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REV Jet – Effects of Torque from Electric Motors on Personal Watercraft Performance

Nicholas Ward, 20755723
School of Mechanical and Chemical Engineering
University of Western Australia

Supervisor

Thomas Bräunl
School of Electrical and Electronic Computer Engineering
University of Western Australia

Co-Supervisor

Adrian Boeing
School of Electrical and Electronic Computer Engineering
University of Western Australia

Abstract

The effect of supplying an excessive amount of torque to a centrifugal pump results in cavitation of water increasing wear and reducing or stalling propulsion. The differing power and torque characteristics between internal combustion and electric motors have necessitated research into the effects on personal watercraft drivetrains.

Drawing on the author and experts experience on existing jet propulsion hardware for effective use following power unit alterations, this thesis will examine the methods available to reduce cavitation in the Renewable Energy Vehicle (REV) Jet Ski following the retrofit of an electric motor. A summary of the options available for performance improvement based on their effects and viability in relation to the projects goals and constraints will be presented.

The methods chosen by the REV Jet Ski team to improve the jet pump performance will be examined using Finite Element Analysis (FEA). Finally an analysis of the results will be presented along with the future work to be undertaken in the project to implement the proposed improvements.

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Nomenclature

REV – Renewable Energy Vehicle

PWC – Personal Watercraft

HP – Brake Horse Power

RPM – Revolutions Per Minute

FEA – Finite Element Analysis

BRP – Bombardier Recreational Products

V – Volts

W – Watts

PF – Power Factor (=electric motor efficiency)

SG – Specific Gravity (=1 – for water)

H – Head (m)

v_s – Velocity at Inlet (m/s)

v_d – Velocity at outlet (m/s)

g – Gravitational Acceleration (=9.81m/s^2)

Q – Flow Rate (m^3/s)

n_s – Specific Speed (dimensionless)

n – Shaft Revolutions Per Minute (RPM)

Solidworks – Commercial computer aided design software used for modelling the desired components for further analysis

ANSYS – Commercial finite element analysis software used for determining the results of this thesis

MRF – Multiple Reference Frame

SDK – Software Development Kit

BEP – Best Efficiency Point

Introduction

The Renewable Energy Vehicle (REV) Project started out as a method to research and build energy efficient vehicles, primarily by retrofitting existing automobiles with electric drive systems on a variety of automobile classes – including retrofitting a Hyundai Getz and Lotus Elise. These vehicles are already finished, however, constant development is done to further improve these vehicles. Other areas of more individual development have centred on competing in the Formula SAE car competitions in both the electric drive and self-driving divisions. This research and development into a vast range of electric drive automobiles has led to the creation of the REV Jet Project to retrofit a petrol powered personal watercraft to run on electric drive.

Personal watercraft (PWC) have been around for over 40 years, originally developed by Kawasaki with the original Jet Ski®. Since then they have increased in popularity and spawned many different forms ranging from; watercraft used by lifeguards along beaches around the world; small nimble forms for personal recreation; to performance vehicles used for racing. PWCs differ from most normal boats in their use of jet propulsion created through the use of an axial pump powered directly from an on-board motor. This removes most of the danger to marine life, people around where the craft are being used and results in a high-powered jet propelling the craft. The REV Jet Project is focused on decreasing this danger further through the use of an electric motor to drive the pump.

The REV Jet is based on a 2008 Sea Doo GTI130 personal watercraft, originally powered by a 1500cc rotary petrol engine producing 130 hp. While able to create large amounts of power from relatively small displacements (and external footprint) rotary engines are less efficient than conventional combustion engines. Resulting in more harmful exhaust gases polluting waterways from exhaust systems' outputting into the waterway the vehicle is running in. In contrast while in use electric drive systems produce either no exhaust material of any kind or in the case of hydrogen fuel cells pure water. When combined with efficient forms of power generation including solar, wind and geothermal sources these vehicles produce zero emissions. Furthermore due to the performance characteristics of electric motors higher levels of torque are produced at far lower Revolutions Per minute (RPM), this is normally used to improve acceleration. Therefore by creating a viable alternative to personal watercraft running on petroleum products the environmental health of waterways will be improved. The electric drive system will also benefit performance.

The REV Jet Project has been in development for 2 years, however, due to the difficulties encountered in designing a waterproof battery enclosure the REV Jet is still in a design phase. While there have been issues in designing some parts many of the systems required to begin construction have been designed and manufacture in preparation to begin construction of the REV Jet. Therefore the aim by the end of the year is to not only have the REV Jet operational but to have conducted tests to determine its performance characteristics. This will determine where further improvements should be made in the future.

One of the performance and ease of use benefits that come with using electric motors is the high low-end torque characteristics of the electric motor. The result is a shorter spin up time compared to petrol motors; an electric motor can be more easily controlled; an electric motor can operate at higher than design characteristics for short periods of time; and a lack of moving parts reduces the need for servicing. The effect of these characteristics is a motor capable of outperforming the operating conditions of the REV Jet due to inexperience on the part of the operator, this will – depending on severity – lead to cavitation or total loss of jet power. In order to counteract this issue the effect of different motor rpm at varying water speed was investigated. The objective was to create a better performing watercraft through the design of a more appropriate drive system and by placing restrictions on how the motor could operate, depending on conditions.

Following consultation with the mechanics at Jet Skis WA it was determined that there were four ways cavitation could be reduced, increasing driveshaft weight; increasing impeller weight; changing the impeller pitch; and limiting the motor rpm relative to water speed. Due to significant budget restrictions and relatively unknown performance characteristics of the electric motor; impeller pitch and motor limits were the two options investigated for this thesis.

Since the project has a sophisticated motor controller, limits can be programmed to avoid cavitation. Due to the continued construction phase of the REV Jet; complexity of pump design; and expense of experimental testing on various impellers, Finite Element Analysis (FEA) was chosen as the method of design analysis.

