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INFLUENCE OF MATERIAL PARAMETERS ON THRUST CHARACTERISTICS AND PROPULSIVE EFFICIENCY IN A BIOMIMETIC UNDERWATER VEHICLE

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Abstract: The article presents the results of an analysis of the influence of material properties on the thrust characteristics and the propulsive efficiency of a wave-based propulsion system in a biomimetic underwater vehicle. The design and implementation of the study were carried out considering the advantages resulting from the application of propulsion systems based on the generation of a traveling wave along flexible propulsive surfaces. The relationship between the applied materials and the resulting thrust force generated in the aquatic environment was examined. The construction is described of the tested vehicle, its geometric and functional parameters, as well as the developed laboratory test stand enabling the execution of measurements. The results made it possible to identify material parameters that contributed to an improvement in propulsion system efficiency and an extension of the operational endurance of the underwater unit. The obtained results constitute a significant step toward the design of more efficient and durable biomimetic propulsion systems.

Keywords: biomimetic propulsion, autonomous underwater vehicle (AUV), material analysis.

1. INTRODUCTION

Unmanned maritime systems constitute a significant component of modern technologies employed in tasks related to the protection and inspection of critical infrastructure located in the marine environment [Kula & Çelebi, 2025]. Due to their autonomy and compact design, they are applied in operations conducted in the vicinity of strategic assets, including areas of deployment of opposing forces, where they can perform reconnaissance, classification, and engineering tasks. Moreover, these platforms are used for the observation of areas designated for offshore investments, as well as for the inspection of subsea transmission installations. Their design also enables the integration of specialized payloads, which in specific operational scenarios makes them a means of influence characterized by a high degree of stealth and low deployment costs.

Among the most widely available solutions, torpedo-shaped vehicles occupy a prominent position [Łarzewski et al., 2022], typically propelled by conventional propeller-based systems located at the aft section of the hull. Although they provide high propulsive efficiency, their primary drawback remains the significant level of generated acoustic noise, which limits their applicability in missions requiring reduced detectability.

In response to these limitations, biomimetic designs are being developed [Szymak et al., 2025], inspired by the morphology and locomotion mechanics of aquatic organisms. Such solutions enable the reduction of hydroacoustic signal emissions and the improvement of maneuverability, while maintaining high energy efficiency. Due to the method of thrust generation, biomimetic structures are classified into two main categories: Body and/or Caudal Fin (BCF), and Median and/or Paired Fin (MPF). In the former case, propulsion is achieved through oscillatory movements of the body or its terminal section, namely the caudal fin, typically segmented and equipped with rotational joints. In contrast, MPF systems utilize a set of horizontal and vertical undulating surfaces whose kinematics correspond to the natural motion of paired and median fins observed in fish [Piskur, 2022].

The experimental analyses presented in the subsequent part of this study were conducted using an unmanned underwater vehicle designated by the codename Nerpa, whose visualization is shown in Figure 1. The vehicle is based on a biomimetic propulsion system in which forward motion is generated by undulating surfaces oriented both vertically and horizontally, producing a thrust force. This approach enables effective horizontal maneuvering while significantly reducing hydroacoustic noise emission. Additionally, the application of horizontal undulating surfaces allows stable depth control and maintenance of the desired operational depth [Piskur et al., 2023].

