Power and Thrust Comparison of Bio-mimetic Pectoral Fins with Traditional Propeller-based Thrusters

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Abstract: A literature review, a datasheet review, and in-house experimental data were used to obtain a real-world comparison between bio-mimetic pectoral fins and traditional propeller-based thrusters. Only power consumption, forward thrust, and propulsive efficiency are compared. Scaling trends for both propulsion forms are discussed. Traditional thrusters are determined to be more efficient than currently available bio-mimetic pectoral fins for forward thrust. However, unlike traditional propeller-based thrusters, bio-mimetic thrusters can produce multiple degrees of freedom of thrust.

Keywords: pectoral fin, bio-mimetic, propeller, efficiency, thrust, MPF, UUV, robot

1. INTRODUCTION

The last decade has experienced an accelerated interest among engineers to create a new generation of nature-inspired locomotion for robotics. It was argued that the living inspirations enjoyed millennia of evolutionary optimization to become amazingly effective, and therefore represent a gold-standard of robotic achievement.

The literature offers an abundance of designs, mechanisms, and functional bio-mimetic and bio-inspired robots. However, that same literature typically lacks an objective quantitative comparison with not just the original living model, but also with other more traditional mechanisms. In order for this new generation of bio-inspired technology to supplant the more tried-and-proven traditional technologies, a scientific analysis must be made to quantitatively weigh its strengths and weaknesses.

For the last decade, our research group has investigated robotic bio-mimetic pectoral fins as an alternative form of aquatic propulsion for unmanned underwater vehicles (UUVs). The common question asked by peers has been, "Which is better: fins, or propellers?" Fins and propellers can be compared with respect to thrust and lift generation, propulsive efficiency, controllability, power consumption, mechanical complexity, cost, thrust vectoring capabilities, and stealth signatures – to name a few metrics. But these comparisons are complicated, as designs for both pectoral fins and propellers vary immensely in size, shape, and many other metrics. The question is actually too over-simplistic, asking to compare 'apples with oranges'.

The goal of this paper is to answer 'which is better' quantitatively, limiting the analysis to only the metrics of power consumption, forward thrust generation, and propulsive efficiency. Only real-world physical thrusters have been compared out of concern that theoretical models could be inaccurate or oversimplified.

2. BACKGROUND ON FIN PROPULSION

Fish have a multitude of fins used in various means for propulsion. These propulsive means are divided into two main categories: the median and paired fin (MPF) type, and the body and caudal fin (BCF) type (Webb, 1984; Gans, 1997). The BCF type relies on body undulations and/or the caudal (tail) fin. The MPF type relies on fins located on the sides and/or top of the body, such as pectoral (side) fins.

MPF can vector 3 DoF (degrees of freedom) of propulsive thrust in any desired direction (Palmisano, 2012). It is therefore holonomic so excels in maneuverability. This gives MPF an advantage over BCF in complex near-shore environments.

BCF excels at higher burst velocities (Webb, 1998; Mussi, 2002; Blake, 2004; Kendall 2007; Palmisano, 2013a; Korsmeyer 2002), and is the predominant propulsion type for long distance cruisers (Blake, 2004; Haroutunian, 2011). However, BCF is relatively ineffective at generating any thrust vector other than forward, making it non-holonomic (Palmisano, 2013a). As such, BCF type propulsion has controllability deficiencies under both low-speed and zero-speed conditions. Additionally, BCF typically requires some amount of full body undulation - making it difficult to use a caudal fin on a stereotypical rigid-body UUV.

Our long-term mission goal is to create a rigid body UUV that can operate in complex near-shore environments; therefore we focused on the pectoral MPF-type fin. Our more in-depth analysis comparing MPF and BCF for UUVs can be found in Palmisano, 2013a.

3. METHOD OF COMPARING EFFICIENCY

Propulsive efficiency is an important comparative metric for thruster design. To determine propulsive efficiency, both input and output power must to be known. The ratio of the two, output over input, is the unit-less efficiency percentage. But while input power for an electrical system can be easily determined by measuring and multiplying input current with voltage, determining output power is much more difficult.

Output power is a function of output thrust and fluidic flow. Thrust is simply measured using force transducers. But there is no available data on output fluidic flow for either the propeller or fin-based thrusters considered in this study. Additionally, the output fluidic flow for fins is highly non-uniform, structurally complex, and time varying – posing a significant challenge to accurately measure and model. Given the lack of available data for determining output power, it was not feasible to determine a unit-less efficiency.

