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ANALYSIS OF BIOMIMETIC CAUDAL FIN FOR PROPULSION OF AUTONOMOUS UNDERWATER ROBOTS AND RECENT EFFICIENT TECHNOLOGICAL SOLUTIONS: A REVIEW

Jaydipkumar N. Baria[1], M. J. Zinzuvadia[2], H. G. Katariya[3,]

[1]P.G student, [2]Associate Professor, [3]Assistant Professor
Mechanical Engineering Department, Birla Vishvakarma Mahavidyalaya Engineering College, Vallabh Vidyanagar – 388120, Gujarat, India

Abstract*— Biomimetic caudal fin propulsion systems is one of the topic that is catching eye of many researchers recently. Fishes have attained their outstanding swimming capabilities by undergoing natural evolution over millions of years by adapting their habitat. Taking inspiration form that, autonomous underwater robots can be designed to achieve best performances. Much work has been carried out in this direction but for a given automated underwater vehicle, the choice of appropriate caudal fin's parameters are not established yet. Notable advances has been made in understanding a few vital mechanisms of thrust generation in oscillating caudal fin but circumstances for attaining high performance and high thrust to drag ratio are not fully clear. In spite of rigorous study going on in this field, very few insights are found which leads towards a better technological solution for achieving fish like ability. This paper presents the examinations of fish locomotion, studies carried out on geometrical shapes and flexibility of caudal fin for optimal propulsion, works on fins with spanwise variable phase, different recent technological solutions adopted to mimic mechanism of thrust production in actual fishes and Wake structure of caudal fin and affecting parameters, its causes and influences on propulsion.

Keywords: Fish locomotion, Biomimetic caudal fin propulsion, Autonomous underwater robots.

I. INTRODUCTION

Science 1970's autonomous underwater robots are being developed [1]. Inspired by the capability of biological creatures in dealing with engineering challenges, biomimetic systems have become the centre of attraction in recent years. The interest here is in propulsion system for investigation class underwater-automated robots. Fishes have acquired their outstanding swimming capabilities by evolving naturally over centuries. Fins performs a dominant part in fish locomotion and various fishes have developed different fins adapting to their distinct living habitat. Fish have different fins and to swim in different modes it uses them combination. Majorly caudal fin as shown in figure. 1 is used for generation of propulsive force in majority of fishes especially the fishes swimming with Body and caudal fin mode. Differently, existing in use man-made underwater vehicles uses thrusters to generate thrust for swimming. Thrusters are simple in operation but undergoes various issues like inferior efficiency, underwater noise of high frequency, harming marine creatures, and cavitation. If fish swimming fundamentals are adapted then that can improve the existing technologies of underwater propulsion and thus let achieve a higher efficiency. Many fishes have been shown to swim with high propulsive efficiency but very rare biomimetic systems with such performance are found in the literature. This might be because of not able to understand the underlying physics of fish swimming yet.

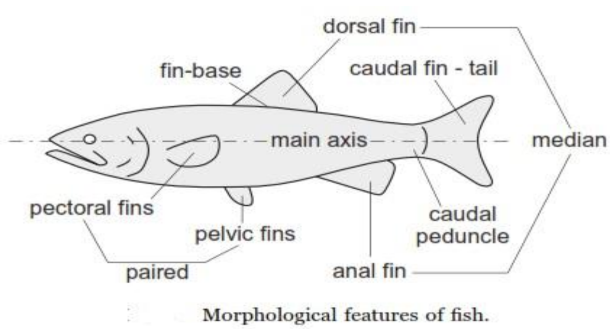

Fig. 1 Morphological features of fish [2]

A Caudal fin as shown in fig. 1 is the tail fin located at the end of fish and is used for propulsion. The swimming characteristics of fish, such as high propulsion efficiency, high manoeuvrability, low noise, and robust long duration routine have inspired human to build fish like robots [2]. Features of caudal fin has an important influence on the thrust produced and are needed to be extensively studied for optimization. This paper desires to provide the reader an ample introduction on the topics, concentrating on fish locomotion, work on geometrical shapes and flexibility of caudal fin for optimal propulsion, work on fins with spanwise variable phase, different recent state of art technological solutions adopted to mimic thrust production mechanism of actual fishes, and Wake structure and vortex generation. The actual aim is to gain basic knowledge necessary to develop underwater robot with caudal fin that is optimized to give highest propulsive efficiency.