Background Information

There is a vast amount of literature present on the use and design of water jets, more commonly considered as pumps. There exist many different forms of pumps with the most common being centrifugal pumps. The pump present in the REV Jet is a variation of centrifugal pumps known as an axial flow pump (Volk 2005). The impeller of an axial flow pump differs from most other forms of centrifugal pumps in that it resembles the design of a propeller. This leads to confusion over whether an axial flow pump really belongs to the centrifugal pump family, however, the equations governing the design of axial flow impellers are the same as for centrifugal pumps and this was reflected in the literature.

The equations for determining parameters discussed later in the section are included below (Stepanoff 1957).

$$Engine\ Power\ P(kW) = \frac{\sqrt{3} * V * I * PF}{1000} \qquad (1)$$

$$Wire\ Power\ P_w(kW) = Q * H * SG * 9.797 \qquad (2)$$

$$Torque\ \tau(N.m) = P * \frac{9.5488}{n} \qquad (3)$$

$$Pump\ Efficiency\ \eta_{pump} = \frac{Engine\ Power}{Wire\ Power} * 100 \qquad (4)$$

$$Total\ Head\ H(m) = H_d - H_s + \frac{v_d^2 - v_s^2}{2g} \qquad (5)$$

$$Specific\ Speed\ n_s = \frac{n\sqrt{Q}}{H^{\frac{3}{4}}} \qquad (6)$$

The use case for a centrifugal pump alters the choice of impeller geometry, from Neumann:

> *"Generally speaking, low n_s (specific speed) values represent high head requirements at moderate or low rates of flow. High n_s denotes demand for high flows against low heads. On the other hand, for the same H and Q requirements, higher speed leads to a smaller and, most likely, cheaper pump."* (Neumann 1991)

In the case of a PWC the head (H) is very low as the water is only drawn up a distance of approximately half a metre and pumped out horizontally. In order to generate motion the flow rate (Q) must be very high, in the case of our REV Jet approximately $10m^3/s$. An axial flow pump is considered to have very high n_s, typically above 10000 (Stepanoff 1957). While some of the factors affecting n_s cannot be modified due to the REV Jet's geometry there is enough freedom to design an impeller to improve performance.

There are two options to consider for designing a new impeller, highest attainable efficiency or highest possible flow rate (Neumann 1991). Efficiency is limited by friction losses due to the geometry of the pump and impeller. Comparing the petrol motor's output of 96kW to the 46kW wire power quoted for the jet pump it is clear that Bombardier Recreational Products (BRP) chose the highest flow rate option. In this case the area open to the impeller (hereinafter referred to, as the impeller eye) and blade length are important considerations.

Physical limitations govern how much flow can be increased, above a point determined by the vapour pressure of the liquid – in this case water – vaporisation will begin occurring. Vaporisation leads to cavitation – where the vapour bubbles collapse creating pressure waves – and this needs to be avoided wherever possible. Depending on the intensity it can cause increased corrosion in components nearest the cavitation site or total loss of power. The best demonstration of the negative effects cavitation has on a PWC impeller is by observing the difference in wear between the REV Jet's impeller and one removed from a similar model due to damage. Figure 1 below shows the two impellers inlet faces; the worn impeller shows large smooth regions at the trailing edge of the blades, whilst the REV Jet impeller has relatively small smooth regions along the trailing edge. Since the trailing edge is the area least likely to encounter debris the smoothing is likely caused from corrosion of the impeller due to cavitation.

Figure 1 PWC Impellers. Left: worn impeller, Right: REV Jet impeller

Consequently the flow can be increased with a larger impeller eye and blade length up to the point cavitation begins occurring while efficiency is improved by doing the opposite.

When designing axial flow pumps like the one present on the REV Jet the efficiency of the impeller is greatly affected by the number of blades used – hereinafter referred to by their technical term vanes. Stepanoff references two tests by Kaplan and Schmidt showing how a decrease in the number of vanes increases efficiency:

"Kaplan has found that for a given wetted area of the vane (l/t) the number of vanes should be a minimum. This was also confirmed by Schmidt's tests which showed that a two-vane impeller is most efficient with a projected vane area of about 63 per cent." (Stepanoff 1957)

Above a certain specific speed Stepanoff found that there was a vane length of peak efficiency for a given number of vanes and above that length friction losses took over without increasing flow (Stepanoff 1957). Schmidt's test results are shown in Figure 2.

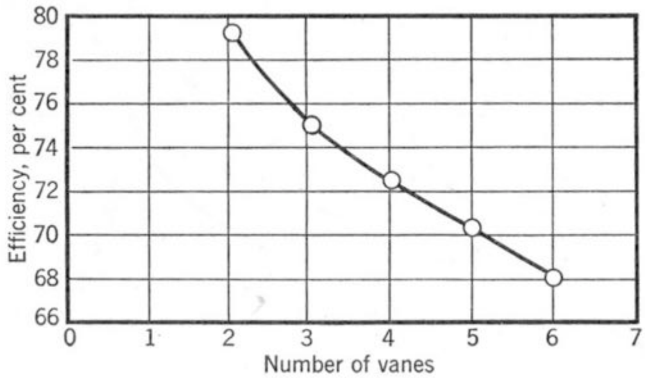

Figure 2 Pump efficiency with different number of vanes and the projected vane area of 63 per cent (Schmidt 1928)

State of the art

Due to a rise in user friendliness and computational power in recent years FEA has gained popularity in design analysis. Given the large number of factors effecting pump performance FEA techniques have become widely used in pump design. Therefore a wealth of information is available on the subject to be used as a basis for improvement of the REV Jet impeller. The complexity effectively rules out analysis of pump systems by hand thereby necessitating the use of FEA software, in this case ANSYS Fluent software was used.

Kiyoshi Minemura and Tomomi Uchiyama studied the correlation between experimental and FEA solutions to multiphase flow of water and air bubbles in centrifugal pumps. Finding that the pressure was minimal at the impeller inlet, increasing to a maximum value at the hub side. The bubbles concentrated in this region of minimum pressure and this was in agreement between the numerical and experimental results (Minemura & Uchiyama 1993).