However it is unnecessary to know output fluidic flow for determining the propulsive effectiveness of a thruster. Efficiency can instead be compared using thrust/power ratios, where a higher thrust/power ratio signifies a higher efficiency (Palmisano, 2013b). Comparative efficiency ŋ is the ratio of output thrust T divided by input power P as in equation (1).

$$\eta \approx T_{out} / P_{in} \quad (1)$$

Efficiency, although still unknown, can be compared between thrusters by using this thrust/power ratio. A greater thrust/power ratio would signify greater efficiency.

4. PROPELLOR TYPE THRUSTERS

Data for sixteen typical traditional propeller-based thrusters were gathered from manufacturer datasheets. To reduce the effects of scaling on our comparison, thrusters significantly larger than the bio-mimetic fins in the literature were not considered. Thruster weight and monetary cost, which are additional determinants of desirability, were not considered in this study.

Fig. 1 plots the collected propeller thrust and power consumption curves as reported by the manufacturers. By plotting thrust and power together, one can determine which thrusters are more efficient and more powerful. The lower and further right corner curves are more efficient than the upper and further left corner curves. In our collected data, the Crustcrawler HiFlow 400HFS (Fig. 2, left) is the most efficient thruster, while the Seamor 90W (Fig. 2, right) is the least efficient. No attempt was made to verify manufacturer data. It was not investigated whether propeller propulsive efficiency is a function of physical size and/or weight.

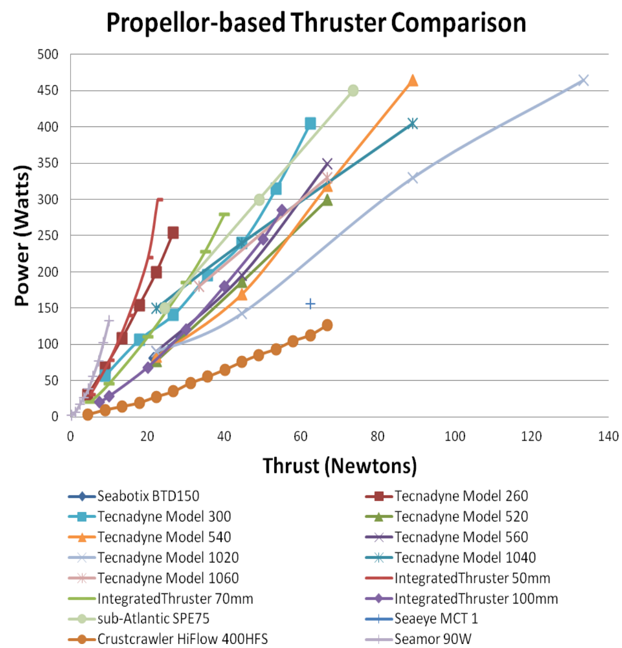

Fig. 1. Forward Thrust vs. Power consumption curves of several off-the-shelf propeller based thrusters.

Fig. 2. Commercially available thrusters:
CC HiFlow 400HF (left), Seamor 90W (right)

5. BIO-MIMETIC PECTORAL FINS

This section will review the bio-mimetic pectoral-type fins that have been considered in this study.

5.1 Pectoral fins: Gen1 v2 and v3

The Gen1 v2 and v3 fins are early unpublished proof-of-concepts we made in 2005 and 2006, and are shown in Fig. 3. Five Futaba S3150 servos actuated the rib structure to modulate the fin control surface in the same manner as described by Palmisano, 2007, while a Maxon 118752 DC motor drove fin rotation using a simulation-optimized four bar linkage. These fins were capable of very high flapping frequencies of 5+ Hz, although the fin angle had a fixed amplitude and rotation rate. Only limited thrust and power data were collected.

For both v2 and v3 versions, fin width is 4.76cm (1 7/8”), where the shortest rib is 6.35cm (2.5”), and the longest is 11.75cm (4 5/8”). Gen1 v3 weighed 355g without the fin rotation motor and platform.