This paper is arranged as follows: Section 2 presents a brief synopsis of fish locomotion; Section 3 shows the work done in analysing geometrical shapes of caudal fin for optimization of propulsion in literature; Section 4 Shows work on analysis of flexibility of caudal fin in literature; Section 5 presents the caudal fin with spanwise variable phase; Section 6 shows different recent technological solutions adopted to mimic mechanism of thrust production in actual fishes and finally studies on Wake structure of caudal fin and affecting parameters and its contribution to improve propulsion is shown in Section 7.

II. FISH LOCOMOTION

Water has features like high density and incompressibility, which allows any fish for swimming and balance their weight. From the vast variety of types of animal locomotion, fish locomotion is the type used by fishes, predominantly by swimming. Different groups of fish swims by different propulsive mechanisms, mostly by moving fish's body and tail in wavelike pattern, and by moving the fins in various specialised fish. There are major two types of biomimetic propulsion systems as classified by Breder namely- Body and/or caudal fin (BCF) propulsion systems and Pectoral and/or median fin (MPF) propulsion systems [2]. A fish swimming in body and/or caudal fin (BCF) propulsive mode twists its body into a backward sweeping wave, which continues up to its caudal fin. The major forms (as shown in fig. 2) of this type of locomotion in fish are anguilliform, in which a wave passes evenly along a long slender body; sub-carangiform, in which the wave increases quickly in amplitude towards the tail; carangiform, in which the wave is concentrated near the tail, which oscillates rapidly; thunniform, rapid swimming with a large powerful crescent-shaped tail; and ostraciiform, with almost no oscillation except of the tail fin.

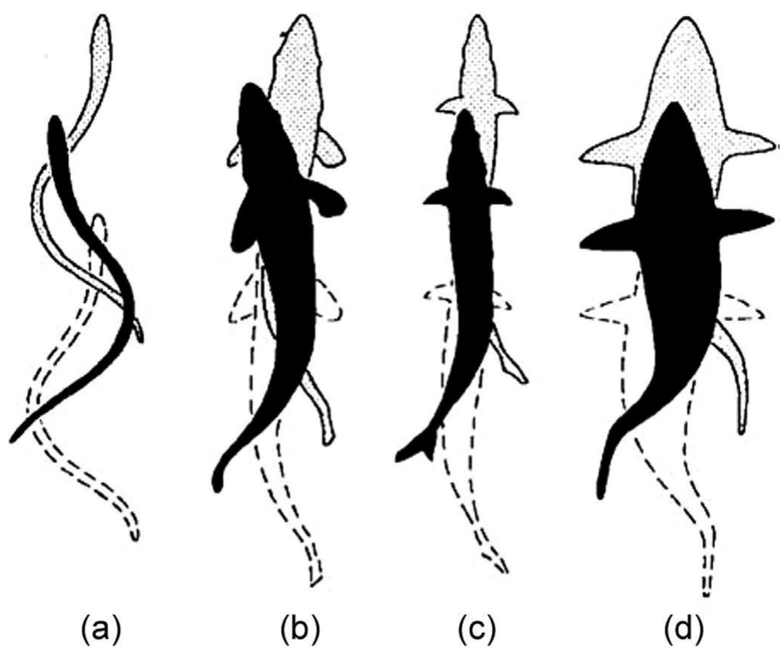

Fig. 2 Swimming modes of BCF – (a) anguilliform; (b) subcarangiform; (c) carangiform; (d) thunniform [3]

Differently, fishes swimming with pectoral and/or median fin (MPF) mode produce thrust using only their median and paired fins. Rajiform mode in which swimming by undulations of pectoral fins only; diodontiform mode in which swimming by passing undulations down broad pectoral fins; amiiform mode in which propulsion is achieved by dorsal fin undulations; gymnotiform mode in which propulsion is achieved by anal fin; and finally balistiform locomotion in which undulation of both the dorsal and anal fins in combination, generate the propulsive forces. Webb [4] categorized fish morphology in three basic optimum design, interrelating to a expertness in accelerating, cruising, and manoeuvring, as show in fig. 3; yet, it does not rule out the possibility of existence of any combinations of swimming modes.

