Post Access Report

Mass of Water TURBINE (MOWT) Paddle Optimisation

Awardee: MWNW Consulting Limited (MWNW)

(formerly Ecosse IP Limited)

Awardee point of contact: Stuart Moir

Facility: Sandia National Laboratories (Sandia)

Facility point of contact: Jesse Roberts

Date: May 31, 2022

1 INTRODUCTION TO THE PROJECT

MWNW Consulting Limited (MWNW) has designed their Mass of Water Turbine (MOWT) (patent-pending), a novel hydrokinetic device which will generate power in rivers, estuaries, and tidal flows – both floating at the surface, or fully submerged. MOWT is a simple, robust conveyor like system which has been designed to operate at low flow velocities, and generates power from multiple paddles attached to the conveyor which hang in the water and propel the conveyor round. Approximately half of the paddles are driven by the flowing water at any one time.

Scottish river trials of the MOWT prototype system indicate that usable power can be generated from water that is flowing at around 1 m/s. Further river tests in Q1 of 2021 will generate power output data for analysis, from the initial prototype configuration.

The overall system development goals for MOWT are to:

- Optimise and commercialise the river-based device
- Deploy single or interconnected river devices to power homes, businesses and small communities on rivers
- Scale up to utility level in order to power businesses and larger communities
- Create coastal versions to provide power and purify water for island and remote communities
- Develop subsea version to operate in bi-directional subsea currents to power underwater assets.

MOWT has been designed to operate efficiently at much slower water flow velocities than traditional water turbines. The system can be configured to operate from a floating position or as a semi- or fully-submerged system, in rivers, estuaries or subsea. This increases the number and range of locations where the system can be deployed, close to the site of power demand.

MOWT has a low environmental impact. The system rotates at the same speed as the water is flowing, making it safe for river or marine life. The system can operate in a floating configuration, resulting in minimal river/ seabed impact from mooring systems.

From conducting in-river trials, it has become evident that the MOWT system has potential to produce usable energy at relatively low flow speeds. MWNW anticipates that the MOWT paddles are a key factor with a significant impact on the device efficiency. As a result, paddle optimization is the focus of the technical assistance required in order to model the overall forces acting on the paddles and to optimize their size, spacing and design for a given MOWT system.

The technical assistance objectives are to conduct computer-based modelling and analysis of paddle configuration to optimise performance. A base model of the device will first be setup. Approximately three variations of each of the tests below will be conducted. A range of analysis goals are included below:

1) Varying water velocity
2) Shape/ size of paddle
3) Optimise number/ spacing of paddles

4) Paddle offset – all the same vs different heights (change of paddle size on model)
5) Proximity of channel

Prior lab and in-field prototype testing has been conducted which has led to the current stage of development whereby it is anticipated that CFD analysis to optimse the device is the next logical step. By utilizing the expertise of Sandia, MWNW will be able to accelerate development of its MOWT technology. This will create a hydrokinetic turbine that can generate energy effectively and efficiently from relatively slow moving water, by harnessing the mass and volume of the water rather than targeting high velocity water. This vastly increases the potential deployment of this type of marine energy generation device and will greatly increase the effectiveness of marine current energy.

2 Roles and Responsibilities of Project Participants

2.1 Applicant Responsibilities and Tasks Performed

- Mike Wilson, MWNW Chairman & Chief Technology Officer
    - MOWT co-inventor, overall technical decision approver, vast experience in deploying technologies in the marine environment.
- Dorothy Burke, EIP Managing Director
    - Involved in aspects of the TEAMER project including approval of documents. Experienced in the offshore industry.
- Stuart Moir, MWNW Projects Engineer
    - MOWT co-inventor, project lead and coordinator for TEAMER project. Involved with MOWT system from inception, including original testing and system designs. Heavily involved in current and ongoing fabrication and testing of the prototype device.
- Stephen Ball, EIP Prototyping & Technical Design
    - input to technical design aspects of the MOWT system. Heavily involved in fabrication and testing of the current prototype device. Experienced in product development from prototyping to commercialisation.

2.2 Network Facility Responsibilities and Tasks Performed

- Jesse Roberts
    - Administration, Contracting
- Chris Chartrand
    - Numerical analysis, reporting

3 Project Objectives

The main parameter that measured was the forces are exerted on each paddle of the MOWT device from the flow of the water around them, how these forces are distributed along the length of the device, and how this changed as the paddle parameters are adjusted. The ultimate goal is to observe the overall forces exerted on the entire device and identify device parameters which optimize the paddle force, and thus the power of the MOWT device.

The study looked at the effects of the following device parameters to quantify the impact of varying each parameter, and to identify efficient designs layouts of MOWT paddles.

1. Effect of varying water velocity
    - MOWT has been designed as a low speed, high torque device
    - Simulating each new setup of the model at different speeds will establish how the device performs across a range of flow rates.
    - Modelling was performed at speeds such as 0.5m/s, 1m/s, 1.5m/s, 2m/s up to 4 m/s and a force curve was fit for each device design.
2. Optimize number/spacing of paddles
    - Currently the prototype device has 4 paddles in the water at any one time. MWNW seeks to optimise paddle numbers by varying the paddle spacing.
    - This interaction should be modelled to determine the best configuration of 'lowest number of paddles' against 'highest power output' to give the most efficient device setup.
3. Optimize shape/ size of paddle
    - On the current prototype device, the paddles are rectangular steel plate.
    - Adjusting the paddle geometry in terms of width and/or depth will be beneficial to indicate future developments of the design.
    - This will show how varying the paddle affects turbulence through the water column.
    - By placing voids in the paddles, this will establish if this aids the flow of water through the device and therefore increases power generation, or alternatively negatively impacts device operation.
4. Effect of paddle offset – all the same vs different heights
    - This would allow us to see the effect of varied paddle geometry on the device. e.g. large/small/large/small
5. Proximity of channel
    - Varying the width of the channel in which the device is moored would be beneficial in highlighting if the device performs better in open water streams or if it performs better in a narrower, shallower stream

By obtaining these results, and by finding the most efficient MOWT system setup, the CFD analysis results will be able to be verified against the in-field prototype device. This will in turn advance the TRL of the MOWT system.

These objectives are deemed of high importance to the development of the MOWT system as it is deemed the most efficient and appropriate use of resources. A CFD analysis will allow a number of the device parameters to be changed and the outputs observed. Although CFD is computationally intensive, overall this is a less resource intensive methodology and will also be highly accurate in that each aspect can be tested with the desired parameters and no external unintended effects, as may be experienced in open water testing.