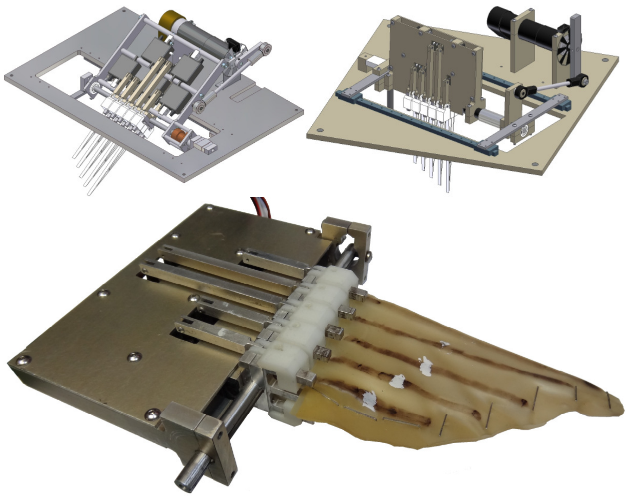

Fig. 3. The Gen1 fins: v2 (top left), v3 (top right),
v3 without fin rotation motor (bottom).

5.2 Pectoral fin: Gen1 v6

Our final generation 1 design is v6, and is shown in Fig. 4. An early iteration of it was described by Palmisano, 2007, control details are described by Palmisano, 2012, and a thrust/power/efficiency analysis of it can be found in Palmisano, 2013b. The Gen1 v6 was designed to be compact for UUV use, and has since been extensively tested on UUVs (Geder, 2008; Geder, 2009; Geder, 2011a; Geder, 2011b; Geder, 2011c). It weighs 74g without the fin rotation servos, and 137g with.

Fig. 4. The last version of Gen1 fin, v6.

5.3 Pectoral fin: Gen2

Our newer generation 2 design, Gen2 as shown in Fig. 5 and Fig. 6, incorporates the knowledge we gained from previous Gen1 designs. Although fundamentally the same, the scaled up Gen2 is different from the Gen1 designs in that instead of bending the ribs to create a shape as described by Palmisano, 2007, they are rotated as described by Geder, 2012. It was printed using proprietary ABS-like material, VeroWhite, with the Objet Connex500 3D printer. The semi-flexible Latex skin layer is attached by screws and hooks. It is actuated by four waterproof Hitec HS-5086WP (3.6 kg-cm, 0.15 sec/60°) servos, and two manually waterproofed Hitec HSR-5980SG (30kg-cm, 0.12sec/60°) servos for fin rotation. The base is 15cm long and 6.1cm diameter, while the fin is 9.14cm wide, 18.54cm long for rib 1 and 8.38cm long for rib 5. The rib rotation axis is not co-located with the fin rotation axis. It weighs 527g without the bulk fin rotation servos, and 651g with.

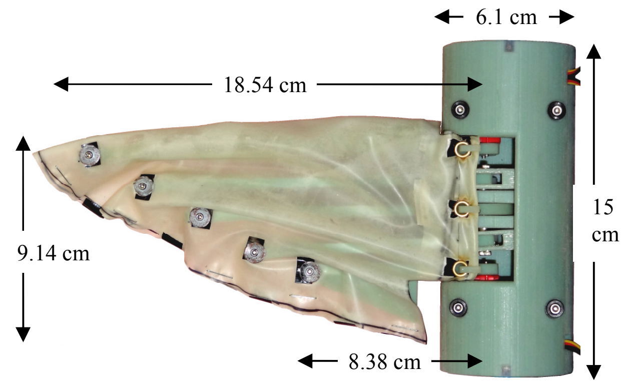

Fig. 5. The Gen2 fin.

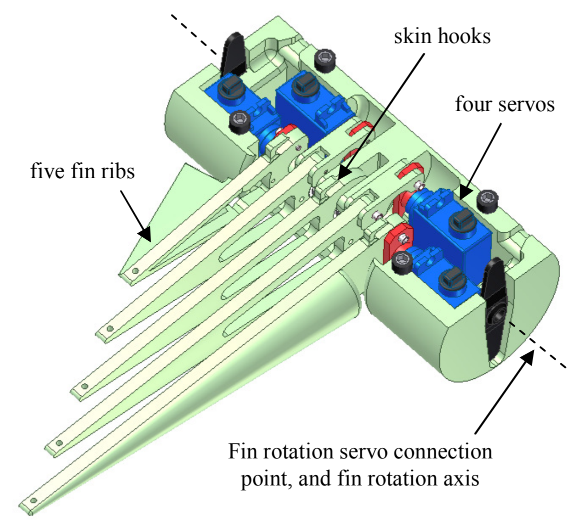

Fig. 6. The internals of the Gen2 fin.
Dual fin rotation servos not shown.

