Chapter 6

Summary and Recommendations

6.1 Summary of Results

This research provides for a direct, empirical comparison between biological and engineering propulsion systems. An underwater vehicle was designed with the capability to produce either a steady or an unsteady jet for propulsion while maintaining the same η_{mech}, therefore allowing for an accurate comparison of the propulsive performance. It was shown that using conventional screw-based propulsion, it was not necessary to mimic the geometry and kinematics of swimming animals in order to replicate their performance provided that similar wake dynamics are generated by propulsion.

From DPIV experiments, it was reestablished that a sufficient formation time, $t^* > 0.4$, was necessary to produced isolated vortex rings. An inner shell opening of 334^o was necessary to produce a pulsed jet with vortex ring formation for the studies with a Re_j equal to 5443 and a pulsing frequency of 2.47 Hz. This inner shell geometry was selected for the propulsive performance studies. From the PLIF experiments, it was evident that the wake of the pulsed jet was larger in size in comparison to the wake of the steady jet. This increase in wake size was attributed to the entrainment of the ambient fluid into the vortex during the vortex ring formation.

Two sets of propulsive performance studies were conducted using two distinct motors of the same model. The studies were conducted using a vehicle capable of self-propulsion down a 40 m water tunnel facility. The pulsed jet configuration had a 40% average increase in Froude efficiency at higher motor speeds when utilizing the initial motor. This increase dropped by 50% when the motor was replaced due to mechanical failure. This decrease in performance resulted from the need to increase motor speed to obtain an equivalent jet speed as generated by the initial motor. This increase in motor speed led to a decrease in vortex ring formation time and, consequently, a decrease in the fluid impulse of the vortex. A model of the Froude efficiency versus vehicle speed was generated by supplying a value of 180 cm/s for U_{avg}, the expected maximum steady state jet velocity. Initial studies suggested that there may be further increases in the Froude efficiency at higher motor speeds. Experiments were conducted at higher vehicle speeds using the second motor. With increased vehicle speed, the Froude efficiency reached a maximum value of 47% for the pulsed jet configuration. This resulting Froude efficiency is close to what has been measured for biological organisms. Information as to whether the Froude efficiency would continue to increase could not be determined from the data. Further higher speed experiments are necessary.

A second metric was used to measure the propulsive performance. The total hydrodynamic efficiency was measured for the two sets of experiments. The pulsed jet acquired a maximum total hydrodynamic efficiency of 54% at a motor speed of 2887 rpm with the initial motor. A further increased total hydrodynamic efficiency was measured for the second set of experiments, reaching a value of 63% at a motor speed of 3767 rpm. Initial studies of motor speeds over 2800 rpm show a 57% increase in the total hydrodynamic efficiency of the pulsed jet in comparison to the steady jet. This increase in hydrodynamic efficiency dropped to 32% for the second set of experiments. The decrease in performance for the second motor can be attributed to a decease in the vortex ring formation time.

To determine if a trade-off exists between improved propulsive performance and power consumption, the power consumed by the motor during propulsion was measured. As the motor speed increased, the power coefficient significantly decreased for both modes of propulsion. Although the pulsed jet configuration utilizes additional power to rotate the planetary gear system, the enhanced thrust production lead to an equivalent or smaller power coefficient in comparison to the steady jet configuration using the rotating shell with the exception of two data points. The largest benefit with regard to pulsed jet propulsion power cost is at the highest motor speeds. At these speeds, the normalized power coefficient was 37% less than the power coefficient for the steady jet propulsion configuration.

Analysis demonstrated that the acceleration of two classes of ambient fluid led to an increase in propulsive performance. The first source of ambient fluid acceleration investigated was the entrained mass that was inducted into the body of the ring and convected downstream with the ring. To quantify the amount of entrained ambient fluid into the jet, the streamwise entrainment ratio was measured for both the steady and unsteady jet. The entrainment ratio was measured for two motor speeds in the steady jet configuration and three motor speeds in the pulsed jet configuration. To obtain a measurement of the entrainment ratio, the velocity profile of the jet was measured. The axial jet velocity profiles were shaped similar to a top hat for both the steady and pulsed jet modes of propulsion and for all motor speeds tested. These profiles are similar to the work of Reynolds et al. (2003) and Ho and Gutmark (1987). The magnitude of the velocity outside the jet was greater for the pulsed jet in comparison to the steady jet for a given equivalent jet speed suggesting increased fluid entrainment due to vortex ring formation.

The velocity profiles for U_x were also measured for three different motor speeds. The magnitude of the velocity U_x was significantly lower than the magnitude of the velocity U_z. As x/r approaches the jet exit, the value of U_x went to zero and maintained a zero velocity within the jet. The decrease in the velocity of U_x was expected as the direction of jet thrust coincided with the z direction. With increasing motor speed and a corresponding increase in body speed, the magnitude of U_x was shown to decrease. In general, the magnitude of the normalized value of U_x was higher for the steady jet in comparison to the pulsed jet. This result may be attributed to the pulsed jet configuration acquiring a higher body speed in comparison to the steady jet configuration with an equivalent jet speed. The root mean square velocity fluctuation in U_x, u$'$, was also calculated. The velocity fluctuations were shown to be greater inside the jet in comparison to the fluctuations in the free stream. As the motor speed increased, there was a corresponding decrease in the velocity fluctuations outside the jet exit. The magnitude of the velocity fluctuations were on the order of the magnitude of the velocity U_x.

