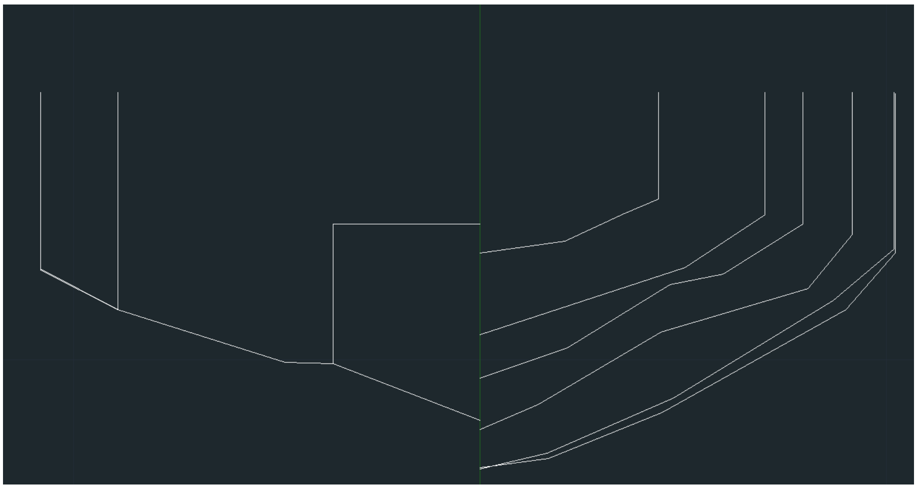

Figure 9. Body plan of REVski (Vertical axis – z axis, horizontal axis – y axis)

This body plan is then exported to computer modelling software Rhinoceros to produce 3D model of the hull of REVski. Each curve from the body plan is shifted to its respective position along the length. Then surface is created by using the loft function. The completed 3D model is shown in figure 10 in multiple views.