Badie, Jonker and Braembussche compared unsteady flow in a centrifugal pump modelled using FEA code SEPRAN in 1994. They found; accurate unsteady flow conditions could be modelled to 2-5% accuracy for medium and high mass flow up to 10% for low mass flow; optimisation was possible for both the volute (with a given impeller geometry) or an impeller (given the volute geometry) to avoid reversed flow; and numerical calculations could be used to include non-symmetrical character flow, useful when determining characteristics like the pressure head (Badie, Jonker & Braembussche 1994).

van Esch and Kruyt examined the effect of additional complexity using unsteady flow FEA models in relation to experimental results. In particular their analysis found that the inclusion of inviscid forces, leakage flow, disk friction and hydraulic losses increased the accuracy of the FEA greatly. However van Esch and Kruyt also found that outside of certain conditions the BEP calculation deviated greatly from the experimental results. This error was attributed to the restriction of modelling the isolated impeller and volute regions with an averaged interface between (van Esch & Kruyt 2001).

Dhruv Arora and Marek Behr have conducted a large body of research into the use of centrifugal pumps in pumping blood with large portions of this research conducted with FEA. Behr et al. presented preliminary findings of their research into centrifugal pumps use as internal blood pumps. They used FEA to model pumps to observe the pressure distribution. Conversely to the analysis presented in this thesis their research attempted to reduce high-pressure concentrations in order to reduce the likelihood of blood clots occurring (Behr, Arora & Schulte-Eistrup 2001). Further research found that haemolysis – the premature damage of red blood cells – could be accurately predicted based on FEA. This model could then be further optimised through experimentation (Arora, Behr & Pasquali 2003) – a common technique when using FEA. Finally Arora and Behr concluded in their journal for Acta of Bioengineering and Biomechanics that:

> *"... computational prediction of ventricular assist device characteristics is possible and viable. In particular, the simulations have reproduced a set of performance curves, relating the flow volume generated at a given angular velocity of the pump impeller to the pressure head imposed across the inlet and the outlet. The agreement was found to be satisfactory, in particular in the lower range of angular velocities, possibly due to the reduced importance of turbulence effects." (Behr & Arora 2003)*

Singer and Johne created a comprehensive study of where pressure vessel design codes – ASME boiler and pressure vessel code and European Standard DIN EN13445 – were applicable to pump design through the application of FEA, finding:

> *"Design-by-Analysis is a powerful engineering method. It has the potential to produce safe designs of high quality which are well-suited to their intended service. When applied in a consistent and rigorous manner, the engineering work is more easily documented, reviewed, and interpreted." (Singer & Johne 2013)*

Finally Ashri et al. and Tian et al. studied vibration effects on centrifugal pumps. Tian et al. analysed the structural loading and mode shapes of the impeller shaft (Tian, Qi & Hu 2011). While Ashri et al. investigated the model effects on various impeller geometries (Ashri et al. 2014).

The analysis presented in this thesis using FEA builds on the basis provided by Minemura and Uchiyama; Badie, Jonker and Braembussche; and van Esch and Kruyt. These three reports compared the results found using FEA techniques to experimental results and concluded that FEA was a viable and relatively accurate method of analysis – provided appropriate conditions were used. The work done by Arora, Behr, Pasquali and Schulte-Eistrup demonstrates the use case for FEA in relation to optimising pressure levels in pumps; while Singer and Johne used similar techniques to analyse design code viability outside of the intended use case. Furthermore Ashri et al. and Tian et al. considered the structural loading due to flow and drivetrain effects; while this is not specifically something addressed in this thesis it will become relevant to any future work in design or modification of the pump. The intention of this theses use of FEA is to not only find where cavitation is likely to occur due to pressure differences created by the impeller but to apply this analysis to a real situation though the creation of operation limits. These limits are designed to increase the achievable performance of the REV Jet and reduce component wear.

Geometry

The main regions to be created for a sufficiently accurate model were the impeller, stator and venturi. These parts were first modelled using measurements taken from these parts following their removal from the REV Jet Figure 3. Then input this geometry using Solidworks resulting in an accurate representation of the parts needed for modelling.

Figure 3 Clockwise from top, impeller and stator, venturi and stator outlet

The commercial ANSYS Fluent via ANSYS Workbench software was then used to simulate the flow through the impeller. In order to simplify solving multiple conditions over a large number of iterations a Multiple Reference Frame (MRF) method was used.

The MRF method consists of multiple fluid regions, basically an inlet, outlet and impeller Boolean. The impeller Boolean – created using impeller geometry from Solidworks imported then subtracted from a fluid region – this results in a fluid only region bounded by the impeller geometry. Additionally by importing the impeller geometry from Solidworks allows for geometry parameters. The advantage of the MRF method is a simplified initial setup technique, modelling of all aspects of fluid flow field and input parameters to test variables. The disadvantage is a lack of analysis for dynamic structural loading, however this can be supplemented by measuring output conditions.