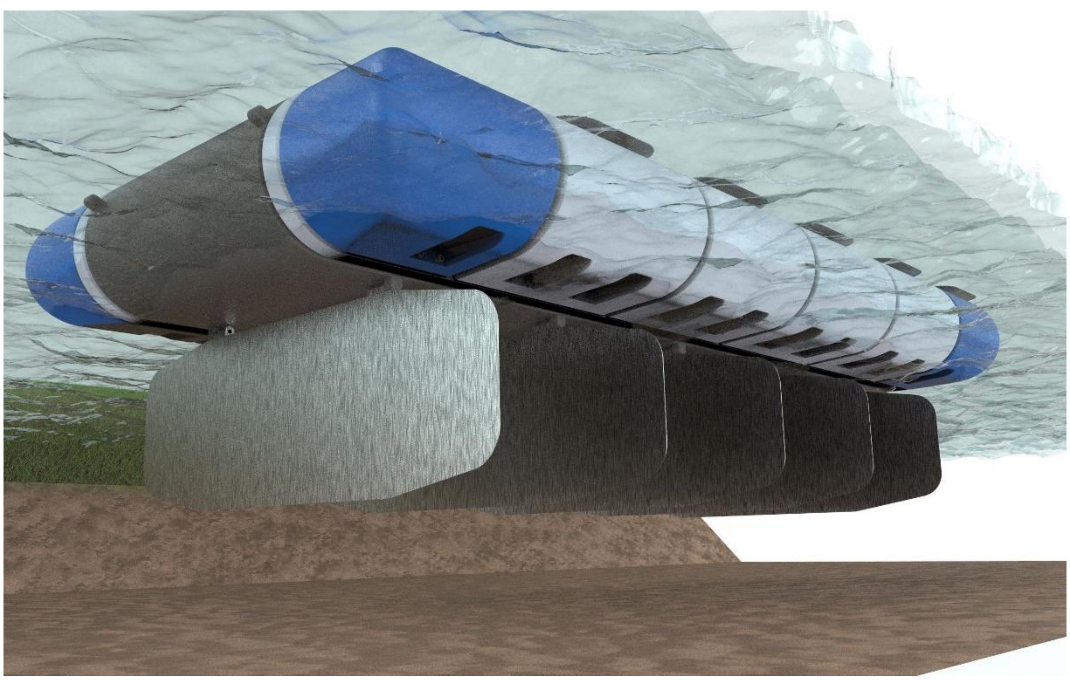
4 Test Facility, Equipment, Software, and Technical Expertise

All analysis will be performed on NTESS computers and clusters, using Siemens Star-CCM+ analysis software. Sandia technical staff trained in CFD simulation will provide the labor and analysis for this project.

5 Test or Analysis Article Description

MOWT is a novel hydrokinetic turbine that will generate power in rivers, estuaries, and tidal flows. MOWT is a simple, robust conveyor-based system that is designed to operate at low flow speeds and generates power from multiple paddles attached to a conveyor. A prototype MOWT scale model has been demonstrated in a river; however computational modelling of the system will be a key tool in design optimisation. This will lead to an enhanced product capable of generating more power and improved reliability. The system has a number of target applications. These include, but are not limited to: power generation for remote communities, utility scale power generation on large rivers or tidal areas, powering offshore subsea assets, small scale devices for remote locations, desalination etc.

The figure below shows an illustration of the MOWT system. It can be seen that the submerged paddles extend out from the conveyor at 90 degrees in order to be caught by the flow of the water to propel the conveyor around. There are main drive shafts at either end of the system, and these are where the data in the prototype model is measured from. The paddles are hinged in order to be able to fold flat when



on the return journey, along the top of the conveyor system. This is required for when operating in tidal flows. Currently the device is moored using four mooring lines, one attached to each corner of the device. This allows swift positioning of the device in the flow and allows the system to be recovered to the river bank if required.

The proposed testing will enhance the technology by providing a better understanding of how the device reacts in flowing water. Better understanding of the device behavior will allow more informed optimization decisions to be made to the physical model, progressing the overall development of the system. It is believed that the paddle design will have a significant impact on the overall performance of MOWT and therefore understanding what aspects of the paddles change outputs is extremely important to the development of the technology. Analysing some of these variables through CFD, allows the analysis to be conducted in a highly controlled manner to ensure that each of the tests conducted is done to the same standard. The CFD analysis will also allow verification against results obtained from physical testing with the prototype device.

A working prototype MOWT device exists and has already been used for some preliminary testing in a small river in North East Scotland, as described above. For this system, the paddles used are 3mm steel plate with a reinforcement brace along the back to reduce the paddles form flexing. The paddles on the prototype measure 2m wide and 0.6m depth. The overall device length is approximately 5m. Data recorded from the prototype device includes the water flow speed, the rpm of the main drive shaft, and the torque on the main drive shaft. A hydraulic braking system has been added to the end of the main drive shaft to apply a load in order to measure the torque.

6 Work Plan

This section should provide a high level description of the research methods. Regardless of the type of support being provided, this section should ***include sufficient detail, within reason, to allow the methods to be duplicated and for all results to be understood and interpreted.***

6.1 Numerical Model Description (Only Required if Numerical Analysis Work is Being Performed, Note that Experimental Projects May Have Some Numerical Modeling)

- Provide a comprehensive description of the numerical model or simulation tool that will be used/was used.
- Identify the simulation tool and provide details on the numerical methods. In addition, any work that will be performed to verify and validate the numerical method should be provided (e.g. mesh and time step studies, ensuring appropriate boundary conditions)
- Provide a discussion of previous studies that have verified the accuracy and validity of the numerical model (e.g. mesh and time step convergence studies, previous validation against experimental results). The applicant and facility should develop the test plan to ensure validity and accuracy of the computational results.

This effort utilized a full Navier-Stokes flow solver along with a k-omega turbulent closure model to predict the fluid velocities for flow around the paddles of the MOWT WEC device. Simulations were performed using a fixed device condition and specifying the flow velocity relative to the paddles. Simulations were run until a steady-state was reached and the surface pressures on the device were recorded and converted into external forces for analysis.

The open source software OpenFOAM was used to perform all CFD analysis on the MOWT device. OpenFOAM is a complete computational fluid dynamics package, which is validated, verified, and widely used by the scientific community. The OpenFOAM software is open source and available free of charge without restrictions. This allows a transfer of all input files and configurations to the awardee so that they may leverage this work for future studies after the termination of the TEAMER project.

Task 1: Device performance dependent on varying water velocity

Discussion: The MOWT has been designed as a low speed, high torque device. NTESS will work with MWNW to select appropriate simulation flow speeds for each new model setup to establish how various device configurations perform across a range of flow rates. NTESS will build and run the models and return the results of the simulations to MWNW for discussion.

Deliverable: NTESS will perform simulations across 3 device configurations at a velocity prescribed by MWNW. Results will be derived in the form of pressure contours across device paddles as well as the total integrated force over the paddle area. Analysis will be performed on the 3D flow field to identify any adverse turbulent or vortical effects of the flow on the WEC paddles which might be mitigated by design modification. All conclusions will be reported to MWNW.