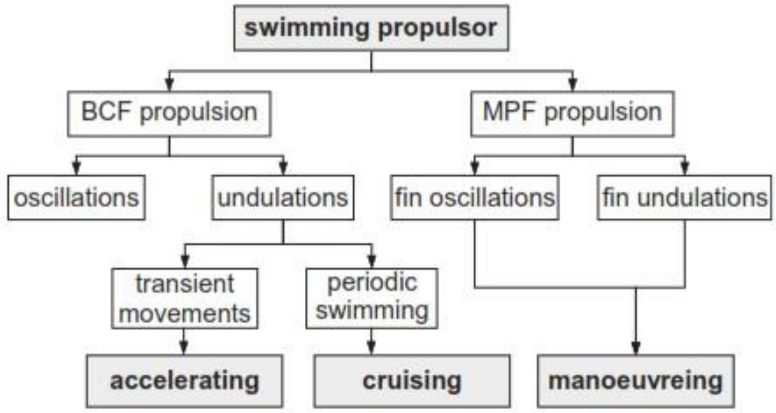

Fig. 3 Relation between swimming modes and swimming functions [4]

Uptill now known, fish produces thrust by forcing water downstream (added mass forces - hydrodynamic principle), and by creating and shedding vortices and increasing thrust from those moving downstream bygone fin surface.

Added mass effect explained as below in fig. 4: The fish twists its body by passing a propulsive wave during which every small portion (propulsive element) of body gives away part of its momentum to the enclosing fluid. Due to this the fluid exerts a reaction force F'_R, on the each propulsive element, in the normal direction to the last. The horizontal leading component of the reaction force F'_R gives thrust, at the same time the lateral component of reaction force F'_L causes the antecedent portion of the body to deflect and recoil.

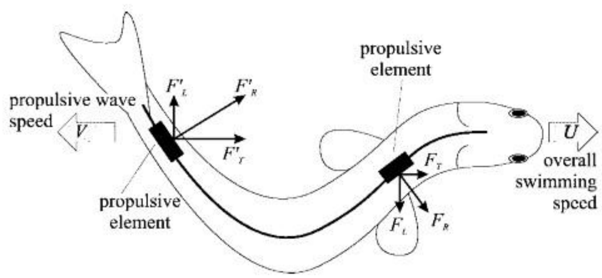

Figure 4: Thrust generation by added mass effect [4]

III. STUDIES ON GEOMETRICAL SHAPES OF CAUDAL FIN

Variety of caudal fin shapes are found in nature. In order to achieve propulsive efficiency like fish, study of effects of shapes of caudal fin are necessary. J. M. Anderson[5] studied thrust-producing harmonically oscillating foil through efficiency estimation by measuring force and power and visualization data by DPIV, to classify the fundamental characteristics of the wake structure behind foil. Visualization data were collected at Reynolds number 1100, and force and power data were measured for a flow with Reynolds number 40 000. High propulsive efficiency of 87% was obtained through experiments under conditions of optimal wake formation. Circumstances for optimal production of thrust were found as follows: Operation at Strouhal number among 0.25 and 0.40; large amplitude of heave motion-to-chord ratio (of order one); large maximum angle of attack, between 15 and 25 degrees; heave lags pitch by about 75 degrees when the reference point for heave motion is at the one-third chord length from the leading edge [5]. However, they performed the analysis for a single delta shape foil only.