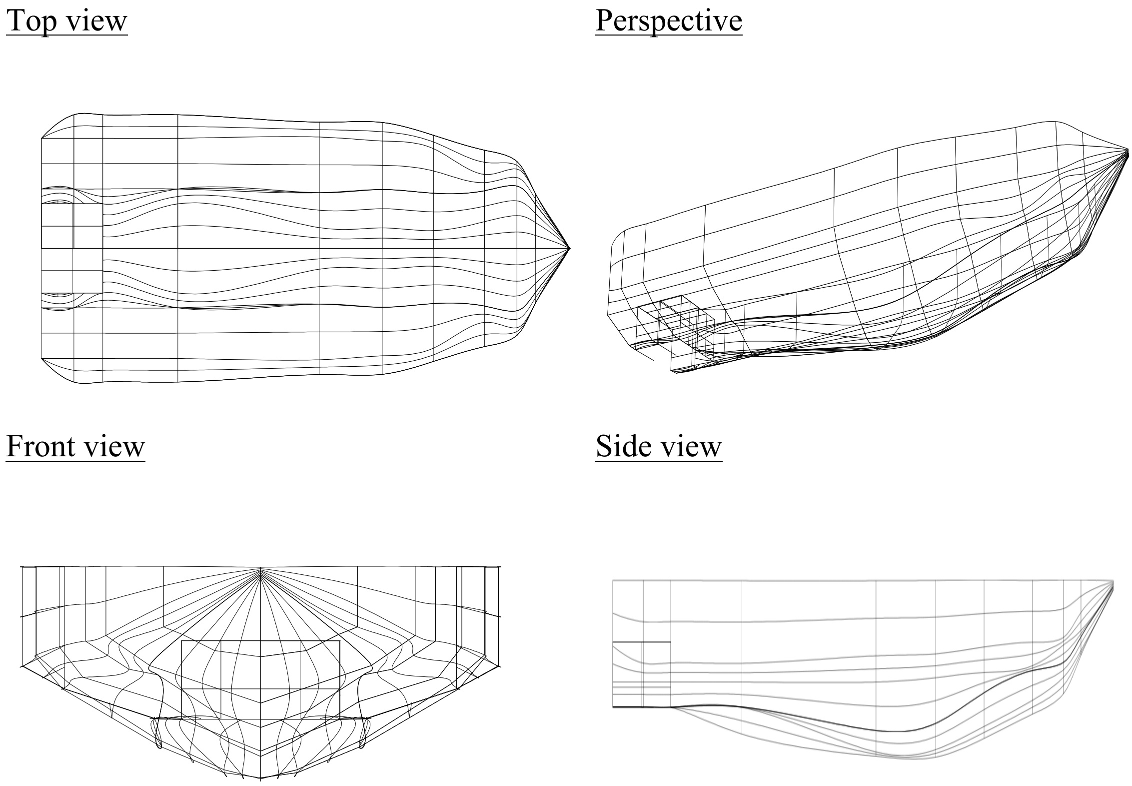

Figure 10. Fully surfaced 3D model

3.3 The Inclining Experiment

Inclining experiment is the commonly used method alongside hydrostatic data to establish longitudinal and vertical centre of gravity of the vessel when a vessel is near completion or it has went through significant modification. Through result from the inclining experiment, GM can be calculated. Also, additional data from the experiment can be used to check against data from the 3D model. Draft marks placed on the REVski and apparatuses used in this experiment are shown in figure 11 and figure 12. To ensure accuracy of the inclining experiment, the following were considered:

- All components with significant weights have been installed
- The watercraft is upright in its equilibrium position

- Inclining weights that should not cause angle of inclination to be more than 4 degrees.
- During the experiment the inclination of the REVski should not be influenced by appreciably by external forces other than the effect of the inclining weights. The effect should be minimized. Hence, weather forecast are checked and have the experiment conducted on sheltered water that is as calm as possible and in light wind condition.

The following are done during the experiment:

a) Multiple draft marks readings are taken at bow, stern and amidships, on both sides of the ship.

b) Weights are arranged in groups as shown in Figure 12 with 4 weights on each side of the REVski and shall be moved in the following sequence:

    1. Weight A to a position in line with weight E
    2. Weight B to a position in line with weight F
    3. Weight C to a position in line with weight G
    4. Weight D to a position in line with weight H
    5. Return weight A, B, C, D to original position
    6. Weight E to a position in line with weight A
    7. Weight F to a position in line with weight B
    8. Weight G to a position in line with weight C
    9. Weight H to a position in line with weight D

c) Inclined angle is then recorded by taking note the angle of list from the inclinometer before the first movement of weight and after each step listed above.

Figure 11. Draft Marks

Weights for Inclinations

Average weight: 2.5kg

Inclinometer (Phone App)

Sensitivity: ± 0.5°

Figure 12. Apparatus used

Draft	Before	After
Forward	± 0.340 m	± 0.345 m
Amidships	± 0.315 m	± 0.325 m
Aft	± 0.290 m	± 0.300 m

Table 1. Draft readings of before and after inclining weights were placed on REVski

To calculate for GM with data obtained from experiment, Eqn 7 shall be used

$$\mathbf{GM} = \frac{w \, . \, d}{W \tan \varphi} \qquad (7)$$

where

w = weight shifted

d = distance of weight shifted

W = displacement

φ = angle of inclination

Place of Inclining Experiment	Maltida Bay
State of weather	Light wind
Initial Angle of Heel	0.5°
Weight of REVski (including 20kg of inclining weights)	520kg
Position of Weight Group	≈ 1.33m from stern and 0.374m above keel

Shifting of Weights	Angle of Inclination (°)	GM (m)
A – E	0.5°	0.36360
B – F	1.0°	0.36357
C – G	1.6°	0.34079
D – H	2.0°	0.36346
E – A	0.4°	0.45450
F – B	1.0°	0.36357
G – C	1.5°	0.36352
H – D	2.0°	0.36346

Table 2. Inclining experiment Data

3.4 Specified Conditions Analysis

Data from the experiment done is now used for the specified condition analysis in MAXsurf Stability. After importing the 3D model into MAXsurf, specified conditions analysis is selected to run the analysis. Three sets of variables – heel, trim and immersion need to be provided to solve for hydrostatic data. Appropriate selections need to be made for each variable as shown in Fig 13. Fixed heel was chosen as no heeling occurs according to the inclinometer. As there was noticeable trimming observed from draft readings, free to trim is chosen and forward and aft draft readings are inserted to conduct the analysis.