The measured streamwise entrainment ratio was shown to decrease with increased motor speed for both modes of propulsion. The magnitude of the entrainment ratio was smaller for the steady jet mode of propulsion in comparison to the pulsed jet mode of propulsion at comparable motor speeds. The pulsed jet produced a 5.87% greater entrainment ratio at a motor speed of 2972 rpm over the steady jet at a motor speed of 2896 rpm. Despite both configurations achieving comparable jet speeds at this motor speed, the measured Froude efficiency for the pulsed jet was 26.13 and 6.58% higher in comparison to the steady jet. The increase in the total hydrodynamic efficiency for the pulsed jet was 11.2% over the steady jet. A similar result was demonstrated at the higher motor speed. The percent difference in the measured entrainment ratio does not completely account for the difference in the measured propulsive efficiencies. However, only the benefit of increased entrainment at one z/d location has been measured and taken into account. A further increase in the entrainment ratio for the pulsed jet compared to the steady jet may be evident at higher z/d ratios. Work supported by Reynolds et al. (2003), Liepmann and Gharib (1992), and Ho and Gutmark (1987) indicate a monotonicly increasing entrainment ratio in the near field of the jet for values of z/d < 10. Further measures of the entrainment ratio at higher z/d ratios are necessary to determine if a similar trend exists with the pulsed jet vehicle.

The role of the added mass effect was investigated for the purpose of increasing propulsive performance. The total impulse in the flow was shown to increase with the presence of vortex ring formation due to nozzle-exit overpressure. A model developed by Krueger (2001) was used to determine the fraction of the total impulse imparted to the flow that was contributed by the added mass effect. As the motor speed increased, the ratio of $I_p(t)/I(t)$ slowly decreased. At the lowest motor speed, the estimated pressure impulse was 7% of the total impulse and decreased to 6.5% of the total impulse at the highest motor speed. The result demonstrates that the added mass effect associated with the acceleration of ambient fluid at the initiation of a starting jet provides an increase in the total impulse, and is thus a source for increased propulsive performance.

A metric for propulsive efficiency was developed to demonstrate the relationship between the propulsive efficiency, ambient fluid entrainment and added mass. The model is sensitive to the value of C_{AM}. Choosing a value of C_{AM} for a circular disk, leads to a lower value of η_{hydro} modeled in comparison to the experimental value of η_{hydro}. Using the estimated value of C_{AM} as the shape of a fully developed vortex ring and the shape of a circular disk bound the experimental measurement of η_{hydro}. These results justify the increase in propulsive efficiency for the pulsed jet configuration in comparison to the steady jet configuration due to the increase in thrust production generated by entrained and added mass forces developed during vortex ring formation. Provided that the values of Q_{avg} and C_{AM} can be estimated, this model serves as another metric for determining the propulsive efficiency of a system. It should be noted that as motor speed increases, the ratio of $I_p(t)/I(t)$ slowly decreases, therefore contributing less to the generation of overpressure at the nozzle exit. An eventual decrease in the overpressure due to increased motor speed will decrease the amount of useful work provided for propulsion and may exhibit a propulsive efficiency comparable to the steady jet configuration. As motor speed increases, the time between fluid pulses decreases, leading to increased vortex interactions. Krueger (2005) has shown that increasing pulsing duty cycle increases the vorticity from preceding pulses near the nozzle at the ejection of each pulse. This behavior requires less fluid to be accelerated by the issuing pulse and reduces nozzle exit overpressure.

6.2 Recommendations for Future Work

Given that the research has shown that the propulsive performance of pulsed jet propulsion was superior to steady jet propulsion, particularly at higher vehicle speeds, modifications in the design of the vehicle may further enhance performance. The increase in propulsive performance was attributed to the presence of nozzle-exit overpressure due to vortex ring formation. The nozzle-exit overpressure is associated with the acceleration of the ambient fluid by vortex ring formation in the form of added mass and entrained mass. Further enhancements of propulsive performance due to increased fluid entrainment may be possible through modification of the jet exit geometry. Work by Ho and Gutmark (1987), Husain and Hussain (1991), and Husain and Hussain (1993) discovered increased fluid entrainment in elliptic jets in comparison to circular jets.

For simplicity in design, the inner rotating shell for the pulse jet configuration was geared to the propeller shaft. This design feature prevented the rotation rate of the inner shell to be set independently of the rotation rate of the propeller. As a result of this limitation, the vortex ring formation time was also dependent on the rotation rate of the propeller. It would be of interest to modify the design of the gear train to allow for variability of the inner shell rotation, and consequently, variability in the vortex ring formation time. Krueger and Gharib (2003) have shown that the total impulse follows a generally increasing trend with formation time until the leading vortex develops a trailing jet or is said to have been pinched off. Typically vortex ring pinch off occurs at a formation time between 3 and 4 (Gharib et al. 1998). It was shown in section 4.4 that there was an increase in propulsive performance attributed to an increase in the vortex ring formation time. It would be worthwhile to investigate if further enhancement in propulsive performance is attainable at higher values in the vortex ring formation time for all motor speeds.

It was apparent in section 4.4.2 that a further increase in propulsive efficiency may be possible at higher motor speeds. Due to power restrictions on the motor, higher speeds were unattainable. A significant amount of energy is also expended due to friction on the flume rails (section 3.4.5). A replacement of the roller bearing system with an air bearing system would conserve energy that would otherwise be dissipated by friction. Unfortunately, due to the 40 m length of the flume rails, the replacement of the roller bearing system is prohibitively expensive.

One objective of the research was to make an accurate comparison between the propulsive performance of pulsed jet and steady jet propulsion. The vehicle was designed to produce both modes of propulsion while maintaining the same mechanical efficiency thus allowing for an accurate comparison of the overall efficiency (η_o). Having shown that pulsed jet propulsion improves propulsive efficiency in comparison to steady jet propulsion, other mechanisms of pulsed jet generation may be explored to possibly further enhance performance and overall efficiency.