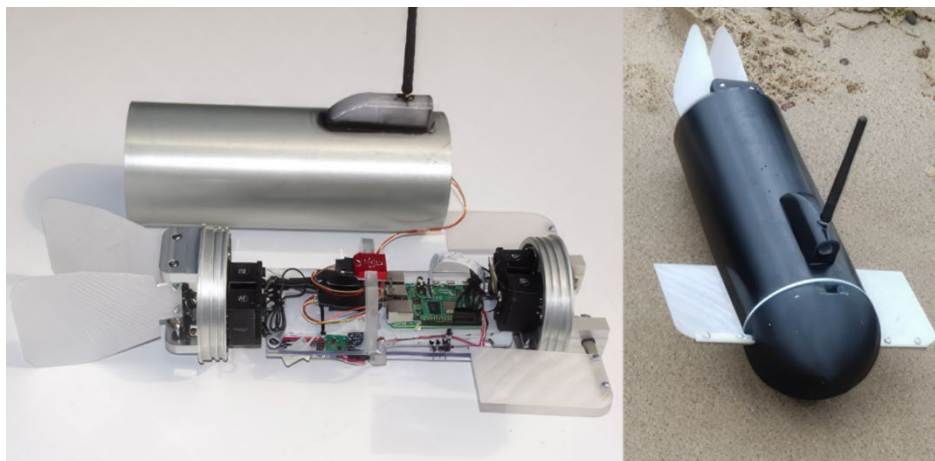


Figure 1. Biomimetic Underwater Vehicle – Nerpa

Source: own study.

2. CHARACTERISTICS OF THE UNDERWATER VEHICLE

At the stage of design and implementation of the vehicle structure, particular attention was devoted to aspects determining its operational suitability under conditions requiring a high level of stealth and reliability. The primary design objectives included minimization of acoustic signature, enhancement of the mechanical integrity of the hull, and reduction of production and operational maintenance costs. A significant advantage of the Nerpa design is its modular architecture, which enables flexible integration of additional functional subsystems, thereby increasing the level of autonomy and expanding the range of possible applications of the vehicle.

Material properties of the undulating surfaces responsible for thrust generation play a crucial role in the performance of the propulsion system [Piskur et al., 2020]. In the baseline configuration, lateral fins made of flexible polymethyl methacrylate (PMMA) were applied, whose mechanical characteristics make it suitable for use in dynamically deformable structures. As part of the conducted research, a detailed analysis of selected parameters of materials potentially applicable in the construction of propulsion elements was carried out, with particular emphasis on their influence on thrust characteristics and the overall energy efficiency of the system. The obtained results enabled the identification of material configurations of working surfaces that enhance the efficiency and reliability of biomimetic propulsion systems.

A characteristic feature of the developed design is the biomimetic wave-based propulsion system, consisting of two pairs of working surfaces moving synchronously in both the horizontal and vertical planes. This system was designed to replicate the characteristic swimming motion of seals, enabling efficient thrust generation while

simultaneously reducing the acoustic signature. Moreover, the lateral fins serve as a maneuvering propulsion system, used for stabilization and control of the vehicle, including depth regulation.

The load-bearing structure of the vehicle was implemented using a hybrid manufacturing approach, incorporating aluminum components, polycarbonate elements, and parts produced using additive manufacturing technologies. The main body consists of an aluminum cylinder, which serves as both the primary structural element and a protective enclosure for key internal subsystems. The geometric dimensions and selected technical parameters of the vehicle are summarized in Table 1.

Table 1. Technical and tactical specifications of the vehicle

Vehicle length (including caudal fins)	410 mm
Vehicle width (including lateral fins)	250 mm
Vehicle diameter	120 mm
Height (excluding antenna)	150 mm
Mass	3200 g
Vehicle operational endurance (baseline algorithm)	210 min
Actuation System for Control Algorithms	Raspberry Pi 5 / 8 GB LPDDR4X-4267 / Broadcom BCM2712 ARM Cortex-A76 64, 2.4 GHz
Control communication	2.4 GHz / 868 MHz
Maximum speed	0.5 m/s
Displacement	Positive
Operational endurance	5 h
Payload carrying capability	700 g

Source: own study.