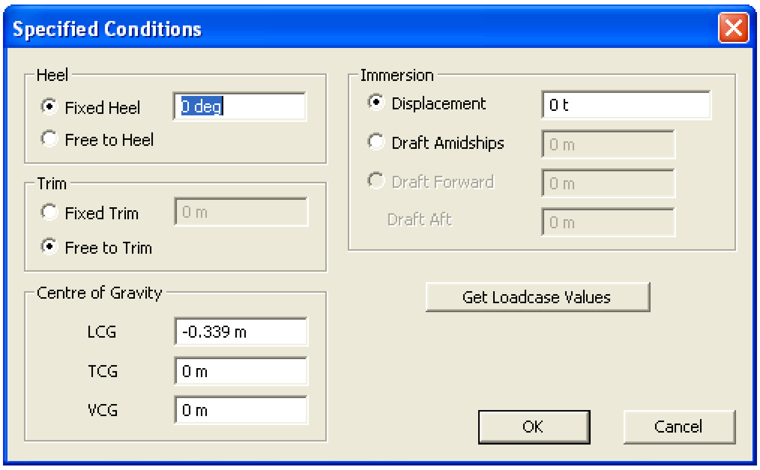

Figure 13. Variables for specified condition analysis

4. Results and Discussion

4.1 Compliance with Standard

Completion of the stability assessments under loading conditions according to requirements of relevant sections in AS1799 shows that the retrofitted REVski is in compliance in term of its stability. It is found that load capacity is the main factor considered when determining the stability of REVski according to AS1799. Safety factor has been taken into account when dividing the maximum load capacity by 90kg and take the lower number to be the number of rider allowed. However, considering that average weights of possible users could be higher and possibility of having two light weight riders. It is decided to allow rider/riders with personal belonging up to 110kg to ride the REVski. A new approved capacity sticker need to be obtained and placed on the REVski to indicate its new weight capacity of 110kg. Additional assessments apart from those specified by AS1799 have been done and shows that when loaded with approximate 110kg at different positions of the REVski, there is still no sign of water shipping onto deck. When loaded on the normal seating with two riders of total weight just over 155kg, this resulted in noticeable small amount of water entering the deck at the stern of the REVski. This test then verified the approximated maximum load capacity calculated. To also comply with stability requirement of ISO 13590, recovery procedure for REvski has been developed by updating recovery procedure of its pre modification state with additional steps (see Appendix C).

4.2 Interpretation of data

From the drafts readings, it can be observed the REVski is trimmed by the bow. With no listing observed from draft readings, vertical centre of gravity can be assumed to lie in the centre of the transverse plane. Hydrostatic data resulted from specified condition analysis is shown in Table 3. Using Eqn 2, KG is calculated by using KM obtained minus GM calculated from experiment data. This KG value obtained is the distance between keel and VCG of the inclining condition. To calculate for VCG of lightship condition, Eqn 5 is used and VCG is found to be 0.34072m.

***Calculation* for lightship VCG**

d = 0.374 – 0.342 = 0.032m

w = - 20kg

W = 520kg

ΔG = -0.00128 m

When attempt to obtain lightship LCG, it is found that LCG was not given in the set of hydrostatic data resulted from specified condition analysis. But from Archimedes' principle, it is understood that G and B will lie on the same vertical line in the equilibrium state. LCG will equal to LCG if there is no trimming occur. However, there is a trim angle of 0.8317° according to hydrostatic data. As it is less than one degree, it is assumed that it is negligible and LCG will be taken as 1.468m from stern and lightship LCG is found to be 1.462m. For conditions where trimming angle is large, LCG can be obtained through application of trigonometry.

Calculation for lightship LCG

d = 1.468 – 1.330 = 0.138m

w = -20kg

W = 520kg

ΔG = -.00552m

Draft amidships (m)	0.323
Displacement (t)	0.4914
Heel degree	0.0
Draft at FP (m)	0.345

Draft AP (m)	0.300
Draft at LCF (m)	0.321
LCB from zero pt. (+ve fwd) (m)	1.468
LCF from zero pt. (+ve fwd) (m)	1.425
KB (m)	0.220
KG (m)	0.342
BMt (m)	0.485
BML (m)	3.725
GMt (m)	0.363
KMt (m)	0.705
KML (m)	3.944
Trim angle (+ve by stern) (°)	-0.8317