Following the creation of inlet, outlet and impeller Boolean the MRF was created by specifying interface regions for the inlet-impeller and impeller-outlet. Following this the meshing constraints were be determined. The geometry could be modelled via symmetry, however given the asymmetry of the stator this proved more difficult and time consuming. Due to this a symmetrical analysis was not beneficial to the outcomes of the model. Furthermore modelling the entire geometry allows for computation of instantaneous flow fields in each channel which generally differs (van Esch & Kruyt 2001). Creating a region that would mesh in a relatively small time – necessitated by the parametric geometry – proved a constraint in terms of the stator and venturi models. Initially these were separate models imported from Solidworks. However, after multiple meshing failures a single outlet geometry consisting of both the stator and

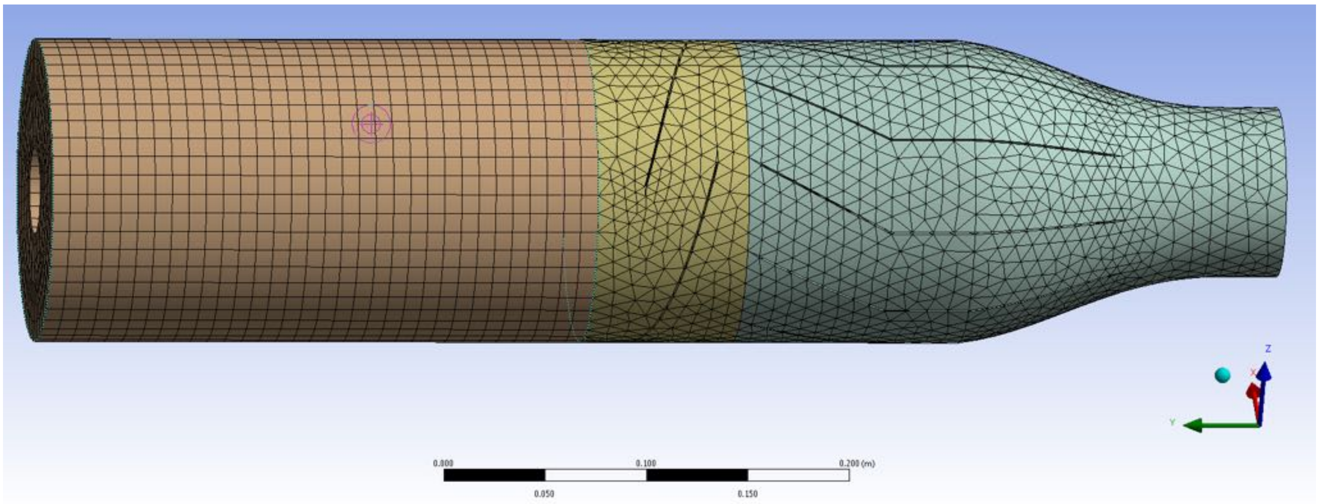

Figure 4 Meshed geometry

venturi geometry was created. This change in geometry had the added benefit of simplifying the interface conditions. Using the design modeller application of ANSYS a fine mesh was specified resulting in a mesh with fine detail around the complex regions of the impeller, stator and venturi geometries along with rough mesh through simple regions, namely the entire inlet and the venturi outlet Figure 4.

Boundary Conditions

Following the meshing setup of the geometry the ANSYS Fluent setup could begin. The following assumptions were made for modelling the flow in ANSYS Fluent:

1. The drag force created by the surfaces of the impeller, inlet, stator and venturi is negligible for the purposes of this analysis. This is a significant assumption and will result in a large error in terms out impeller power output. However, since this is not the main objective of the thesis the decision was made to ignore friction effects.
2. The inlet flow velocity is assumed to be equal to the water speed of the REV Jet. There will be an error in this value, which could be corrected for with enough experimental evidence, the inlet flow velocity can then be calibrated for a specific water speed.
3. The density of water is 1000kg/m^3 and air pressure is at 101.3kPa
4. The temperature of water is assumed to be approximately 20°C to determine the vapour pressure value and does not increase or decrease through the geometry. This is consistent with the average water temperature in Perth (*Australian climate variability & change - Average maps* 1990).

Results and Discussion

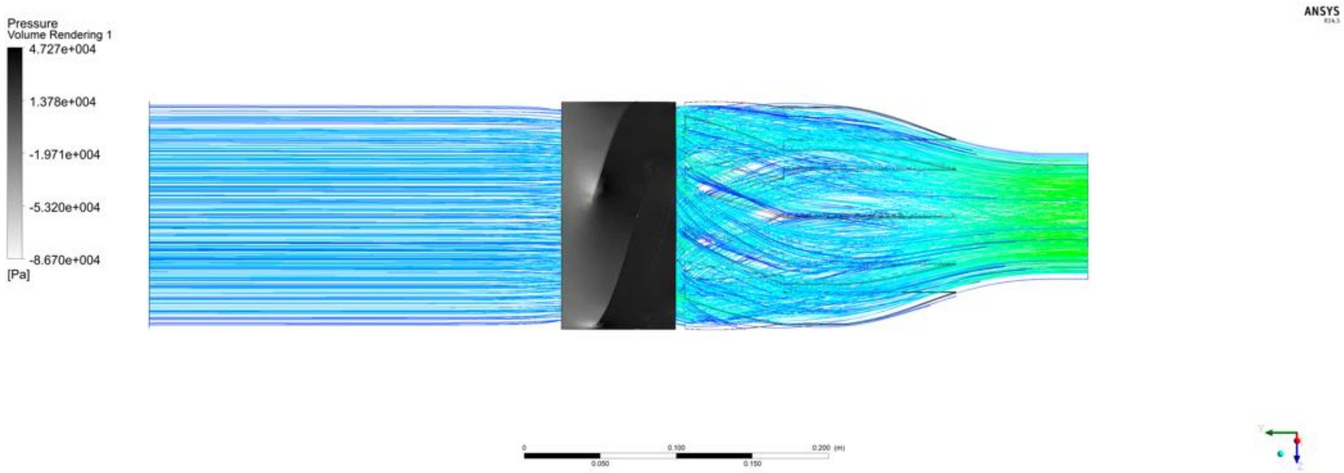

Figure 5 Normal impeller operation

Results

After running the FEA at various water speeds and motor rpm values ANSYS produced a parameter table with output values for pressure, velocity and flow rate. The value of interest for placing limits on the motor rpm is the minimum static pressure measured inside the impeller fluid region. For cavitation to begin occurring the static pressure needs to be lower than the vapour pressure of water at a specific temperature. The static pressure of water at a depth of 0.25m is approximately 103.8kPa; the vapour pressure at a temperature of 20°C is 2.3kPa. In this FEA the pressure is measured as gauge pressure so if the static pressure is below -101.5kPa cavitation begins occurring.