Task 2: Varying shape & size of paddles

Discussion: The present prototype MOWT uses rectangular steel plate. Adjusting paddle geometry in terms of width and/or depth will be beneficial to indicate future design by showing how different paddle geometries affect turbulence through the water column. Further, simulating void spaces in each paddle geometry will establish if this helps or hurts device performance. NTESS will work with MWNW to select several paddle geometries and void configurations to simulate. NTESS will build and run the models and return the results of the simulations to MWNW for discussion.

Deliverable: This deliverable will be much like Task 1. Simulations will be performed on the geometries (informed by Task 1) and pressure contours, and integrated forces will be calculated and reported. Changes in vortical structures and turbulent quantities will be reported and any conclusions drawn from these results will be shared with MWNW.

Task 3: Varying number and spacing of paddles

Discussion: This task will characterize the effects of varying the number and spacing of paddles on the MOWT. The goal is to determine the best configuration that uses the lowest number of paddles while producing the highest power output. NTESS will work with MWNW to select paddle spacing and number configurations to simulate. NTESS will build and run the models and return the results of the simulations to MWNW for discussion.

Deliverable: In task 3, the effects of paddle number will be quantified. Specifically, the total force on the WEC device paddles will be calculated and reported as a function of paddle spacing. Three-five configurations will be tested and their performance tabulated. This information will be communicated to MWNW for use in cost-benefit analysis.

Task 4: Paddle offset

Discussion: The previous tasks simulate the MOWT using a single paddle size for all paddles. This task will consider varying paddle sizes within a given simulation. NTESS will work with MWNW to select paddle offset configurations to simulate. NTESS will build and run the models and return the results of the simulations to MWNW for discussion.

Deliverable: Similar to task 3, the performance effects of 3-5 paddle sizes will be quantified. Specifically, the total hydrodynamic force on the WEC device paddles will be calculated and reported as a function of paddle size. This information will be communicated to MWNW in the form of a performance table.

Task 5: Angle of Attack (AOA)

Discussion: This task will investigate the effects of varying the incident flow direction to the MOWT effects device performance. This is an over target effort and will only be performed if time and funds allow. NTESS will work with MWNW to select incident flow angles to simulate. NTESS will build and run the models and return the results of the simulations to MWNW for discussion

Deliverable: This study will deliver total paddle forces to MWNW tabulated as a function of paddle AOA for 3-5 predetermined paddle angles.

Task 6: Model Verification

Discussion: Where data is available from infield testing, this effort will be compare model results to infield testing data. NTESS will work with MWNW to field tests to simulate. NTESS will build and run the models and return the results of the simulations to MWNW for discussion and to build confidence in the method employed in Tasks 2-7.

Deliverable: Model output comparing field tests to simulation results will be delivered to MWNW. Predicted forces will be compared empirical forces and errors will be reported as a percentage of the data, with all results reported to MWNW.

6.2 Data Management, Processing, and Analysis

6.2.1 Data Management

All data generated is currently stored on Sandia's Mass Storage System. All configuration files, input conditions, analysis, post processed data and reports are being retained by Sandia and are available at request for distribution to MWNW.

6.2.2 Data Processing

Data has been processed using Python scripts for calculating and plotting the total net normal forces on each paddle, and also in aggregate. Graphical 3D visualization has been performed using ParaView. ata from early simulations have been reviewed and compared to expected data as provided by MWNW. No anomalies or oddities were identified.

6.2.3 Data Analysis

Data was collected natively by the simulation software for pressure, velocity and paddle forces. The principal quantity of interest identified by MWNW prior to simulation was the net paddle force. During early stage simulation flow velocity and streamlines were identified as informative metrics for flow field understanding and design improvements. Paraview's post-processing software was used to calculate streamlines.

7 Project Outcomes

7.1 Results

Clear and concise results should be presented in this section. The following guidelines for reporting results should be adapted to best suit each project:

- Graphical presentation of results is encouraged, where possible. Pictures and block diagrams illustrating processes should be used wherever this would provide greater clarity in the methods
- A tabular overview presentation of results is recommended for situations involving a series of results for varying physical/numerical conditions.
- Each figure and table should be accompanied by a concise descriptive narrative explaining the results and conclusions that are drawn
- Verification and validation results should be provided, if applicable

Per the award agreement, Technical Support Recipient (TSR) must:

1. At a minimum, TSR will upload to the MHK-DR the quantitative data underlying "figures" (including, but not limited to, all charts, graphs, and tables) contained in the TSR's final report. This data must be formatted in a way that makes it clear how to reproduce each figure from the published data and, in the case of relatively complicated figures, the submission should include any required scripts or narrative to achieve that objective.

2. All Post Access Reports will be reviewed and approved by the TEAMER Facility and the TEAMER Technical Board prior to acceptance. Artificially limiting the number of figures in the final report to avoid providing underlying data will be considered non-compliance with final reporting requirements.

The main quantity of interest from the simulations is the total force on the MOWT paddles. This value is calculated by integrating the pressure on each paddle over the paddle area.

All studies used a reference density of 1000 kg/m^3 for water which was used for calculating pressure forces and determining drag coefficients. the cross sectional area of a single paddle was used as the reference area in determining the default configuration ($A_{ref} = 0.6484\ m^2$) to ensure consistent comparisons across designs. The following drag equation,

$$F = \frac{1}{2} C_d A \rho u^2$$

Was used to determine the drag coefficient for each test with the following reference values:

$$\rho = 1000 \text{kg}/m^3 \quad \text{and} \quad A = \text{W} \times \text{H} = 0.975m \times 0.665m = 0.648\text{m}^2$$

This force is a vector in the paddle normal direction, with the net force being the directional sum of the forces on both sides of the paddle.

In addition to the paddle force, the simulations were able to provide information about the velocity and pressure fields, to help inform the designers of the detailed flow phenomena in the device vicinity, which are sometimes not apparent in experimental testing. The following sections detail these findings in the form of color contours for pressure and velocity fields, and visual representations of the flow direction using arrows.

7.1.1 Paddle Number

The current prototype device used 4 paddles. A study was performed to analyze the drag dependence of the device if 3 or 5 paddles were used. Simultaneously, the velocity was varied between 0.5 and 3.0 m/s to determine the dependence on inflow velocity.

The results shown in Figure 1, the total drag force on the device seems largely unaffected by moving to a 3-paddle or 5-paddle design. The points on the plot represent the specific test cases run, and the solid line is a quadratic curve fit of the data using the drag equation.

It can be seen from the plot that the data points align with the quadratic curve quite well, implying that a drag coefficient itself (specific to a given design) it adequate to describe the device forces, and one or two test points can be used to characterize future designs.

The drag coefficients resulting from the curve fit are show in Table 1. From the table it is seen that the 3-paddle design slightly increases the drag over the 5-paddle design, implying that manufacturing costs can be reduced by simplifying the design and reducing material requirements.