Table 3. Hydrostatic data of 3D model

For the values of G and B obtained, it may only be used as approximates, as there are inaccuracies in data from experiment and data from analysis where the inaccurate weight of REVski and inaccurate 3D model created have contributed towards the inaccuracies. To ensure most accurate possible data is collected, the REVski was brought to few weighbridge for weighing. Most accurate weighbridge weighs the REVski to be 500 ± 20kg and 500kg is used in the calculation for GM. This would have contributed to the level of inaccuracy in result obtained. Possibility of inaccurate draft marks placements and drafts readings were reduced by having another person check the draft mark placements and two people present to read the drafts during the experiment. Two separate inclining experiments were done on separate time to obtain accurate and reliable data. Consistency and accuracy in data collected in second experiment was improved by replacing pendulum used in first experiment with inclinometer. Data collected in second experiment (see Table 2) shows better consistency in comparison to data collected from first experiment and assumed to be more reliable (see Appendix D for result of 1st experiment).

Even though there are multiple ways to improve accuracy and reliability of data to be collected, accuracy of the 3D hull model created depends on the judgement of the users if model is not created by 3D scanning method such as CMM, laser scanning, photogrammetry etc. In this case, accuracy of 3D model of the REVski created is limited by sample size and measuring tools. More samples may be needed to have a better representation of the hull shape. In addition, it is also limited by the experience and skill of the user. Computer would not be able to tell which way is best to fit the surface to the curves to have an accurate representation and it is up to the user to inspect and make changes. In the event where fairing is done to make the shape of the hull looks better, it might no longer represent the real shape of the hull. The change in hull shape would results in change of the positions of B and M, as these parameters are dependent on the hull. Thus, faired 3D models were not use for computer analysis.

5. Conclusion and future work

Standards have been developed to serve as guide for designers and manufacturers to achieve a certain level of safety and reliability of a product. However, each standard provides a different set of requirements. In this thesis stability assessment has been conducted according to AS1799 and found that the REVski has met its stability requirements where stability is considered to be sufficient if there is no loss of freeboard. Also, it is crucial to remember that stability of REVski is related to GM. If VCG is shifted higher up, GM will reduce. Thus, it is important to consider weight distribution in the system if any component needs to be added or moved as stability of watercraft only improves when G is lowered. In addition, REVski is also in compliance with stability requirement of ISO 13590 with the 'kill switch' installed being operational and righting procedure available for users in the event of REVski rolling over. On the other hand, it is interesting to find that there is no stability criteria or requirements stated in NSCV part F for pwc. Instead, associated risks when riding a pwc is considered and those risks needs to be controlled to a level that is considered to be tolerable. Also, riders need to meet certain requirements and are also required to be aware of the risk involved.

While method of calculating position of G and B is correct, values obtained shall only be used as approximates. Even though advancements in computer and software technology have provided a mean to obtain unavailable information about the real objects through conducting computer analysis on 3D model of the real object, there are still limitations to computer aided analysis. To obtain reliable final results or data, first an accurate 3D model is needed to begin with. Where inputs are needed and obtained from testing to produce a simulation, these inputs inserted need to be accurate too. If inaccuracies exist in both the 3D model and input data, there will be a cumulative effect that leads to significant error in the final results. While accuracy of test data can be improved by using higher accuracy tools or conduct multiple tests to check for consistency in result, creation and ensuring accuracy of 3D model requires experiences.

With the recent completion of construction phase of the REVski, few on water tests had been done to assess safety and reliability of the system and also overall performance of REVski. With more data collected, adjustments could be done to fine-tune the REVski. While the REVski have meet static stability requirements of AS1799 and recovery requirements of ISO 13590, it is also worth to find out dynamic stability of the REVski as it is related to safety of riders. Research needs to be done to investigate for any possible effects that trimming may have on the REVski as REVski is observed to be trimmed by the bow. Cornering test as suggested by previous year REVski team member Alex Beckley could be done to assess under what condition the REvski would possibly roll over and identify the associated hazards. Measures could be then developed to avoid roll over from occurring. If roll over is inevitable, safety of rider shall be the priority and safety measures shall be developed to prevent injuries to the rider when REVski rolls over.