The vehicle structure is divided into four main functional sections. In the forward section, a transmission mechanism for the lateral fins is located, enclosed within a buoyancy fairing that simultaneously serves a protective function for protruding mechanical components and provides a streamlined hull shape. Directly behind this section, a hermetic electronics compartment is situated, housing a lithium-ion battery pack, actuators for both lateral and caudal propulsion, an onboard control computer, RS232 to USB port converters, and a set of navigation sensors that includes INS and DVL. In the upper part of the hull, a dorsal module is installed, in which a vision camera, a GNSS receiver, and a communication antenna are integrated. In the aft section of the structure, the transmission mechanism of the caudal fins is located, responsible for generating forward thrust in the horizontal plane. The vehicle is designed for fully submerged autonomous operation using dead reckoning navigation. When position correction is required, periodic surfacing is performed, followed by synchronization of navigation parameters using GNSS data. Communication between

the vehicle and the shore station, defined as the mission planning and monitoring computer, is carried out via a wireless link operating in the 2.4 GHz band. Redundancy of the communication link is ensured by an additional radio channel operating at 868 MHz. Data exchange is implemented using the UDP communication protocol, which does not require maintaining a continuous connection between the client and the server. The UDP server is installed directly on the vehicle, while the client application is executed on the operator station. This approach ensures communication system stability even in the event of temporary signal loss, as communication is automatically restored once the link is re-established. The designed vehicle structure enables the transport and remote detonation of a payload with a mass of up to 700 g, which significantly extends the operational capabilities of the platform in specialized mission scenarios. The functional architecture of the control and monitoring system is presented in Figure 2.



1 – biomimetic unmanned underwater vehicle; 2 – transport case; 3 – transceiver unit; 4 – mission planning and monitoring computer.

Figure 2. Vehicle control and monitoring system

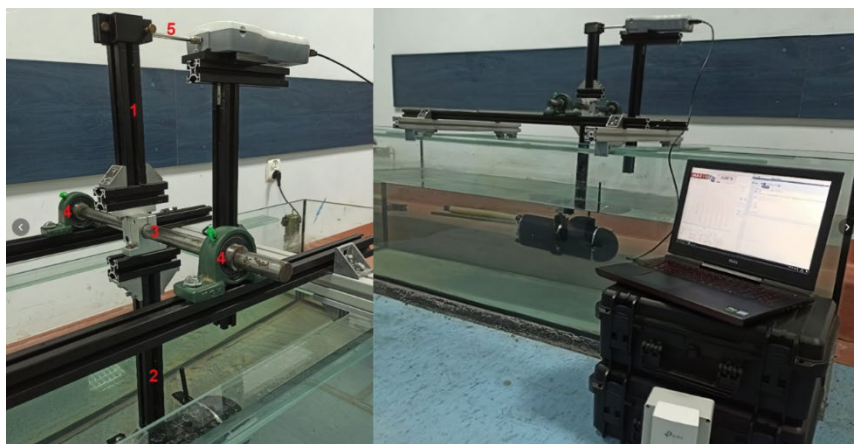
Source: [Powarzyński, 2025].

3. MEASUREMENT STATION

In order to conduct a detailed analysis of the operating parameters of the biomimetic propulsion system, a laboratory test stand was developed, enabling simultaneous measurement of the thrust force generated by the undulating surfaces and the electrical

energy consumption of the vehicle actuation system, namely the propulsion servomechanisms. Particular emphasis was placed on reproducing conditions close to real operational scenarios, while ensuring high accuracy and repeatability of the recorded data. A key aspect involved careful configuration of the experimental setup and precise calibration of the measurement apparatus.

The designed and constructed test stand, shown in Figure 3, has dimensions of 2000 mm × 600 mm × 600 mm. The structure enables direct measurement of the thrust force generated by the wave-based propulsion system, which forms the basis for further analysis of the system energy efficiency as a function of the applied propulsion materials. A lever system with a length ratio of 2 to 1 is mounted on the support arm. This system is based on a steel shaft supported by two axial ball bearings, ensuring free and stable motion within the measurement plane [Powarzyński, 2025].



1 – upper arm; 2 – lower arm; 3 – round shaft; 4 – thrust ball bearings; 5 – FC5 strain gauge force sensor.

Figure 3. Measurement station

Source: [Powarzyński, 2025].