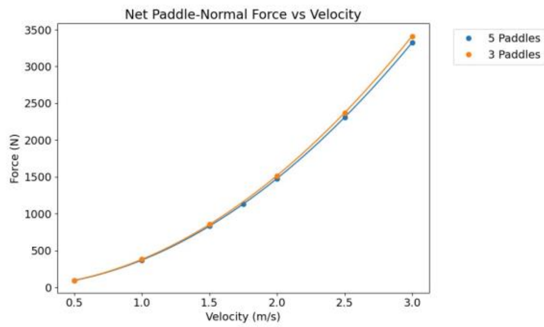


Figure 1 : Total net force on MOWT paddles vs relative velocity for the 3 paddle and 5 paddle designs.

Design	Drag Coefficient
5 paddles	1.1403
3 paddles	1.1707

Table 1: Drag coefficient for the 3 paddle and 5 paddle MOWT designs.

Figure 2 shows a contour plot colored by pressure for each of the two designs at a relative velocity of 2.0 m/s. Overlayed on the plot are vectors showing the flow direction in the computational domain. The pressure contours indicate that most of the drag force on the MOWT device is a result of the leading paddle which redirects the flow downward. The flow recovers near the end of the device, and impinges again on the final paddle in both designs, however the extra paddles of the 5-paddle layout do not absorb much momentum from the flow.

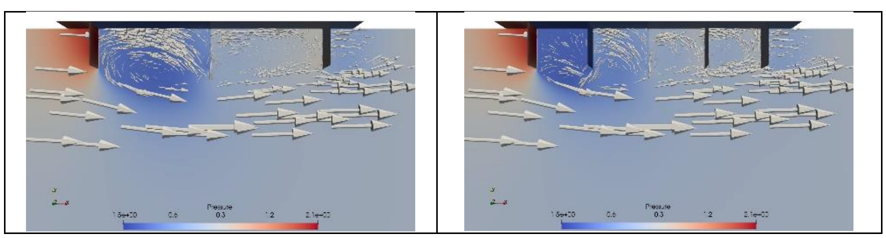


Figure 2 : Velocity vectors superimposed over contour plots colored by pressure for the 3 paddle and 5 paddle designs.

The 5-paddle layout is an approximate model of a prototype system that was designed and tested by MWNW in a small river environment in Scotland. Figure 3 shows the prototype system deployed in the river. This prototype was setup to measure the torque of the main shaft as the paddles on the conveyor system were driven round by the flowing water. Using the torque on the shaft and the rotational velocity, it was possible to calculate the power of the system. The prototype was based on a chain conveyor system to allow different system configurations to be trialled, such as number of paddles.

Figure 3 : MOWT Prototype System

The initial test configuration of the prototype was the same 5-paddle layout as shown in Figure 2. The device was aligned parallel to the flow, with the flow coming from the right as indicated in Figure 4. Marked up in red is the position of the paddles during one test. The paddles were attached to the conveyor on hinges with a restrictor, allowing them to move to a certain point. It was observed that paddles 1 and 2 appeared to harness some of the flow. Paddles 3 and 4 were flapped back towards the head of the device indicating that the flow was circulating at the back edge of these paddles. Paddle 5 appeared to be almost vertical in the flow (same as paddle 1), indicating that the flow was exerting a force on the front edge of paddle 5.

Figure 4 : Prototype with 5-paddle layout

The observations from the physical prototyping correlate well with the outputs from the CFD modelling in Figure 2. The velocity contours of Figure 2 correlate with the directions of the paddles in Figure 4. The pressure contours of Figure 2, indicating most of the force is exerted on paddle 1, with a slight recovery of flow for paddle 5 also appears to correlate well with the physical prototype.

With the physical prototype, the number of paddles on the device was also changed to represent the 3-paddle layout of Figure 2. Again, there was good correlation between the CFD model and the physical prototype as the prototype with fewer paddles (3 in the water) generated approximately the same power as the device with more paddles (5 in the water), as was observed in the CFD where the net force exerted on the 3-paddle layout was very similar to the net force exerted on the 5-paddle layout.

7.1.2 Paddle design

Multiple paddle designs were studied to analyze the dependence on device shape, paddle height and width, and paddle spacing. Figure 5 shows velocity contours of the flow past the 3-paddle MOWT design including the effects of adding a gap between the paddles and the underside of the MOWT device. As seen in the figure, including a gap spacing in the design allows flow to pass above the paddles, and impart momentum on the latter paddles. As seen in Figure 7 and Table 2 this gap results in an increase in the drag coefficient, however of note is that the difference between the standard gap spacing (0.225H) and a double gap spacing is hardly noticeable. In Figure 7 the two force curves (green and orange) are near indiscernible, and the drag coefficient in Table 2 is identical to the third decimal. The conclusion being that there is not much advantage to extending the paddles further downward

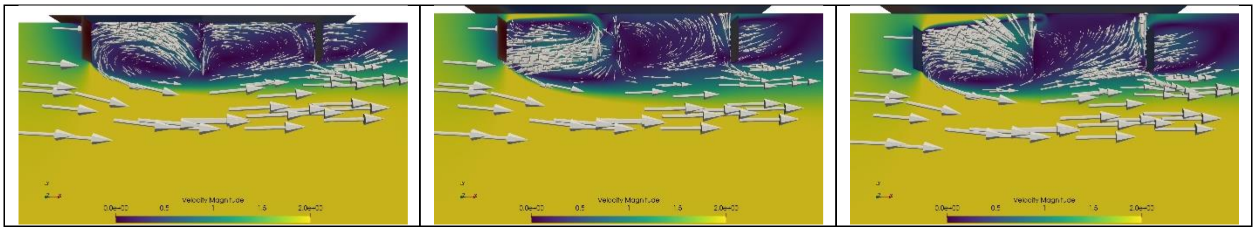


Figure 5 : Velocity vectors superimposed over contour plots colored by velocity magnitude for the 3 paddle design with no gap (left) a gap of 0.225H (center) and a gap of 0.241H (right)

Two additional paddle designs were analyzed, which were a porous paddle design, and a nozzle paddle design. Shown in Figure 6 are the additional paddle design studied. While the flow in the porous paddle design appears very similar to the flow around the standard 3 paddle design, and indeed the drag coefficient for the porous design (seen in Table 2) is nearly identical to the standard 3 paddle design.

However, the paddle design with the nozzle inducing side paddles does result in a large increase in paddle forces and drag coefficient. It should be noted that while the drag coefficient is double the coefficient of the 3 paddle gap design, this is likely due to the much large cross sectional area of this device. Ultimately it was decided that a simply doubling the impingement area of the 3 paddle design would be a more simplistic and cost effective approach to obtaining the same drag forces on the MOWT.