ZHANG Xi, SU Yu-min and WANG Zhao-li [6] studied the effect of the caudal fin’s shape on the propulsive performance of a caudal fin in performing heaving and pitching motion. Three shapes as shown in fig. 5, were compared differing in aspect of projected area- the whale caudal fin with the largest projected area, the dolphin caudal fin with the intermediate projected area, and tuna caudal fin with the smallest projected area, by conducting numerical simulations and hydrodynamic experiments. The numerical simulation was conducted based on unsteady panel method. Hydrodynamic experiment were performed in a circulating water channel, to provide the incoming flow with constant speed. With increase in strouhal number St from 0.25 to 0.38, the mean thrust was found to be increasing and the efficiencies was found to be decreasing for all 3 shapes. The maximum thrust coefficient was found for the fin with the largest projected area and vice versa, while maximum efficiency of 79.8% was found at St = 0.25 for tuna caudal fin shape as shown in fig. 6. Here it can be clearly observed that projected area has an influence on thrust production and propulsive efficiency, but geometrical features of shape were not related directly with propulsive performance.

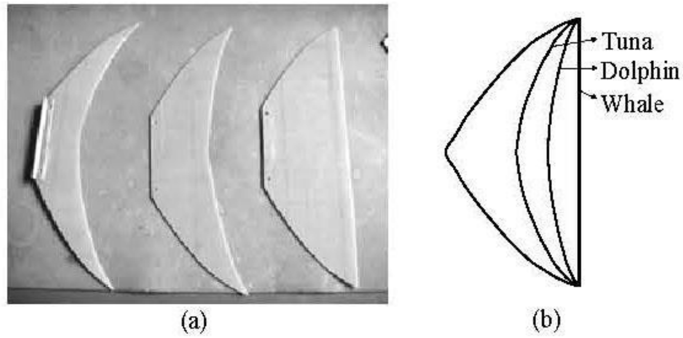

Fig. 5 Three caudal fin shapes [6]

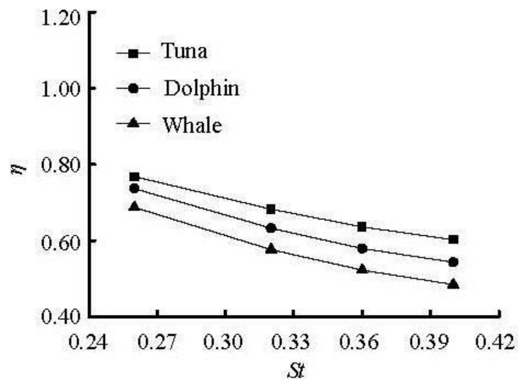

Figure 6: Comparison of Tuna, Dolphin, and Whale fin efficiencies for various Strouhal numbers [6]

Geder[7] designed a bio-inspired robotic fin and analysed it for underwater propulsion. Computational Fluid Dynamics and experimental analysis were carried out. Examination performed by Geder[7] revealed that with the increase in surface area of fin, there is a threefold increase thrust production.

Krishnadas at el.[8] compared different Caudal fin shapes having same surface area but varying particularly in fin's delta angle and their amount of forking, in the conditions suitable for small bio-inspired vehicles through numerical simulation. First by performing 2D simulations, Strouhal number range (0.2 to 0.3) for large efficiencies was obtained. 3D simulations were performed using the obtained range and highest propulsive efficiency was found near to strouhal number value of 0.25 [8]. Lower leading edge angle was found to generate vortices, which were able to grow quicker and also separate earlier resulting in producing low pressure for high thrust by consuming high power while for same leading edge angle, the effect of forking was found to reduce thrust. Highest propulsive performance was obtained for an intermediate shape having limited caudal peduncle and little forking [8]. They did not carried out any experimental work. Validation was done on basis of existing literature, that also of the delta shape only.

Thus very few works are found on shapes of caudal fin and works directly relating shape parameters to propulsive efficiency are very rare. Also experimental work focused on this topic is yet to be carried out for fin optimization.