The measurement arm is connected to a certified strain gauge force sensor of type FC5 via an MHK 101 measurement connector, enabling accurate recording of the forces generated by the tested propulsion system. To ensure stability of the tested object, a mounting clamp is attached to the lower part of the arm, maintaining the vehicle in a fixed position during operation in the aquatic environment [Zhang et al., 2024]. This configuration allows measurements to be conducted without disturbance while preserving full functionality of the propulsion system under test conditions.

The recorded measurement data are transmitted in real time to a computational unit, where they undergo further quantitative analysis. The adopted methodology enables a reliable assessment of propulsion efficiency as a function of varying material parameters.

4. RESEARCH RESULTS

Prior to the execution of the main performance measurements, a series of preliminary studies was conducted to determine the geometric parameters of the propulsion fins. The investigations were iterative in nature and included several dozen fin variants differing in length and width. In the first stage, the influence of the length of the forward fins was analyzed, starting from 330 mm and reducing it in increments of 10 mm down to 100 mm. Subsequently, the effect of width, defined as the working diameter, was examined within the range of 55 mm, 50 mm, 45 mm, 40 mm, and 35 mm. Based on the obtained measurement results, it was established that a fin configuration with a length of 150 mm and a width of 55 mm exhibited a local maximum of thrust force within the tested operational parameter range. These parameters were adopted for the main experimental study [Powarzyński, 2025].

The propulsion fins, serving simultaneously as actuation and operational elements, must satisfy a range of functional requirements. The most important include appropriate flexibility and dynamic elasticity to ensure efficient thrust generation, high mechanical durability to withstand cyclic loading, and low unit cost to enable cost-effective serial production and rapid replacement in case of wear. Taking these criteria into account, materials with diverse mechanical and technological properties were selected for the study, as illustrated in Figure 4. These include polycarbonate, polylactide, polypropylene, polyethylene terephthalate glycol modified, and polycyclohexylenedimethylene terephthalate glycol modified [Prajapati et al., 2024].



Figure 4. Fins fabricated from materials with diverse mechanical and technological properties

Source: own study.

4.1. THRUST FORCE MEASUREMENT

Based on the experimental results, which included measurements of the thrust force generated by lateral undulating surfaces fabricated from materials with diverse mechanical properties and varying thicknesses, a dataset was obtained enabling the evaluation of the influence of material parameters on propulsion system performance. The measurements were carried out under controlled aquatic conditions with identical control parameters, where the oscillation frequency was set to 4 Hz and the fin deflection amplitude to 40° [Powarzyński, 2025]. Each measurement lasted 30 seconds, and to confirm repeatability, the procedure was repeated six times for each experimental configuration. Figure 5 presents the repeatability of the conducted measurements for selected configurations.

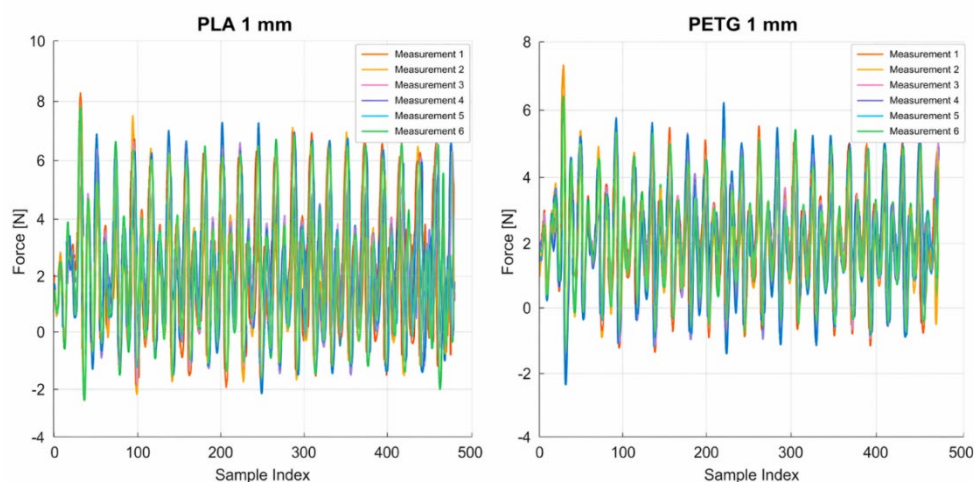


Figure 5. Repeatability of thrust force measurements for selected parameters

Source: own study.