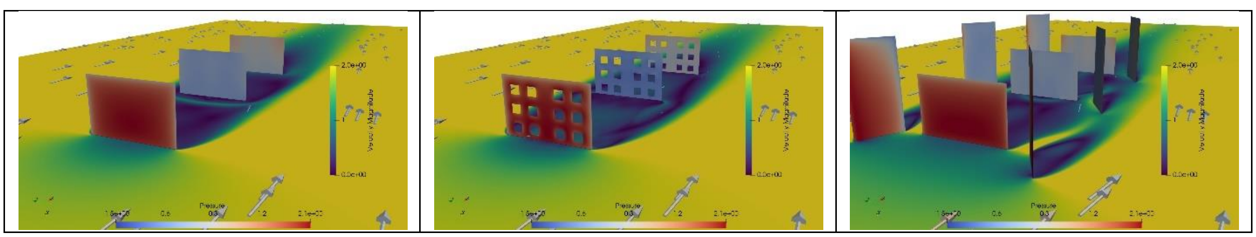


Figure 6 : Inverted view of three paddle designs. The 3-paddle design (left) a porous 3-paddle design (center) and a 3-paddle design with nozzle side paddles (right)

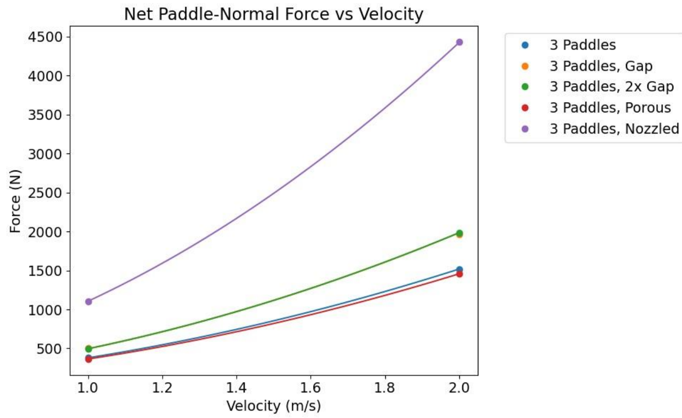


Figure 7 : Total net force on MOWT paddles vs relative velocity for the 3 paddle and 5 paddle designs.

Design	Drag Coefficient
3 paddles	1.1710
3 paddles, Gap	1.5306
3 paddles, 2xGap	1.5306
3 paddles, Porous	1.1238
3 paddles, Nozzle	3.4131

Table 2: Drag coefficient for the 3 paddle and 5 paddle MOWT designs.

Following onto the research performed by Ehrlich *et. al.*[1], the effects of paddle aspect ratio was also studied with 3 new ratios analyzed. The standard design used a ratio of $W/H = 0.975m/0.665m = 1.466$. The current study looked at paddles of aspect ratio 2, 5 and 10. These geometries are shown in Figure 8.

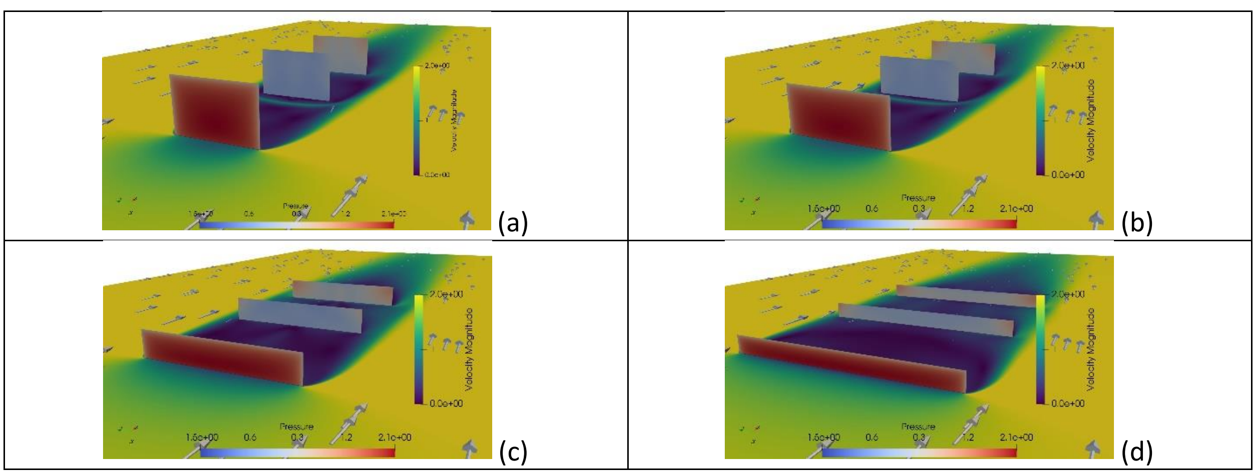


Figure 8 : Inverted view of the standard three paddle design (a), a 3-paddle design of aspect ratio 2 (b) a 3-paddle design of aspect ratio 5 (c) and a 3-paddle design of aspect ratio 10 (d)

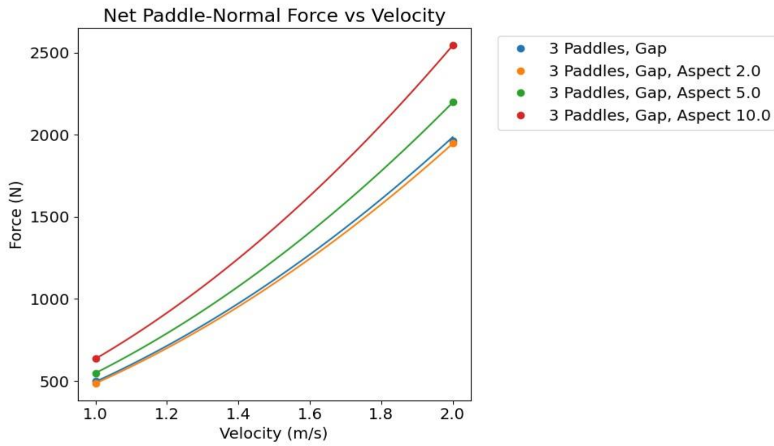


Figure 9 : Total net force on MOWT paddles vs relative velocity for the various aspect ratio designs.

Design	Drag Coefficient
3 paddles	1.5306
3 paddles, Aspect 2.0	1.5002
3 paddles, Aspect 5.0	1.6934
3 paddles, Aspect 10.0	1.9611

Table 3: Drag coefficient for the various aspect ratio designs.

Figure 9 and Table 3 show that the total net force from the aspect ratio of 2 is quite similar to the total net force on the standard (aspect ratio of 1.466) however as the aspect ratio increases, a distinct increase in paddle forces is seen. The explanation for this seems to be that the flow redirection caused by the leading paddle in much more pronounced in the lower aspect ratio cases than in the higher aspect ratio flows. This can be seen in the images in Figure 10. The paddles which cause less flow redirection allow for a faster recovery of the wake, and more impingement of the momentum containing flow on the latter paddles.