IV. STUDIES ON FLEXIBILITY OF CAUDAL FIN

Flexibility of the fish's fin has a great influence on thrust production still very rare works (numerical as well as experimental) were found on this topic. Lauder [9] found that Continuous thrust production is due to fin flexibility which enables some part of the fin to generate thrust at all times and to smooth out oscillations that might arise at the transition from outstroke to instroke during the movement cycle. In study of Esposito [10] thrust was maximized when stiffness was increased 500X stiffness fin rays and lift was maximized when stiffness was increased 1000X stiffness fin rays. The hydrodynamic performance of the flexible fin is better than that of the rigid fin for low flow velocity while the reversed situation occurs for high flow velocity [11]. Body stiffness modulation and its effects were studied by Ardian Jusufi [12] using pneumatic soft actuators. The contractions and co-contractions leading to stiffness modulation of pneumatic actuator were found to affects thrust production and short co-contractions were found to help in rapid acceleration. Srinivasa Reddy N, Soumen Sen, Chandan Har [13] conducted numerical optimization study using ternary search method to investigate on the flexibility distribution of trapezoidal fin giving maximum thrust force(refer fig.7). He found that maximum thrust is generated when the fin has varying flexural stiffness distribution along its chord, stiffer to softer, starting from the joint (proximal) leading towards tip (distal) respectively [13]. Srinivasa Reddy N [13] also carried out experiments with 12 trapezoidal fins with varying flexure stiffness distribution and found that a fin with the optimal flexural stiffness distribution showed improvement in propulsive force production than a uniform thickness fin. Also Yong Zhong[14] suggested that for robotic fish swimming with different modes should have fin with different flexibility as it is a parameter governing the locomotion mode.

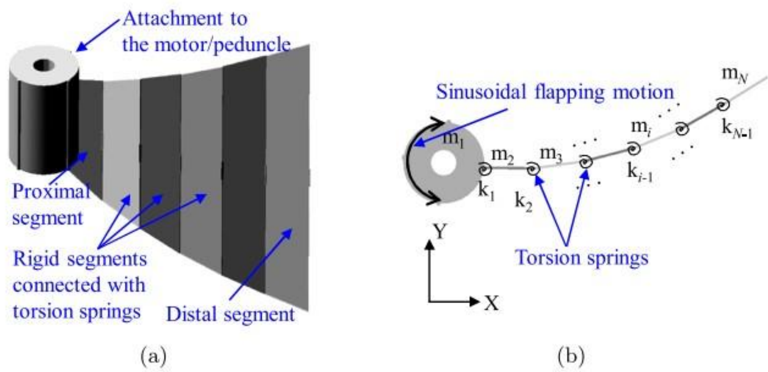

Fig. 7 (a) Segmented model of the varying flexural stiffness fin (b) Top view indicating torsion springs [13]

Ternary search method to find optimal flexural stiffness of a fin

In this optimization technique, first, the fin is divided in to number of segments, say 6 segments and a stiffness range say $[k_l; k_u]$ is considered for each fin segment. Now each stiffness range is divided into number of equal number of partitions, say three. Thus, this creates four different values of stiffness for each fin segment $[k_l, \acute{k}_l, \acute{k}_u, k_u]$. Here, the subscript l stand for the lower extent while the subscript u stand for the upper extent. $\acute{k}_l$, $\acute{k}_u$ are the equi-spaced values of stiffness in middle of k_l and k_u [13]. Thus for 6 segments of the fin considered, 4^6 possible combinations of stiffness profiles are obtained. Now, the maximum mean thrust force per cycle is investigated numerically for a particular stiffness in each segment and based upon the respective values of stiffness, one of two, lower portion $[k_l; \acute{k}_l]$ or the upper portion $[\acute{k}_u; k_u]$ of the range is scrapped [13]. If the lower part is scrapped, then the new stiffness range becomes $[\acute{k}_l; k_u]$ and if the upper part is scrapped, then the new stiffness range becomes $[k_l; \acute{k}_u]$, which is then considered for the following iteration. If there arises a unique case in which $[k_l; \acute{k}_l]$ and $[\acute{k}_u; k_u]$ both are found to produce same maximum mean thrust force then $[\acute{k}_l; \acute{k}_u]$ is established as the new stiffness range [13]. The investigation for optimal stiffness characterization is carried on with the revised stiffness ranges as far as the stiffness range under examination turns too confined and reaches a picked tolerance value.