Figure 5 shows what normal flow through the impeller looks like; the streamlines indicate the flow direction and velocity – darker lines meaning higher velocity. The centre of the image (the impeller) is a volume render of pressure with lightest shading indicating lowest pressure. Viewed from this angle the impeller will appear to be rotating downwards; thus there is a pressure increase as flow enters the impeller – the darker shading. As expected the area of lowest pressure is on the trailing edge of the impeller vane entry – shown by the lightest shaded areas; this is where the onset of cavitation will begin at higher motor rpm.

The images in Figure 6 show the various states of operation of the impeller. All images were taken from the same water speed condition – 45 km/h – while the motor rpm was varied between six and eight thousand rpm to determine the cavitation onset. Clockwise from the left is, normal operation (6000 rpm); optimum operation (7100 rpm); visible cavitation (8000rpm); and initial cavitation (7200 rpm). The images for initial and visible cavitation have been adjusted to -100kPa to demonstrate the severity of cavitation; where white indicates below cavitation threshold while grey or black indicate cavitation.

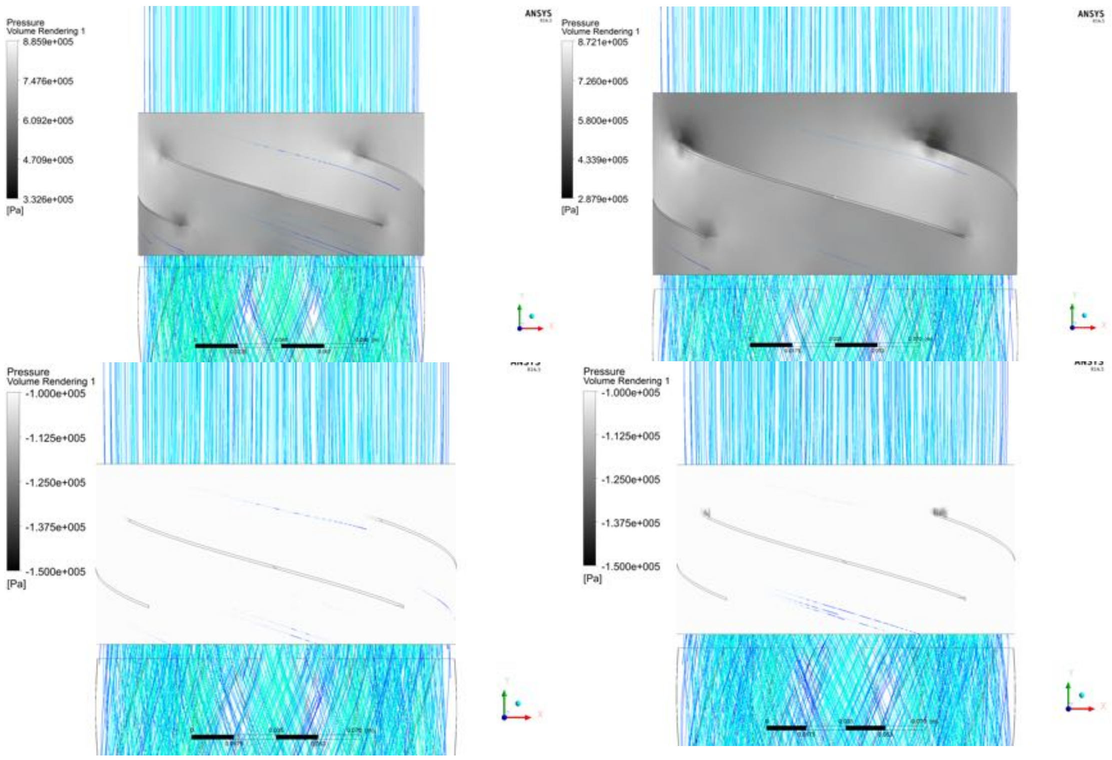

Figure 6 Pressure renderings at 45km/h

Continuing the analysis at values much higher than the cavitation onset increases the size of the region operating below vapour pressure – as shown by Figure 8 and Figure 7 it can be seen that the area where cavitation is occurring has extended so far along the trailing edge of the impeller it reaches the next vane prior to returning above vapour pressure. Thereby increasing the number and severity of transient bubbles – some of which during collapse can reach temperatures of 15000K and create pressures of 1000MPa. This would result in a total loss of pump power, which is observable from the noticeable difference in the number of inlet and outlet velocity streamlines in Figure 7 compared to normal operation shown in Figure 5.