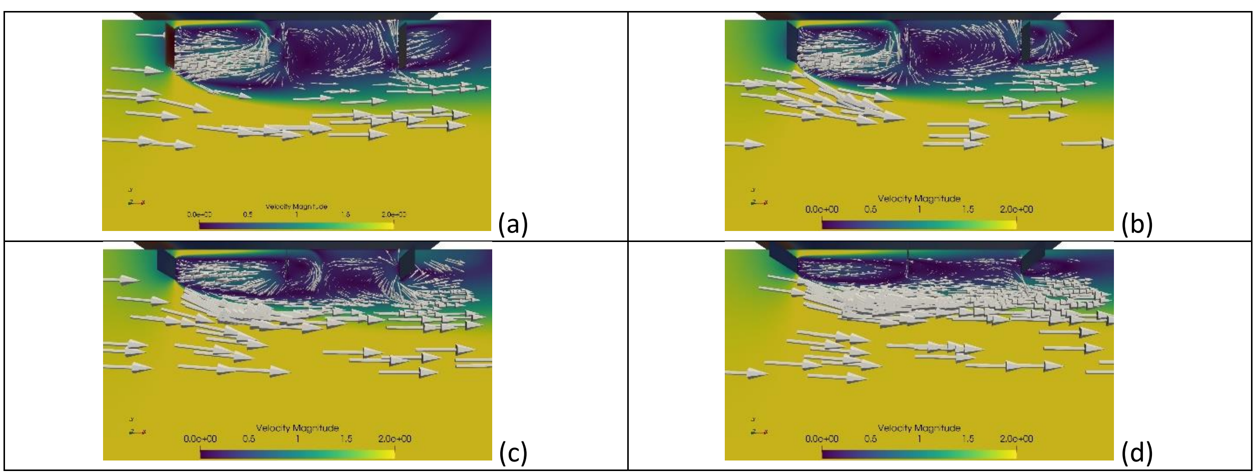


Figure 10 : Side view showing velocity vectors overlayed on contours of velocity magnitude for the standard three paddle design (a), a 3-paddle design of aspect ratio 2 (b) a 3-paddle design of aspect ratio 5 (c) and a 3-paddle design of aspect ratio 10 (d)

7.1.3 Paddle Layout

The effects of paddle layout were also analyzed. Paddle layouts of various angled orientations were tested and additionally a convex 3-paddle design was conceptualized in which the paddles were laid out radially from the device. Figure 11 shows the convex MOWT configuration with the 3 paddles extending radially from the device as well as an example of the pitched device configuration which extend deeper into the flow field. Figure 12 illustrates the yawed device configuration in which the device remains level with the water surface, but is rotated with respect to the oncoming flow.

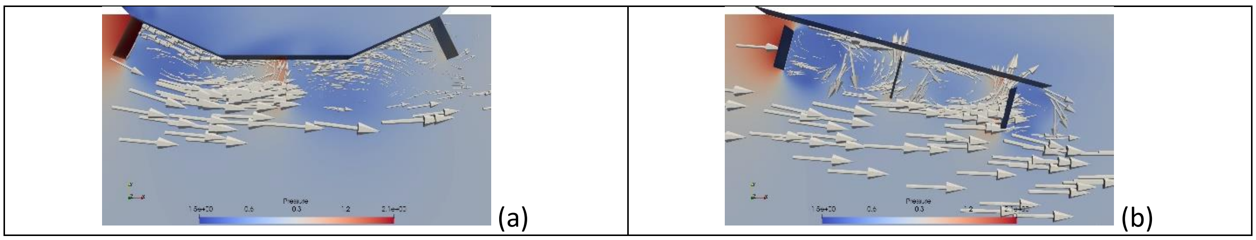


Figure 11 : Side view showing velocity vectors overlayed on contours of pressure for the convex bottom(a) and a 15° pitched orientation (b)

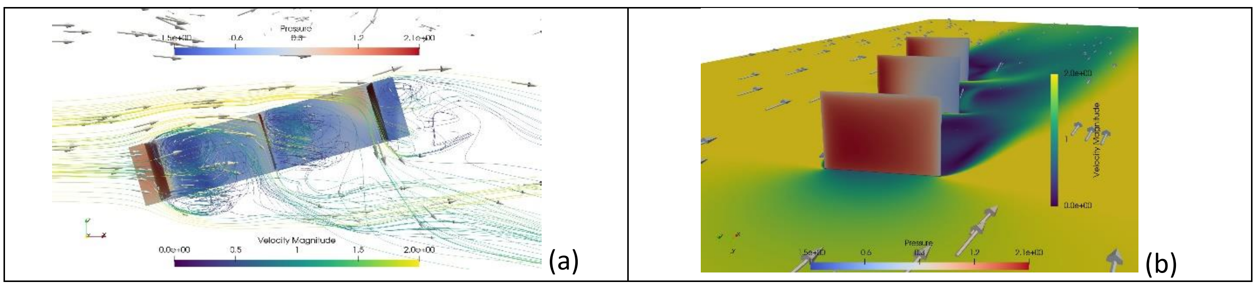


Figure 12 : Images of the 15° yaw simulation. A bottom up view of streamlines colored by velocity magnitude over the MOWT geometry colored by surface pressure(a), and an inverted view of paddle pressure and a velocity magnitude cutting plane(b)

Figure 13 and Table 4 below show the results of the paddle layout study. What is seen is that each of these layout results in an improvement to the net thrust on the device, with the largest return coming from the 30° yaw layout, and similar performance from pitching the device between 30° and 45°. It is not surprising that each of the layouts tested increases the force on the device since, they causes an increase in the apparent cross-sectional area of the device. What is of interest to the designers is the impact of yawing the device. Positioning the device at an oblique angle to the incident flow is a slightly unintuitive result of this study, and is a fairly simple modification to make to the device to improve performance.

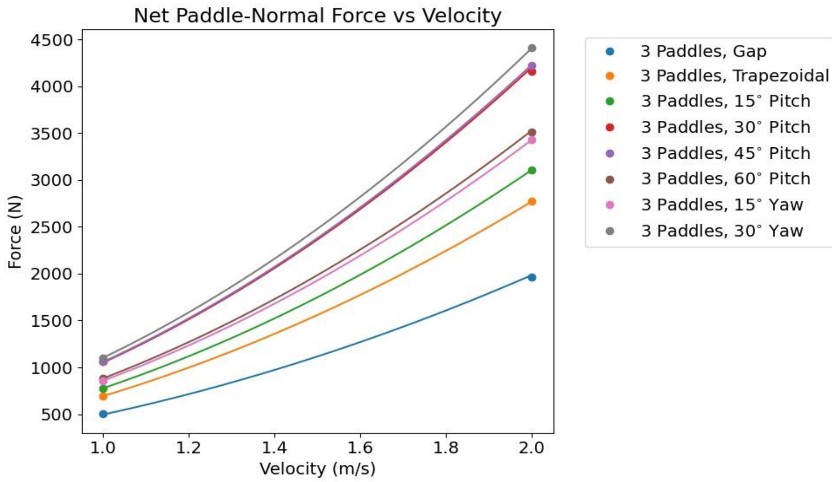


Figure 13 : Total net force on MOWT paddles vs relative velocity for multiple paddle layout designs.