V. STUDIES ON FINS WITH SPANWISE VARIABLE PHASE

Dongwon Yun [15] proposed a novel waving caudal fin with vertical phase differences as shown in fig. 8, for a robotic fish and carried out theoretical analysis for the reaction torque and thrust force. The swimming of a robotic fish with vertical phase differences (i.e., $p = 2\pi$) was found 78.6% faster than that with a plate type caudal fin (i.e., $p = 0$) for the same output power of the motor[15]. The caudal fin with a specific shape factor fig. was found to improve the motion stability of a robotic fish under water by reducing the reaction torque significantly.

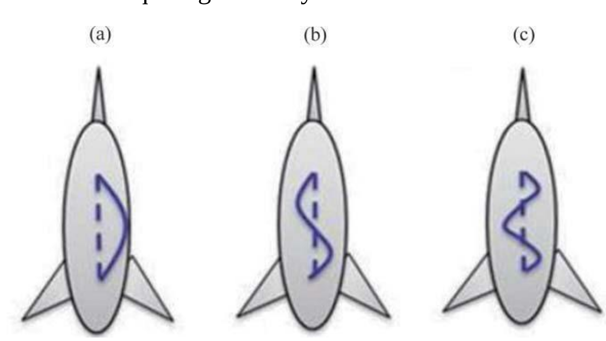

Fig. 8 Shapes of waving caudal fin with vertical phase differences: (a) $p = \pi$. (b) $p = 2\pi$. (c) $p = 3\pi$.

Esposito [10] developed and studied six fin-rayed robotic caudal fin employing data acquired from biological studies of a bluegill sunfish. Five caudal fin motion programs were identified from the swimming behaviours in a bluegill sunfish, and were utilized to program the collection of kinematics: flat motion of the full fin, cupping motion of the fin, W-shaped motion of fin, fin undulation and rolling motions as shown in fig. 9 [10]. Thrust and lift forces were found to increase with increasing flapping frequency. During 84% (21 out of 25; $P<0.001$) of comparable trials, the mean thrust force produced by both the symmetrical and asymmetrical movement were found smaller than those produced by the cupping motion. The forces in the three symmetrical movement – flat, W, and cupping were majorly found along the direction of thrust and the mean of the magnitude of the thrust force over a cycle was found 4% more than that of mean of the magnitude of the lift force. In asymmetrical motions, both lift and thrust were found of similar magnitudes.

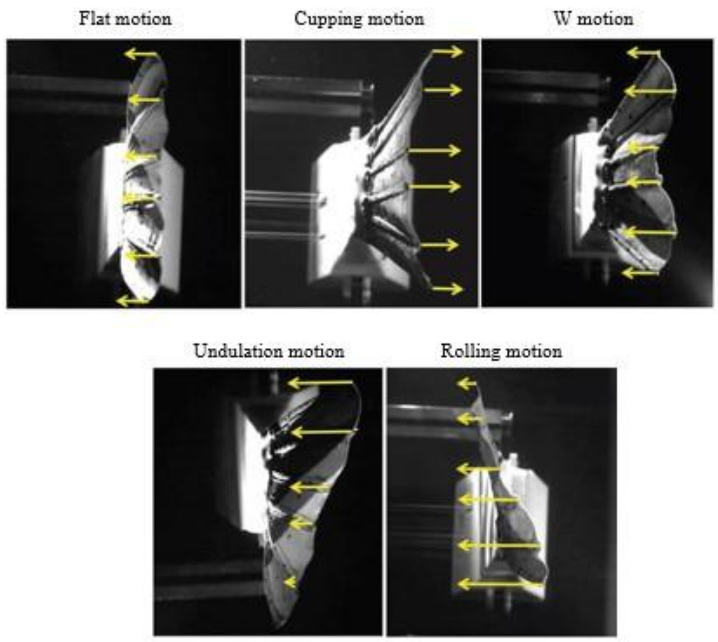

Fig. 9 movement programs for the robotic caudal fin based on observed sunfish caudal fin kinematics [10]