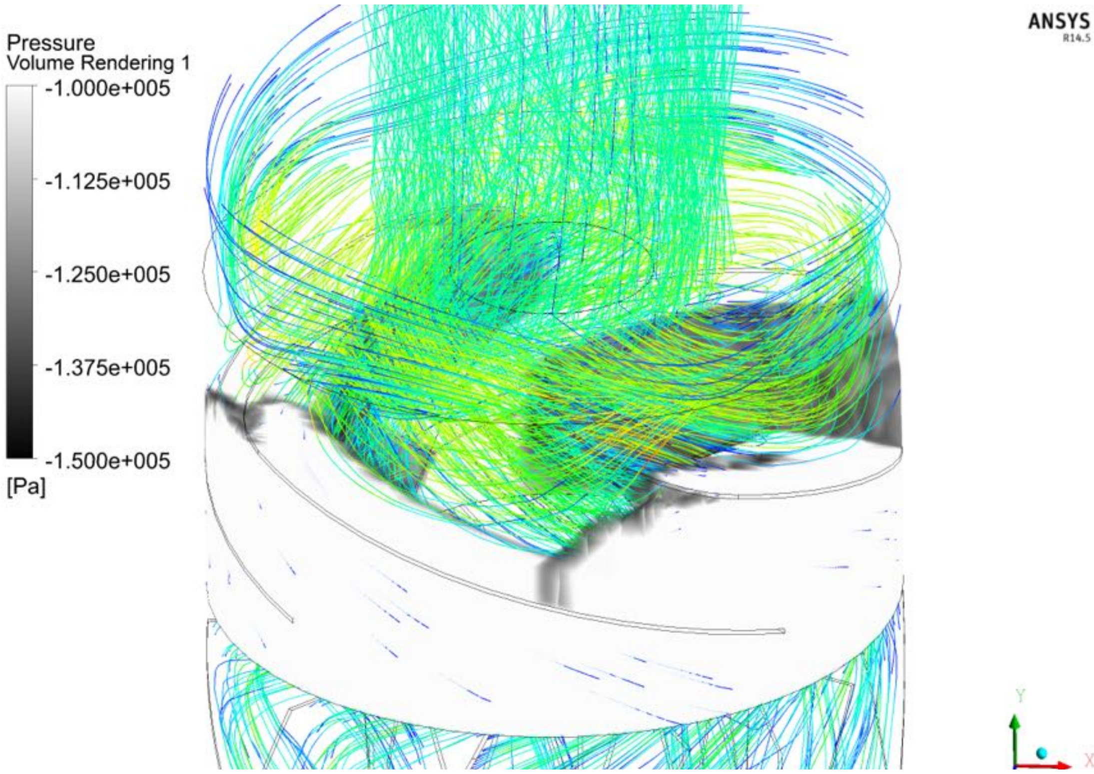

Figure 8 Destructive cavitation

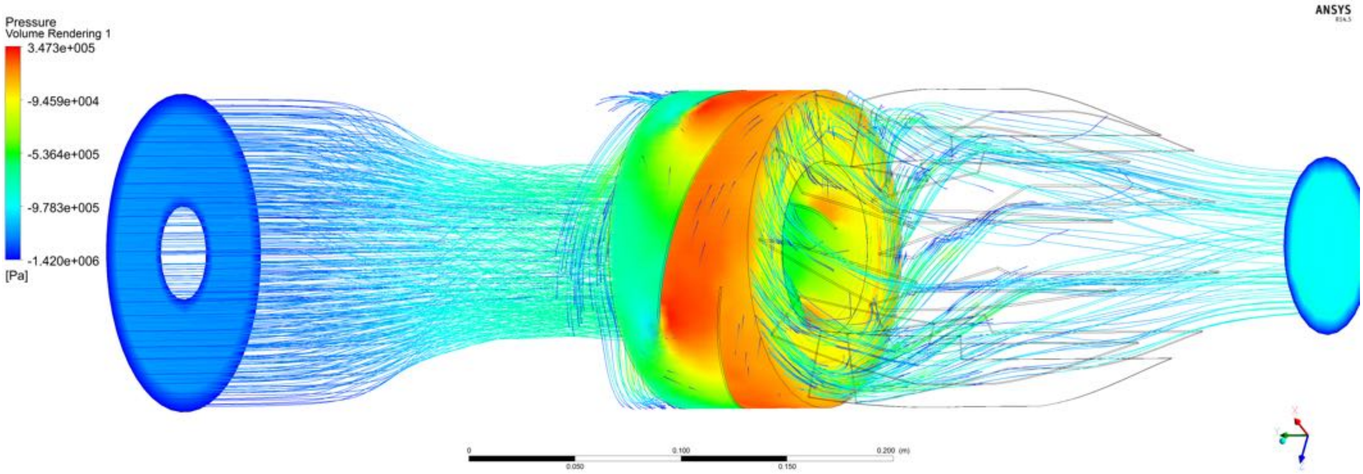

Figure 7 Massive cavitation velocity streamline

This data is now analysed over a water speed varying between 0 and 45 km/h resulting in the plot presented in Figure 9. This is to be used as the rpm limit for the motor, the points indicate the rpm just below the onset of cavitation bubbles forming.