Design	Drag Coefficient
3 paddles, Gap	1.5306
3 paddles, Trapezoidal	2.1373
3 paddles, Pitch 15°	2.3969
3 paddles, Pitch 30°	3.2421
3 paddles, Pitch 45°	3.2634
3 paddles, Pitch 60°	2.7212
3 paddles, Yaw 15°	2.6446
3 paddles, Yaw 30°	3.3998

Table 4: Drag coefficient for multiple paddle layout designs.

Adding the yaw to the device was also trialed during the physical prototype testing as seen in Figure 14 A small angle, of approximately 15 degrees was applied to the device relative to the incoming flow. The physical results correlated with the computational results. This was confirmed by the conveyor rotating at a higher speed when the device had a yaw applied compared to a slower rotation with the device positioned parallel to the flow. This confirms that increasing the apparent cross-sectional area has a positive impact on the total net force on the device. The prototype also showed that applying yaw is a relatively simple thing to implement in real-life situations.

Figure 14 : Prototype with yaw

7.1.4 Device Scaling

The 3-paddle 15° yaw case was rerun at 10x and 0.1x scales to measure the dependence of thrust on device scale. For even comparison, the drag coefficient for these cases was calculated using a corresponding (100x and 0.01x respectively) scaled reference paddle area. Figure 11 shows the 15° yaw MOWT configuration scaled by 10 times. Figure 12 illustrates the streamlines and paddle pressures for the same device configuration.

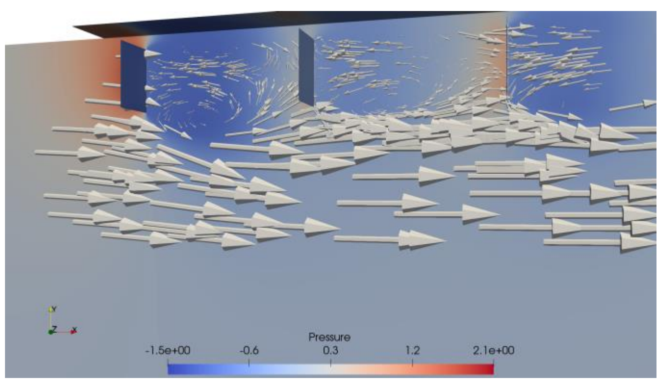


Figure 15 : Side view of the device showing velocity vectors overlayed on contours of pressure for the 10x scaled 15° yawed

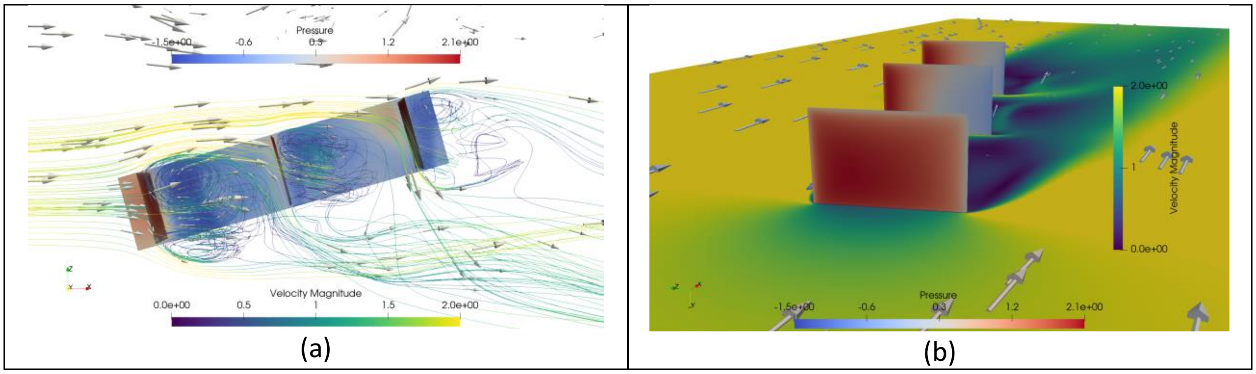


Figure 16 : Images of the 10x scaled 15° yaw simulation. A bottom up view of streamlines colored by velocity magnitude over the MOWT geometry colored by surface pressure(a), and an inverted view of paddle pressure and a velocity magnitude cutting plane(b)

Figure 17 and Table 5 below show the results of the scaling study. To compare the forces between the three cases, the forces plotted in Figure 17 for the 10x scaling and 0.1x scaling are normalized by their respective area multiples (100x and 0.01x). What is shown is that each of the two scalings produces an almost identical drag coefficient as the baseline case, implying that the drag model produces an accurate drag estimate, even for a scaled device.

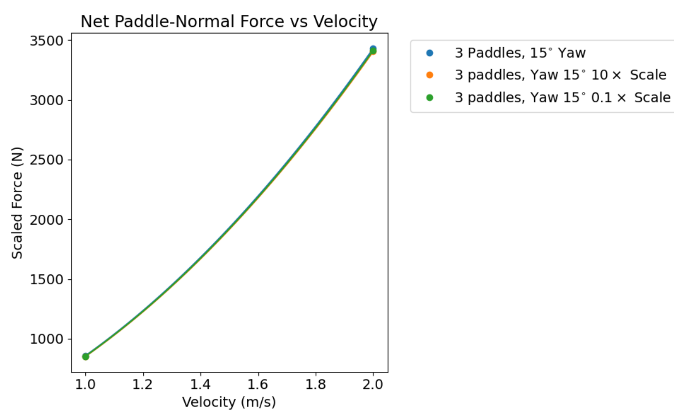


Figure 17 : Total net force (normalized by the scaling factor squared) on MOWT paddles vs relative velocity for multiple paddle layout designs.

Design	Drag Coefficient
3 paddles, Yaw 15°	2.6446
3 paddles, Yaw 15° 10x Scale	2.6252
3 paddles, Yaw 15° 0.1 Scale	2.6323

Table 5: Drag coefficient for multiple paddle layout designs.

7.2 Lesson Learned and Test Plan Deviation

Describe any lessons learned during the execution of the project that would improve the execution of future projects under the TEAMER program. The lessons learned could involve any aspect of the project execution. For example, the lessons could involve any of the following areas:

- Project planning

- Numerical procedures
- Testing procedures
- Instrumentation
- Sensors
- Data processing and storage
- Data quality
- Uncertainty quantification and propagation
- Safety procedures and protocols
- General efficiency and time management
- Any other lessons that could improve the performance of follow on projects

Describe deviations from the approved test plan, why these occurred, how they were addressed, and how they could be avoided in similar, future work.