Dongwon Yun [16] studied robotic fish with waving caudal fin that exhibits spanwise variable phase. Variable phase or phase differences in fins means that each subfin oscillates with same amplitude and frequency but different phases in rotation angle thus by adjusting rotation angle properly, smooth waving motion can be generated in fin as shown in fig. 10. For this, a caudal fin composed of horizontally narrow subfins such that each fin oscillates with a different phase was considered. An equation to calculate the thrust of a caudal fin with spanwise variable phase by dividing the velocity of a mass of water into two directions was developed and used to identify the thrust difference between a plate-type caudal fin and a waving caudal fin with spanwise variable phase [16]. The thrust produced by spanwise variable phase fin was found lesser than plate-type fin but it didn't vary much at a particular flapping frequency while plate-type fin produced thrust that varied much at a particular flapping frequency, refer fig.11.

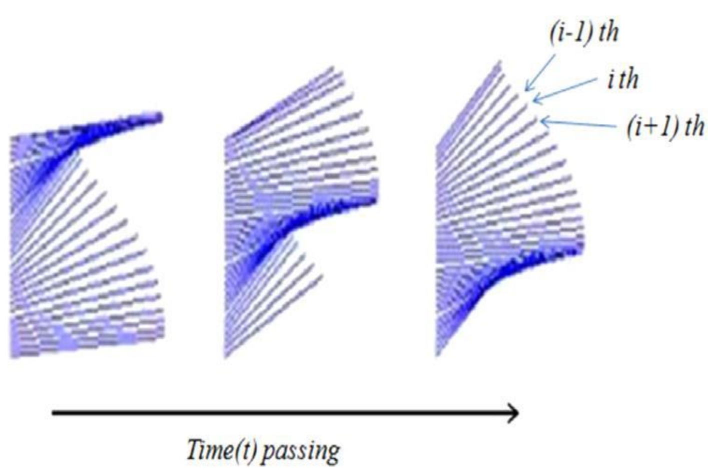

Fig. 10 The concept of a waving caudal fin with spanwise variable [16]

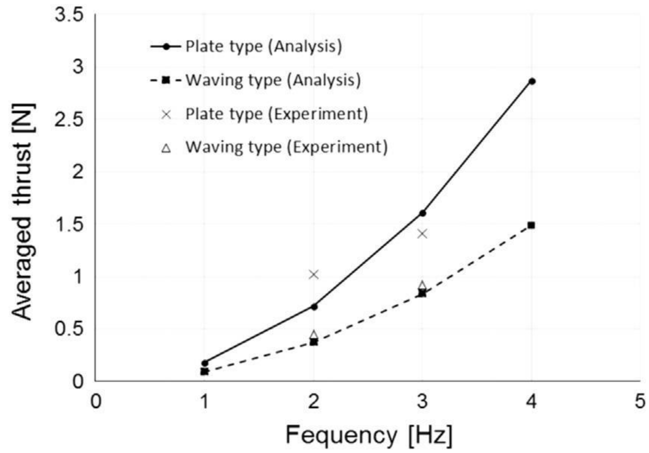

Fig. 11: Thrust comparison between theory and experiments of waving caudal fin and plate type caudal fin [16]

VI. DIFFERENT RECENT TECHNOLOGICAL SOLUTIONS EMPLOYED IN BIOMIMETIC UNDERWATER VEHICLES TO EXPLOIT FISH PROPULSION MECHANISM.

The Following section describes few recent technological solutions employed in biomimetic underwater vehicles to exploit fish propulsion mechanism and to achieve better propulsive efficiency.

Rahulkumar [17] developed the trevally crescent-shaped caudal fin fish, based on the biological observation and bionic research, established the fish swimming model of trevally crescent shaped caudal fin mode, and designed the three degrees of freedom, tail- tail fins - pectoral fin, robotic fish based on carp fish. Straight swimming and turning movement was achieved by tail composed of two DC motor-driven linkage joints while the rising and diving movement was achieved by a stepper motor as pectoral fin.