The thrust force values obtained for individual materials and fin thicknesses are summarized in Table 2. The analysis of the presented data enables the identification of material and geometric configurations that ensure the maximum generated thrust force for the investigated propulsion system.

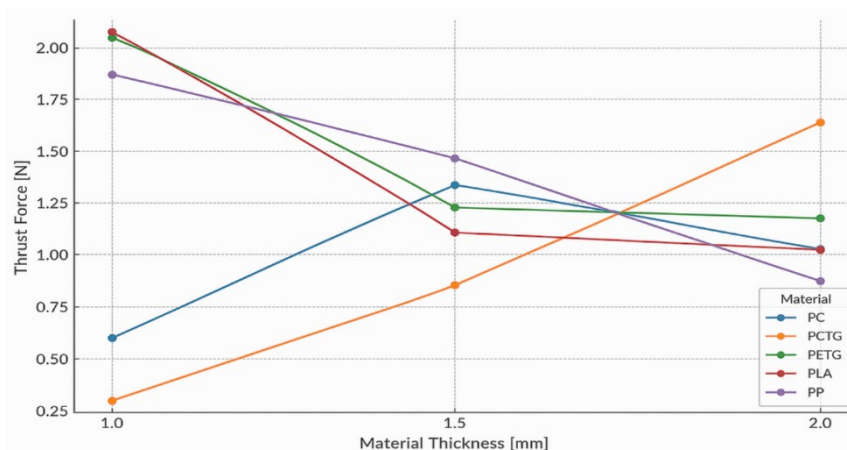
The highest thrust force values were recorded for PLA and PETG materials at a thickness of 1.0 mm, reaching 2.08 N and 2.05 N, respectively. The obtained results suggest that fins of lower thickness, while maintaining moderate flexibility and low moment of inertia, can provide favorable conditions for efficient conversion of oscillatory motion into forward thrust. For both materials, a clear decrease in thrust force was observed with increasing thickness, indicating a limitation in fin deflection dynamics resulting from increased structural stiffness. This effect is also confirmed for

Table 2. Thrust force summary

MATERIAL	THICKNESS	THRUST FORCE [N]
PC polycarbonate	1.0 mm	0.60925
	1.5 mm	1.32952
	2.0 mm	1.02654
PCTG Polycyclohexylenedimethylene terephthalate glycol modified	1.0 mm	0.31376
	1.5 mm	0.91314
	2.0 mm	1.65284
PETG Polyethylene terephthalate glycol modified	1.0 mm	2.05287
	1.5 mm	1.23080
	2.0 mm	1.19262
PLA polylactic acid	1.0 mm	2.07654
	1.5 mm	1.09545
	2.0 mm	1.01962
PP polypropylene	1.0 mm	1.85589
	1.5 mm	1.46736
	2.0 mm	0.89336

Source: own study.

polypropylene, where an increase in thickness from 1.0 mm to 2.0 mm resulted in a reduction of thrust force from 1.86 N to 0.89 N [Tangorra et al., 2010]. The nonlinear relationship between fin thickness and generated thrust force is also evident for polycarbonate, where maximum force values occur at intermediate thickness levels of 1.5 mm. This indicates the presence of local extrema associated with the resonant response of the mechanical system or an optimal compromise between stiffness and fin mass. These results are illustrated in the graph presented in Figure 6.

**Figure 6.** Thrust force as a function of material type and fin thickness

Source: own study.