When first establishing the test plan, it was always a possibility that the results of the initial simulations may lead to last minute changes with the test plan. This process allowed adaptability with the simulations ensuring that the most beneficial results were obtained by being based on previous simulations depending on those results. All aspect relating to the initial test plan have been investigated to some degree with a greater focus on some areas than others. It became apparent that there would be sufficient time and resource within the project to allow the simulations to encompass a broader range of investigations, looking at a greater number of changes that could be made to the device and to observe what affect these changes had on the device.

Being able to computationally simulate the technology allowed many different aspects of the device to be investigated relatively simply, and within a relatively short time period. It also allowed easier comparisons and ensured that constants remained throughout the investigations, such as paddle surface area when investigating the aspect ratio and comparing it to the base case. To model all of these aspects physically would have required a longer time period and would have been more costly. It would also have been very difficult to keep the constants exactly the same when physically modelling the system. Despite this, what was possible was to compare some of the simulation results with some physical modelling results from a prototype device. This provided a level of verification to the simulation results and it was found that the simulations and the prototype device yielded similar results and behaviors for the setups that could be compared. Further physical testing of the prototype will allow further verification of more of the simulations. To further enhance the verification process, there may be a possibility to look at conducting some laboratory experiments as a future project.

The simulations allowed for the flow recovery to be interpreted based on the visuals produced. This showed the high pressure and low pressure areas and also the velocity profiles of the flow, and also the arrows showing how the flow was diverted around the device. These visuals proved very useful in interpreting how the flow was affected by the varying device setups, and they were useful in determining the next simulations to conduct as well as some proposed setups that were deemed no longer necessary based on how the flow had reacted to some of the previous simulations. Prior to this project, during the physical prototype testing of the device it was very difficult to observe what the flow was doing as it interacted with the device. The simulation work provided confirmation to some hypotheses that were made of the prototype and have provided a good visual representation of the flow interaction. An example of this can be seen when looking at the paddle aspect ratio. From the simulations, it can be concluded that the greater the aspect ratio, the quicker the flow recovers. This was not possible to observe from the physical modelling that was conducted.

There was deviation from the test plan, but this was determined based on results of simulations to ensure the resources were best utilized to further the development of the technology. The deviations arose following discussion of simulation results. It was always the intention of this project that the test plan may be somewhat fluid to ensure the best results were obtained. One of the intentions of this project was to optimize the device design and therefore this meant that some of the proposed simulations were driven by the results of other simulations. This has helped to accelerate the technology development. As an example, of this, investigation of device pitch and yaw was not in the original test plan, however, this has become a hugely important aspect to consider as the design is progressed due to the pitch and yaw yielding some of the greatest results from the simulations.

8 Conclusions and Recommendations

Describe the major conclusion that your team has drawn from the results presented and any recommendations for follow on work in this area of research. A discussion of whether project goals and metrics were achieved should be included.

A number of key conclusions can be drawn from the simulation work. The foremost conclusion is that the surface area of the paddle has the greatest impact on the force that is measured on the device. In short, the larger the paddle area, the greater the recorded force. This will be incorporated into the design process to ensure that the paddle size is of more importance than the paddle shape. Although the higher aspect ratio yielded greater results than the lower aspect ratio, it is thought that if the water depth allows, that increasing the paddle size is of greater value than the aspect ratio.

When investigating paddle shape, it was found that the greatest drag coefficient was generated when the paddle was a simple rectangle. The flat edges of the rectangle lead to an increase of the drag coefficient over, for example, considering a curved paddle.

It was observed that the greater the aspect ratio of the paddles, the quicker the flow field recovered as it interacted with the device. This meant that the additional paddles on the device with the aspect ratio of 10 had a more positive effect on the total force recorded than the lower aspect ratio simulations.

When considering a device aligned parallel to the flow, it was concluded that the first paddle takes most of the force of the water and the trailing paddles have little positive impact for the device, with some of the trailing paddles recording a negative force, and therefore having a negative effect on the device. This observation does, however, allow the number of paddles to be reduced for a parallel aligned device, reducing fabrication costs for the physical model.

By applying a degree of pitch (or yaw) to the device, the force was greatly increased when compared with the same device set up but aligned parallel to the flow. This is mainly because there is more total paddle area open to uninterrupted flow. The significant improvement on the total force recorded when considering pitch/ yaw means that this is an important aspect of the device design that will be incorporated into future designs.

At the outset of this project, there were five main goals to be investigated. These were:

1) Investigate the effect of changing water velocity,
2) Investigate the effect of the shape and size of paddle,
3) Investigate the effect of changing the number of paddles and spacing between paddles,
4) Investigating paddle offset
5) Investigating the proximity of the channel to the device

Each of these project goals has been achieved with CFD simulations to investigate each of the goals. Changing the water velocity is essentially a base case that was simulated for each of the different setups of the device to see what effect the velocity had on the total force. The shape and size of the paddle has been investigated, concluding that the larger the paddle, the greater the force will be. The shape has little effect. The number of paddles and the spacing between the paddles was investigated and concluded that for a device parallel to the flow the first paddle took most of the force with the trailing paddles having little effect. When altering the angle of flow into the device by applying a pitch or yaw angle, the trailing paddles had a greater effect on the device. The paddle offset was investigated by adding a gap between the body of the device and the paddle. This allowed some of the flow to go over the top of the paddle and have a positive effect on the next paddle. Proximity of the channel to the device was investigated with positive results of positioning the device within a tight channel to force the flow through the device. Although yielding good results within the simulation, this setup may not be as feasible on a physical model.

Project resource allowed further investigations into aspects of the device design that were not initially considered, and these are detailed in the above sections.

Completion of this project has highlighted a number of optimization points for the MOWT system. Some of these points will be incorporated into the next prototype design phase, and building the next prototype will be the next stage of development of the MOWT system. By testing a further prototype system, some of the simulation results will be further validated in an operational environment. The next prototype will allow various paddle aspect ratios to be tested as well as the ability to alter the pitch and yaw of the system during testing.

9 References

Include any literature or standards cited in the report.

1. Ehrlich, I. R., J. A. Mercier, and I. Tanaka. *Studies in hydrodynamic track propulsion*. STEVENS INST OF TECH HOBOKEN NJ DAVIDSON LAB, 1966.

10 Acknowledgements

Include any acknowledgements of key personnel who contributed to the success of the project, but are not authors of the report.

11 Appendix

Detailed data and descriptions that need to be included for context, but that are not appropriate for the body of the report, should be included as appendices.

An Appendix has been submitted with this report, showing the individual pressure, velocity, streamline and force results of the over 70 simulations run for this project, the details of which would have detracted from this report.