Detailed information on testing methods can be found in Palmisano, 2012. Early Gen2 results showed a propulsive efficiency improvement over the latest Gen1 v6 design (Palmisano, 2013b) by a factor of ~3x. Gen2 kinematics have not yet been sufficiently tested or refined, meaning improved kinematics could allow for thrust higher than reported in this study without increasing power consumption. Maximum measured forward thrust for the Gen2 fin is 1.1N.

5.4 Pectoral fin: the Tangorra fin

The Tangorra actively controlled curvature pectoral fin, reprinted in Fig. 7 (Gottlieb, 2010), was developed by

Tangorra and his team as a means to better study fish pectoral fins. Of all pectoral fin designs published to date it is the most biologically realistic and has the greatest number of independent actuators. Their publications list thrust production but not power consumption (Gottlieb, 2010; Tangorra, 2010; Phelan, 2010).

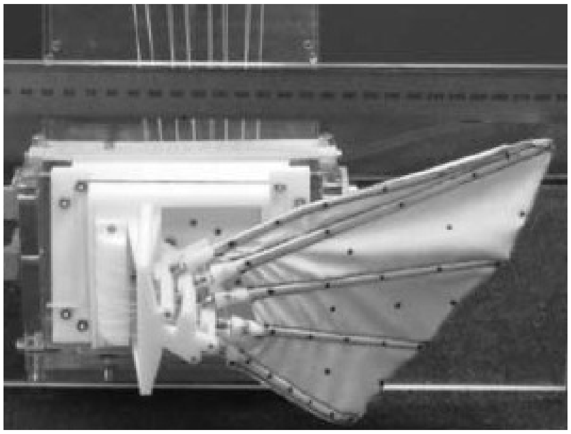

Fig. 7. The Tangorra fin,
modeled from a sunfish pectoral (Gottlieb, 2010).

5.5 Pectoral fin: Razor, rigid type fin

Beyond the complex actively controlled curvature designs, there are also simpler rigid and passively bending plate designs for pectoral fins. The rigid pectoral fin of the Razor AUV, reproduced in Fig. 8, is the most powerful of all pectoral fin-like propulsors in the literature for forward thrust. It is also the largest and heaviest, when considering all motors and electronics. The study (Beal, 2012) reported a maximum forward thrust of 12N at 30W, and a more efficient run of 10N at 20W. However, the Razor fin power draw values were reported to exclude unspecified "hotel costs," and attempts to contact the authors for clarification have been unsuccessful. Given the datasheet listed power requirements of the employed DC motors, total power consumption for an individual fin could exceed 150W. Given this uncertainty, power consumption for the Razor fin is unlisted in this comparison study. Total thrust produced by the fin is equivalent to similarly sized propeller-based thrusters.

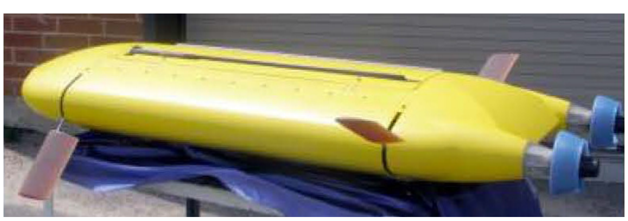

Fig. 8. The Razor AUV and fin (Beal, 2012).

5.6 Pectoral fins: Kato, rigid and passive type fins

Kato has published both rigid type pectoral fins (Kato, 2003; Suzuki, 2008) and passively flexing types (Kato, 2008; Suzuki, 2008), which are reprinted in Fig. 9. Similar fin experiments were carried out by (Liu, 2012) to determine the effect on thrust of fin rigidity on passively flapping fins.