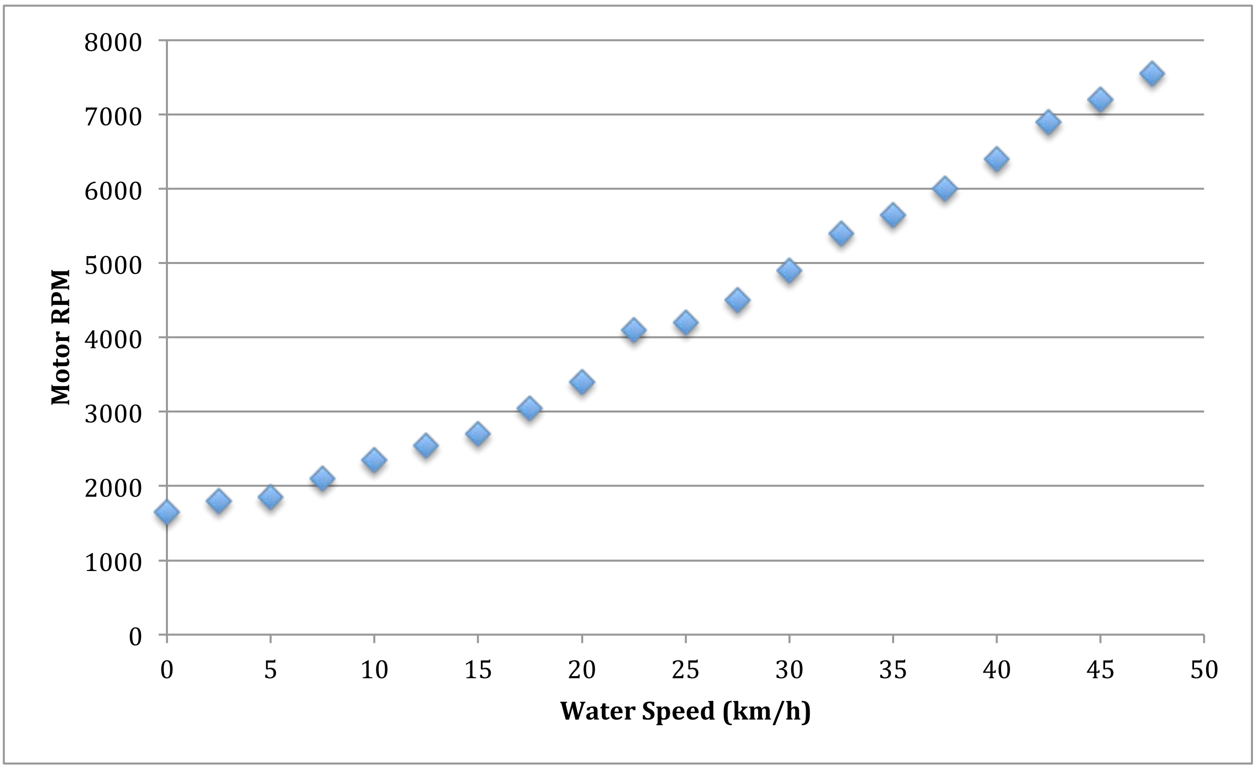

Figure 9 Cavitation onset graph

While the data does allow for a useful optimisation of motor rpm it is by no means perfect. The inconsistencies result in odd inlet flow conditions – represented by inlet conditions below vapour pressure, Figure 8 and Figure 7 – and a difficulty in finding a consistent velocity and flow rate output. Another interesting result of this analysis is the onset of cavitation at high water speeds and low motor rpm. This in not inherently an unexpected result but is worthy of examination during empirical testing. As a result of theses unexplained inconsistencies further parametric analysis was not conducted at this stage and will be addressed in the future work section of this report.

Verification and Validation

Adrian Keating of the University of Western Australia Mechanical Engineering faculty raised the issue of validation via the creation of a previously researched geometry using the techniques used in this thesis simulation as a method of predicting model errors prior to the running of expensive tests. Unfortunately due to time restrictions this validation could not be conducted prior to the submission of this thesis. However the author agrees that validation of the model is a necessary step prior to conducting experimental tests; particularly given the reduced running time of the REV Jet compared to petrol powered PWC. Therefore it is proposed that in order to validate this FEA a reproduction of Stephan Geerts axial flow pump model should be created. Geerts' PhD thesis *'Experimental and Numerical Study of An Axial Flow Pump'* examined the validity of models produced via FEA, comparing them against experimental results (Geerts 2006). For proper validation Geerts' model of an impeller and stator inside a mixing tank should be recreated under the same boundary conditions and modelling methods as this thesis. By running Geerts' FEA for the same conditions any errors – manifested in the form of large variations (greater than 5%) between Geerts' presented results and the reproduced model – in choice of turbidity, multiphase or other model conditions could be found. Following the refinement of boundary and model conditions to within reasonable degree of error of approximately 5% the FEA of the REV Jet pump could be rerun to produce accurate results, which could then be verified.

Verification of the results of the finite element model is difficult due to the complexity of the cavitation measurement, geometries involved and various other unknown fluid variables. Thus often industry design is governed by empirical results or FEA is used to determine the likelihood of cavitation occurring (White 1999). This presents a problem when trying to determine the accuracy of results determined in this thesis. As the REV Jet is still currently in the construction phase the pump characteristics cannot be compared with the FEA solution for validation of the model. Therefore as part of the conclusions and future work section and outline will be presented for how the FEA can be calibrated to produce reliable data. This data can then be used to set limits on motor RPM via the controller based on the water speed.

Discussion

Following the output of the results presented above and reviewing various resources pertaining to FEA of axial flow pumps it is the authors opinion that while this FEA outputs expected results it may not be accurate enough to achieve a reliable restriction on motor rpm for a given water speed. The reason for this conclusion is based on the results obtained for the extreme cases at high and low motor rpm.

Under a low motor rpm and high water speed it appears possible to induce cavitation on the opposite blade side to the trailing edge. This result is not inherently unexpected – it would be equivalent to running the impeller in a reverse direction. However, the result demonstrates a limitation in the chosen FEA software – ANSYS Fluent. Under realistic conditions when the impeller was effectively rotating slower than the fluid would tolerate – thereby creating the low pressure area along the impeller – the pressure differential would produce a force on the impeller, thus keeping the rpm higher than cavitation pressure.

Furthermore, at low water speed and high motor rpm three unexpected results occur. Firstly the inlet region begins to show pressures below that of the cavitation onset pressure indicating a restriction in the inlet mass flow. This is of issue for determining the wire power of the FEA pump model as the pressure differential forms the part of equation 5 for pressure head calculation. Secondly the motor rpm is the parameter instead of motor power. In certain instances – in particular high rpm at low water speed – the motor may be incapable of producing such an output. Possibly the most concerning result occurs at stationary water speed; here the motor rpm limit is approximately 1650 rpm which when consulting the Sea Doo shop manual was the petrol motor's idle rpm. This result is not impossible by any means – although it would be unlikely for BRP to set a motor rpm idle above the cavitation threshold – but indicates that the actual limit is higher therefore there must exist a certain degree of error in the FEA. The expectation for a higher limit than anticipated is bolstered when observing the pressure renderings through the impeller immediately prior to and post cavitation onset pressure. In Figure 6 the lower left rendering is at 45 km/h and 7100 rpm while the lower right image is 8000 rpm; the cavitation onset occurs at the 7200 rpm value, however comparing adjusted images from 7100 and 7200 rpm it is impossible to distinguish between the two cases.

Mitigating these errors would require a more detailed analysis consisting of relatively similar geometry with two distinct differences.

1. The impeller could not be set to a specific motor rpm.
2. The fluid entry speed would need to be a more complex model.