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7. Appendices

Appendix A

TABLE 5.1
LOADING ARRANGEMENTS

Number of persons	Persons on centre-line	Persons on one side
1	–	1
2	1	1
3	1.5[(1)]	1.5[(1)]
4	2	2
5	2	3
6	3	3
7	3	4

NOTES:

1 For three persons, one person is on the centre-line, one moves to the side and one is located half-way between the two.

2 The 'normal position' specified in item (v) means that if weights are used instead of people, each 80 kg weight is placed on a seat or thwart at the side of the boat with the centre of gravity in the athwartships direction located to represent the centre of gravity of a person sitting at that position.

3 As far as practicable, the trim intended by the manufacturer with the specified number of persons on board is to be maintained.

Appendix B

	x	y	z
Station 0	0.00	0.00	0.661
	0.00	0.180	0.661
	0.00	0.180	0.496
	0.00	0.240	0.498
	0.00	0.445	0.56
	0.00	0.445	0.816
Station 1	0.19	0.00	0.661
	0.19	0.18	0.661
	0.19	0.18	0.496
	0.19	0.24	0.497
	0.19	0.445	0.56
	0.19	0.54	0.607
	0.19	0.54	0.816
Station 2	0.36	0.00	0.661
	0.36	0.18	0.661
	0.36	0.18	0.496
	0.36	0.24	0.498
	0.36	0.445	0.56
	0.36	0.54	0.608
	0.36	0.54	0.816
Station 3	0.80	0.00	0.429
	0.80	0.18	0.496
	0.80	0.24	0.497
	0.80	0.445	0.56
	0.80	0.54	0.607
	0.80	0.54	0.815
Station 4	1.63	0.00	0.373
	1.63	0.084	0.384
	1.63	0.225	0.438
	1.63	0.45	0.56
	1.63	0.51	0.626
	1.63	0.51	0.815
Station 5	2.00	0.00	0.371
	2.00	0.083	0.39
	2.00	0.238	0.456
	2.00	0.434	0.571
	2.00	0.509	0.631
	2.00	0.509	0.816

Station 6	2.3	0.00	0.418
	2.3	0.072	0.448
	2.3	0.223	0.533
	2.3	0.403	0.584
	2.3	0.457	0.648
	2.3	0.457	0.817
Station 7	2.6	0.00	0.479
	2.6	0.108	0.514
	2.6	0.233	0.589
	2.6	0.299	0.601
	2.6	0.397	0.66
	2.6	0.397	0.816
Station 8	2.79	0.00	0.53
	2.79	0.252	0.609
	2.79	0.351	0.672
	2.79	0.351	0.817
Station 9	2.9	0.00	0.627
	2.9	0.104	0.64
	2.9	0.177	0.674
	2.9	0.22	0.69
	2.9	0.22	0.817

Appendix C

Recovering capsized REVski & Reboarding

To return the REVski upright

1. Turn off isolator
2. Move to the side of the REVski, grab the inlet grate, step on bumper rail and use body weigh to rotate the watercraft
3. When watercraft is back upright, reboard REVski from the stern of REVski
4. Turn isolator on
5. Start REVski to check for any malfunction
6. Turn bilge pump on to check for presence of water in bilge

Appendix D

Data from 1st Inclining Experiment

Note: 1. Only 4 bricks were used for inclinations, as GM is unknown.
2. Pendulum was used.
3. Pendulum length shall be kept constant for calculations as sin θ ≈ tan θ at small angles.

Mean draft	Before	After
Forward	± 0.330	± 0.335
Amidships	± 0.320	± 0.325
Aft	± 0.290	± 0.295

To calculate for GM with data obtained from experiment

$$\mathbf{GM} = \frac{\boldsymbol{w} \, . \, \boldsymbol{d} \, . \, \boldsymbol{pendulum\ length}}{\boldsymbol{W} \, . \, \boldsymbol{Deflection}}$$

Place of Inclining Experiment	Maltida Bay
State of weather	Light wind
Pendulum length	0.186 m
Initial pendulum deflection	0

Shifting of mass	Deflection (m)	GM
A – C	± 0.002	0.30088
B – D	± 0.003	0.40118
C – A	± 0.003	0.20059
D – B	± 0.005	0.24071