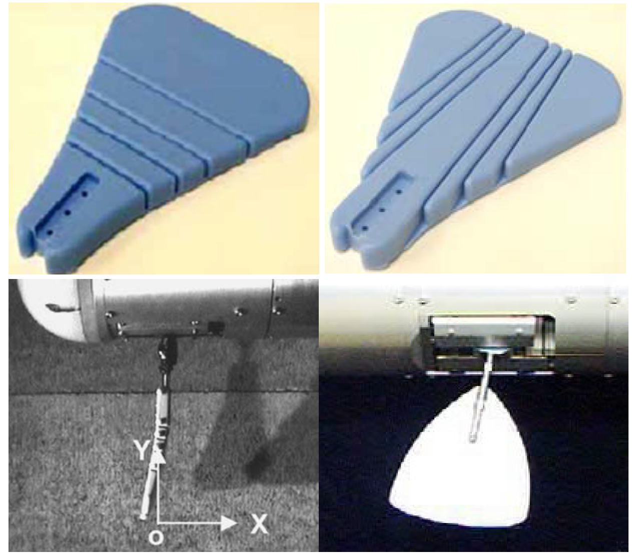

Fig. 9. left, passive flexing vertical grooves fin (Suzuki, 2008);
top right, passive flexing level grooves fin (Suzuki, 2008);
bottom right, rigid plate fin (Kato, 2003)

5.7 Pectoral Fin Results Compilation

While there are many other pectoral-like fin designs which can be found in the literature, there was insufficient thrust and power consumption data published with those works to draw any quantitative conclusions as to their propulsive effectiveness. Some publications reported an author-defined 'coefficient of power' and/or a 'coefficient of thrust,' but provided insufficient information to determine power and average thrust at zero flow rate speeds. As such we have not included those works within this study.

Works that only reported thrust, but not power consumption, are included in this study. Although conclusions towards propulsive efficiency cannot be determined, thrust can be compared. This paper did not discriminate between pectoral fin size, shape, mechanical design, kinematics, rigidity, or actuator type (DC motor, pneumatic, etc.).

Quantitative data for the previously listed fins are plotted in Fig. 10 against several traditional propeller curves for comparison. Data points located at 0 watts mean a thrust value was reported, but power data was unavailable. Point clouds exist because pectoral fins have variable power consumption and output thrust dependent on selected kinematics. Point clouds are useful in that they demonstrate how efficiency, power consumption, and maximum thrust can be traded depending on operational requirements.

Fin thrust data collected from the literature is reprinted in Fig. 11. For some fins, large quantities of data are available within point clouds. To be succinct yet still representative, only selected points where maximum thrust, maximum power consumption, and/or maximum efficiency occurred are listed.

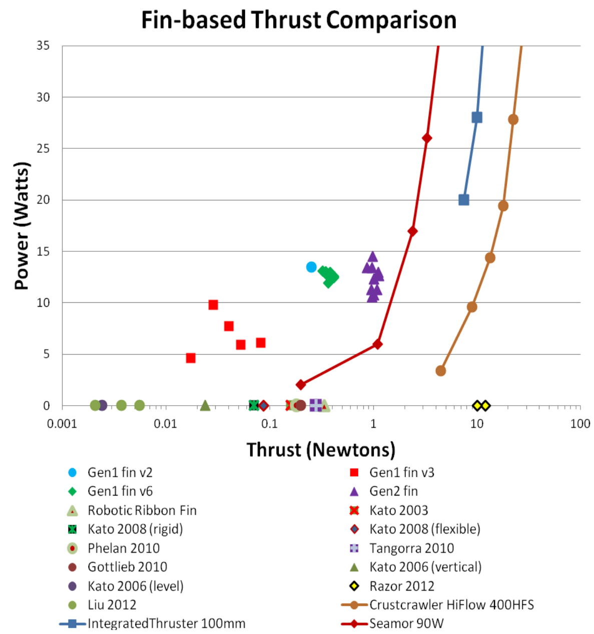

Fig. 10. Power and thrust of bio-mimetic pectoral fins compared with traditional thrusters.

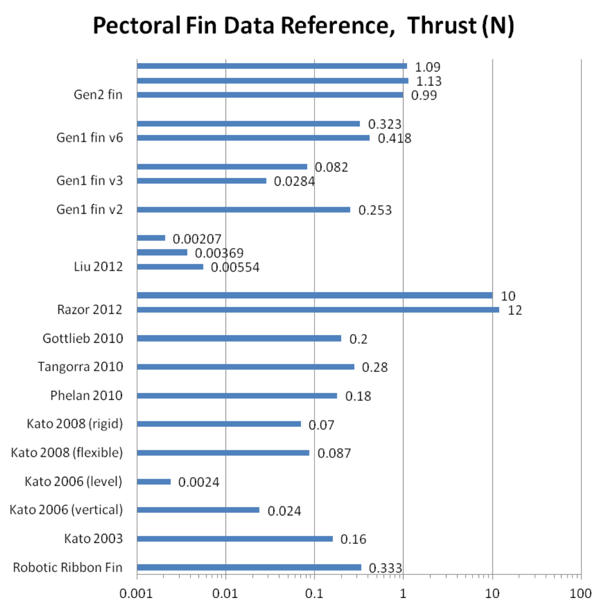

Fig. 11. Reference chart of pectoral fin thrust data.