A different trend was observed for PCTG, where thrust force increased systematically with increasing fin thickness, reaching a maximum of 1.65 N at 2.0 mm. This may suggest that, unlike the other materials, PCTG exhibits more favorable dynamic properties at higher stiffness levels, which may result from its internal molecular structure and inherent damping characteristics.

The obtained results for different materials indicate the necessity of precise matching of stiffness to the operating frequency. The phenomenon of tuned stiffness [Tangorra et al., 2010] confirms that the material must be sufficiently stiff to transfer loads, while remaining flexible enough to enable the structural deformation required for effective thrust vectoring [Shao et al., 2022].

4.2. ENERGY CONSUMPTION ANALYSIS

In parallel with thrust force measurements, the electrical energy consumption of the servomechanisms responsible for generating the motion of the undulating surfaces was recorded. The objective of the analysis was to determine the influence of fin material properties, in particular material type and thickness, on the energy load of the propulsion system under steady operating conditions. The measurements were conducted using identical control parameters and a repeatable operating cycle, ensuring comparability of the obtained results. The data recorded for individual material configurations are summarized in Table 3, presenting the average current consumption values over the analyzed time interval.

Table 3. Energy consumption summary

MATERIAL	THICKNESS	CURRENT [mA]
PC polycarbonate	1.0 mm	2.46
	1.5 mm	2.38
	2.0 mm	2.33
PCTG Polycyclohexylenedimethylene terephthalate glycol modified	1.0 mm	2.51
	1.5 mm	2.39
	2.0 mm	2.38
PETG Polyethylene terephthalate glycol modified	1.0 mm	2.46
	1.5 mm	2.36
	2.0 mm	2.30
PLA polylactic acid	1.0 mm	2.34
	1.5 mm	2.34
	2.0 mm	2.42
PP polypropylene	1.0 mm	2.49
	1.5 mm	2.40
	2.0 mm	2.45

Source: own study.

The analysis of the results presented in Table 3 indicates that the highest average current consumption across the entire range of tested thicknesses was observed for PCTG, particularly at a thickness of 1 mm (approximately 2.51 mA), which may indicate increased loading of the servomechanism at lower structural stiffness. The lowest current consumption values were recorded for PETG with a thickness of 2 mm (approximately 2.30 mA), as shown in Figure 7, suggesting that in this configuration the propulsion system operated under minimal load conditions. An increase in fin thickness resulted, in most cases (PC, PETG, PCTG), in a reduction of current consumption, which may be associated with improved operational stability and reduced deformation amplitude. A different trend was observed for PLA and partially for polypropylene (Figure 7), where a noticeable increase in current consumption occurred when transitioning from a thickness of 1.5 mm to 2 mm. This behavior may result from differences in the elastic and damping properties of the materials.

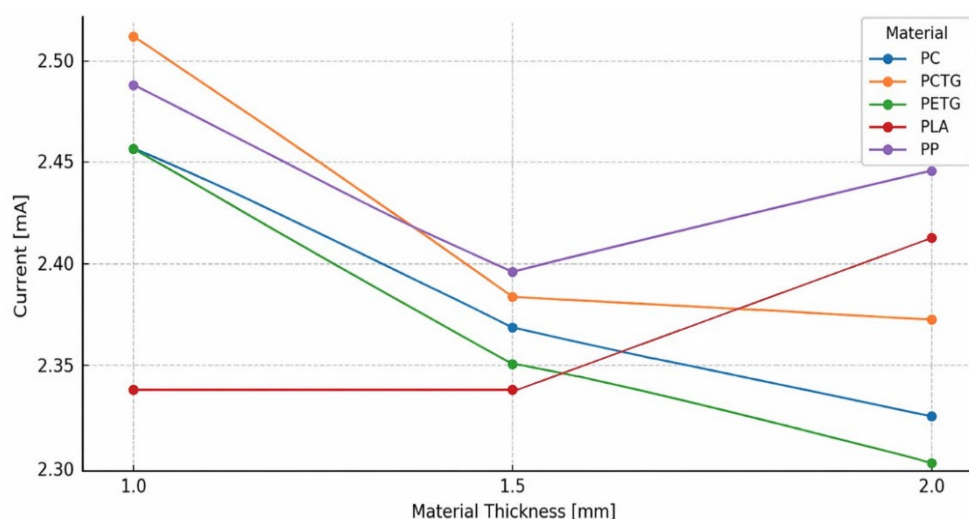


Figure 7. Energy consumption as a function of material type and fin thickness

Source: own study.