Expanding on the first point, the motor rpm should not be a set parameter but rather and output variable. This would require the model to be dependant on the power delivered to the impeller via the driveshaft. This would result in a model that varies the rpm up to the limit of the motors capability – at this stage an expected peak output of 50kW. Additionally, since the rpm would be an output variable the motor rpm limit could still be factored into the REV Jet design. Instead of an analysis including impossible rpm values far above the motor capability; a plot could be produced showing not only where cavitation will occur but speeds at which cavitation is unlikely to be an issue at all.

On the second point, a complex model conditional on both the REV Jet's water speed and the increase in fluid velocity upon entry into the inlet would achieve more reliable results. Currently the inlet velocity condition not only sets the fluid velocity but also due to ANSYS Fluent restrictions the flow rate also is limited – as part of the conservation of mass principle present in the software's coding. Because of this condition when the motor rpm reaches a certain value a pressure reduction begins occurring along the inlet section of the model. Upon increasing the motor rpm further the length and severity of this low-pressure region increase. In reality this low-pressure region could occur but would be an extreme case. Prior to this result more water would be pulled through the inlet resulting in a higher flow rate and fluid velocity while keeping the same overall inlet pressure. Figure 7 demonstrates this limitation where it can be noted that the velocity streamline through the inlet has been draw closer to the driveshaft side along with exhibiting turbulent flow characteristics. This is not only a problem specifically associated with the FEA software but also the result of the second boundary condition. It is possible for this error to be reduced or mitigated entirely with the placement of a water speed sensor just prior to the impeller eye; placement of a flow rate sensor at the inlet; or a pressure differential measurement on the inlet and outlet. Conversely a more robust model of inlet conditions in ANSYS Fluent could solve this issue. The inclusion of an underside geometry of the REV Jet where the water speed can be created at a point far before the pump inlet may result in more accurate readings. However the restriction on conservation of mass may still be present possibly requiring a sufficiently large water volume so as to reduce this error – this would of course slow down solving time depending on meshing present and volume required relative to pump volume. Finally more research – either through literature, FEA or experimental methods – needs to be conducted into the onset of unstable bubble formation, which will give a true indication of the realistic limit for operation.

Conclusions and Future Work

The validity and usefulness of FEA is increasing every year with advances in computer power and software becoming increasingly more user friendly and broader in capabilities. However there are still risks associated with FEA use for design and testing; this is possibly best summed up by the sport of Formula One where FEA and computational fluid dynamics use has lead to dramatic failures in car design recently. This demonstrates the need to correctly assess the accuracy of the derived solutions. This thesis has presented not only the validity of FEA use – especially for projects with low amounts of funding like the REV Jet project. There do exist drawbacks to the use of FEA techniques mostly related to inexperience on the part of the user. This is in part the reason there may exist significant errors associated with the final values presented in this report. However in the context of the use case for this thesis – implementation on a development vehicle – the value of producing the data allows for further experimentation. The use of FEA techniques to improve the usability of an emerging field of electric vehicle applications is a worthwhile endeavour, particularly if it lowers possible entry point for consumer versions of electric vehicle technology.

The results presented in this thesis are by no means comprehensive; there are many more possibilities for refinement and further development. Prior to this though the REV Jet must first be completed to a level satisfactory enough for on water use and this is the initial goal that will be worked towards in the coming months. Great progress has been made over the last six months on building to the goal of a functioning electric PWC, hopefully resulting in a working REV Jet in the near future. Additionally there must now be work completed towards the possible implementation of such a system which will be discussed in the future work section below.

- Benefits of use of FEA, drawbacks
- Explanation of how results need to be used

In order to best design a new impeller for the REV Jet the performance characteristics of the motor must first be determined. Due to the lack of engine dynometers in Perth the motor has not yet been performance tested. Given the difficulty in preparing the motor for such a test it will not be performed prior to REV Jet construction. However as the motor will be driving a jet pump with a known efficiency the true performance characteristics can be determined with the aid of various sensors. Measuring the engine power from voltage and current sensors will accomplish this, along with the flow rate or velocity of flow measurements taken at both the inlet and outlet to determine the wire power. Shaft revolutions will be measured using the rotational encoder already included in the REV Jet design (Beckley 2013). Graphing this data at a specified time step will give accurate impeller performance characteristics along with the motors torque output at various values of n.

Following the completion of this body of work and completion of the construction phase of the REV Jet; the rpm limits need to be programed into the motor controller. Programming of the controller was identified as a potential issue by Alex Beckley who noted that it would be possible to create limits on motor rpm based on inputs from sensors; however, this would require the Software Development Kit (SDK) which is prohibitively expensive for a project of this size. Manipulating the throttle control prior to its input into the controller could produce this level of control. This would require the creation of a throttle control system, which ideally would feature a microcontroller that could be easy programmed and hold multiple settings for use in testing. The inclusion of a separate throttle control mechanism would also enable a further modification for autonomous operations.

Ideally a base programming without limits should also be kept for validation of FEA. The motor controller also needs to be given the input of water speed taken from the original water speed sensor on the REV Jet – since the motor controller is completely new the speed sensor will likely require calibration. Once the controller is programed correctly, tests need to be run to measure the accuracy of the FEA. The best way to test for the onset of cavitation will be to place a wideband microphone placed after the impeller to measure sub harmonics as outlined by (Neppiras 1968). By combining the data of cavitation onset, motor rpm and water speed measured from the impeller the FEA can be validated. Should there be significant error in the model there should be analysis into what produced this error and include this element in future models. Furthermore due to the relatively unknown torque levels of the motor testing should measure what performance limits the motor creates. As it is not known if an rpm of 7500 is achievable at a stationary water speed.

Finally following the validation and verification of the FEA presented in this thesis a further parametric analysis could be conducted on the impeller and in theory on other aspects of the REV Jet pump geometry. This would be achieved through the programming of parametric values in the Solidworks models used for this FEA. Using the add-in functions between Solidworks and ANSYS Workbench, parametric analysis can be conducted on almost any design variable the user chose. The result of a parametric analysis could be the discovery of an optimal Best Efficiency Point (BEP) for this particular axial flow pump.

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