6. DISCUSSION

6.1 Comparing Bio-Mimetic Fins to Propellers

Fig. 10 plots several thruster curves along with the data-point clouds of fin output. The lower and further right corner designs are more efficient than the upper and further left corner designs. It can be seen specifically for forward thrust that traditional propellers are more efficient than fins. However this result should *not* be misconstrued as 'propellers are better than pectoral fins.' Unlike propellers which have only 1 DoF, pectoral fins have 3 DoF (Palmisano, 2012) thereby convoluting the comparison. To traditionally vector thrust with propellers, UUVs require additional propeller-based thrusters and/or a motorized gimballing to achieve the equivalent 3 DoF thrust vectoring of a single robotic fin, with additional associated power, weight, size, complexity, and monetary costs. There is not yet enough data within the literature to compare fins to propellers on each of these other important engineering parameters. Studies are also lacking on whether fins have more desirable stealth signatures, and if using shape deformation to intelligently adapt to external flows could significantly improve fin propulsive efficiency.

6.2 On Coefficients of Thrust and Power

The literature often reported author-defined unit-less coefficients of thrust and power, and in many cases opted to not report actual fin thrust and/or power. A coefficient is defined as the ratio of an experimentally measured value over a calculated value from a theoretical model, where the coefficient is used as a multiplier to account for the difference. These coefficients are used to help predict the performance of a specific fin design under varying parameters, with the expectation that scaling effects and other difficult to model characteristics would be accounted for.

However the use of these coefficients is disputable, as no published study has demonstrated their viability and accuracy for describing a complex fin system across a range of variables. There have been no conclusive experimental studies on bio-mimetic fin scaling, and no studies at all on how coefficients for robotic pectoral fins are affected by scaling. Varying fin shape, flapping frequency, flapping amplitude, and other parameters could also have a significant effect on unique wake interactions which are not represented by these coefficients. The optimal fin curvature time-histories are directly dependent on fin shape and flapping frequency – directly affecting resultant thrust and power usage. As such, a separate coefficient for each fin gait would be required.

The use of coefficients is also problematic when comparing fin systems which vary in design. Significant differences in mechanical structure, material rigidity, skin elasticity, gearing efficiency, kinematics, actuator type (DC motor, artificial muscle, pneumatic, etc.), and power source would all affect coefficients of thrust and power.

It is for these very reasons why direct thrust and power comparisons must be used when comparing non-similar fin systems.

6.3 Which is More Efficient – Bio-Mimetic Fins or Actual Fish Fins?

Determining the comparative efficiencies of robotic fins require the use of a voltage sensor, current sensor, and force sensor, so from an engineering perspective is straight forward. However, determining efficiency of fish is not so easy.

Measuring oxygen consumption is a well known technique to indirectly measure fish energy consumption. But it does not effectively differentiate between energy solely spent towards flapping a fin and the total energy consumed by the entire fish (Webb, 1971; Stevens, 1982; Nelson, 2011). Measurement is also susceptible to various environmental conditions, body mass, diet, water quality, training, and experimental error (Fry, 1948; Stevens, 1982; Steffensen, 1989; Kieffer, 2000; Nelson, 2011). As such it is not currently possible to accurately isolate and measure solely the energy a fish expends for pectoral fin propulsion.

Measuring pectoral fin thrust production has been equally difficult. Beyond pectoral fin drag forces of dead fish (Blake, 1981), no direct (invasive) pectoral fin force production measurements have been identified within the literature. Theoretical non-invasive methods have included CFD simulations using experimentally measured fish pectoral fin motion and dimension data (Ramamurti, 2002), and using DPIV to extract force data from vorticity fields (Drucker, 1999; Drucker, 2000; Peng, 2007). Neither non-invasive technique has the capability to fully determine required energy costs.

While an efficiency comparison between current bio-mimetic fins to actual fish fins would be highly informative, the thrust and energy consumption data currently available for biological fin systems is insufficient.