The characteristics of PC, PCTG, and PETG exhibited a monotonic and predictable decrease in values with increasing thickness. In the case of PLA, the current consumption remained nearly constant between 1 mm and 1.5 mm, followed by a noticeable increase, whereas polypropylene, after a slight decrease up to 1.5 mm, reached a higher value again at 2 mm.

The observed differences can be attributed to the varying mechanical properties of the analyzed materials, including stiffness, elasticity, and density, which determine the torque required to actuate the fin under steady operating conditions.

5. CONCLUSIONS

Wave-based propulsion generates thrust through a traveling wave of deformation propagating along a flexible surface. This approach constitutes an alternative to conventional propellers and water jet systems, offering several advantages in terms of energy efficiency, reduced signature, maneuverability, and operational safety [Li et al., 2023]. Owing to the combination of high efficiency at low speeds, precise controllability, low signature, and a safe, modular, and cost-effective design, wave-based propulsion represents a particularly promising solution for biomimetic underwater vehicles [Piskur et al., 2021]. The conducted study and resulting conclusions contribute to extending the operational endurance of the investigated vehicle design and highlight the advantages associated with the application of the analyzed materials in such propulsion systems [Piskur et al., 2023].

The experiments were performed under constant kinematic conditions and stable aquatic environment parameters. Each measurement was conducted under identical conditions and repeated six times. Fins manufactured from PC, PCTG, PETG, PLA, and PP with thicknesses of 1, 1.5, and 2 mm were analyzed, with average current consumption and average thrust force recorded. Current consumption remained relatively consistent across all configurations, ranging from 2.30 to 2.51 mA, indicating that differences in thrust primarily determine the effective performance under a given kinematic regime. The highest thrust values were obtained for PLA at 1 mm (2.077 N, approximately 887 N/A) and PETG at 1 mm (2.053 N, approximately 835 N/A), followed by PP at 1 mm (1.856 N, approximately 745 N/A). The influence of thickness was found to be material dependent. For PLA, PETG, and PP, increasing thickness significantly reduced the thrust, with decreases of approximately 51%, 42%, and 52%, respectively, when transitioning from 1 mm to 2 mm. This indicates that excessive stiffness limits beneficial undulating deformation and momentum transfer. In contrast, PCTG exhibited an increasing trend, with thrust rising with thickness and reaching a maximum at 2 mm (1.653 N, approximately 686 N/A). For PC, the optimal performance occurred at an intermediate thickness of 1.5 mm (1.330 N, approximately 559 N/A).

These results have direct design implications. For servomechanism operation at an oscillation frequency of approximately 4 Hz, PLA at 1 mm and PETG at 1 mm are recommended when maximizing thrust under constant electrical load is the priority. PCTG at 2 mm represents a viable alternative when thicker and more mechanically robust components are required, while PC at 1.5 mm may serve as a compromise solution in applications where dimensional stability and material durability are critical. In general, optimal configurations are material specific and shift with changes in effective stiffness, therefore fin thickness should be tuned to the target operating frequency and amplitude. The limitations of the study arise from the use of a single propulsion kinematic configuration and the absence of direct power balance measurements. Future work should include a systematic investigation of the influence

of material type, thickness, operating frequency, and motion amplitude, extended with power measurements and identification of system stiffness and dynamic damping. This will enable a more precise correlation between observed thrust maxima and material properties, and will further support the effective application of biomimetic propulsion systems in underwater platforms.

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