6.4 The Relationship Between Thrust and Efficiency

Data for both thruster types were plotted in Fig. 12 to understand the relationship between thrust and η_{fin}. For most propeller models considered, the available data shows that traditional thruster efficiency remains relatively constant across the entire range of thrust values.

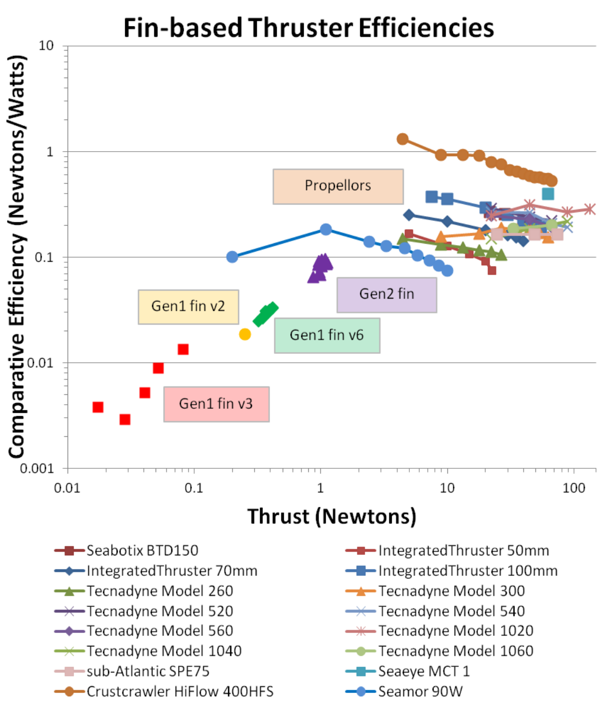

Fig. 12. A comparison between pectoral fin (bottom left data points) and traditional thruster (top right data curves) efficiencies.

Our previous work, Palmisano, 2013b, detailed the complex relationship on how flapping amplitude, flapping frequency, and kinematics affect power consumption, thrust output, and propulsive efficiency.

6.5 Clues Toward Fin Scaling

Knowledge of how scaling affects fin performance would be a powerful tool for engineers. It is currently unknown whether fins are only appropriate for small UUVs, or whether they could be effective at the very large scale such as with submarines. While there is currently insufficient data in the literature to definitively show how scaling affects bio-mimetic pectoral fins, the literature offers many clues.

The fin scaling study by Geder, 2012, experimentally showed that increasing fin dimensions by ~3x resulted in a fin with 8.5x more thrust and 7x higher efficiency. However, this result was conflated by improved mechanical design. Additionally, total fin mass had increased by ~4.7x.

The fin efficiency study by Palmisano, 2013b, showed that kinematic and fluidic energy losses were insignificant compared to efficiency losses inherent to fin actuator mechanisms. As such, fins are likely to have a thrust/power/size scaling relationship strongly matching that of how its actuating mechanisms themselves scale.

The allometric study by Palmisano, 2013a, showed that the velocity of an UUV that employs MPF-type propulsion linearly increases with both its mass and length. As UUV drag increases exponentially with velocity, this hints that fin thrust likely exponentially increases with mass and size, too.

Fig. 12 suggests that bio-mimetic fins must achieve a thrust/power ratio greater than ~0.2 N/W to compete efficiency-wise with propeller-based thrusters of similar physical size and thrust. The Gen2 fin has achieved a thrust/power ratio of 0.1 N/W. Assuming a linear scaling relationship for an individual fin, increasing Gen2 fin dimensions upwards by ~2x would result in a fin with η_{fin} and thrust matching that of a traditional propeller-based thruster. Future experiments involving a scaled up fin would be needed to validate this claim.

7. CONCLUSIONS

It has been demonstrated that traditional off-the-shelf propeller-based thrusters are more energy efficient at producing forward thrust than existing bio-mimetic pectoral fins. This is because fin propulsors trade off high propulsive thrust for the ability to dynamically vector thrust. However, the evidence suggests that the use of higher efficiency actuators and dimensionally scaling upwards has the potential to raise the fin thrust/power ratio to greater than ~0.2 N/W – allowing fins to compete efficiency-wise with propeller-based thrusters of similar physical size. Coefficients of thrust and power were determined ineffective means to compare fin efficacy of non-similar fins.

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