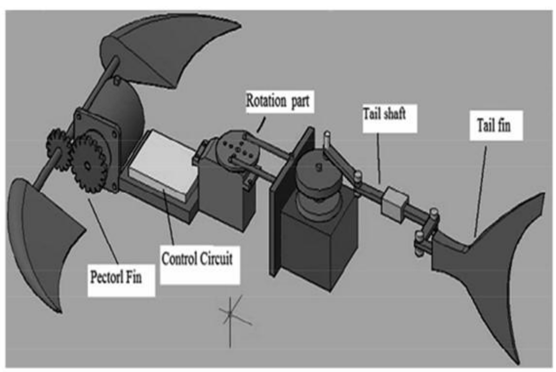

Fig. 12 structural design and control system [17]

Xingyu Chen [18] developed a magnetically actuated 89 mm long robotic fish shown if fig.13. Through law of electromagnetic induction, the corelation among current and magnetic induction intensity was analysed and utilised in the control mechanism. Also a new unique tail-beat rhythm for the magnetic actuator was suggested. The miniature robotic fish was found to achieve a highest speed of 171.05 mm/s at the tail-beat frequency of 10 Hz.

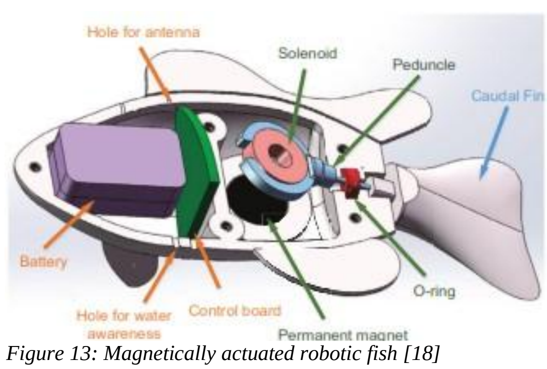

Figure 13: Magnetically actuated robotic fish [18]

Florian Berlinger [19] designed autonomous underwater robot with multiple flapping fin capable of high maneuverability with use of low-cost magnet-in-coil actuators. The MIC propulsors as shown in fig.14, reduced the mechanical complexity compared to traditional rotary shaft actuators by eliminating the need for a shaft exit through the watertight hull. It also reduced the overall cost because of the low-cost of $1 per propulsor.

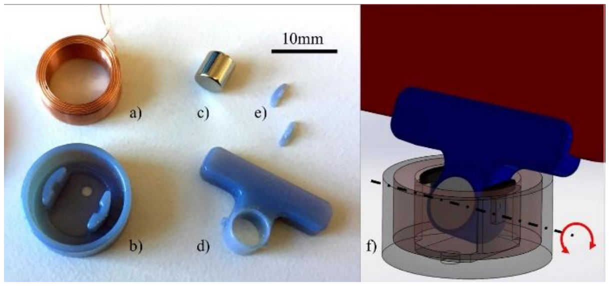

Figure 14: MIC propulsor [19]

Jun Shintake, Aiguo ming, Makoto Shimojo [20] developed a flexible caudal fin propulsive underwater robot, that moved at high speed producing large propulsive force. Also, pitch and roll motions were achieved by affixing two pectoral fins on the robot. Piezoelectric fibre composite, namely Macro Fibre Composite (MFC) was used to actuate the underwater robot. William Coral(William Coral, Rossi, Curet and Castro, 2018) developed a robot that is composed by a deformable structure and muscle-like linear actuators based on shape memory alloys wires.

More advancements are currently being made for creating autonomous soft-bodied robots capable of rapidly achieving continuum-body motion. Andrew D. Marchese [22] described design, modelling, fabrication, and control of the soft robotic fish, concentrating on facilitating the robot to perform quick escape responses. The fish was designed to mimic escape responses along with forward swimming of fish because such manoeuvres require quick body accelerations and continuum-body movement. Here fluidic elastomer actuators with pneumatic control mechanism were used. Fluidic channels as shown in fig.15 were created which were filled and emptied necessarily and hence fish continuum body movement was achieved.

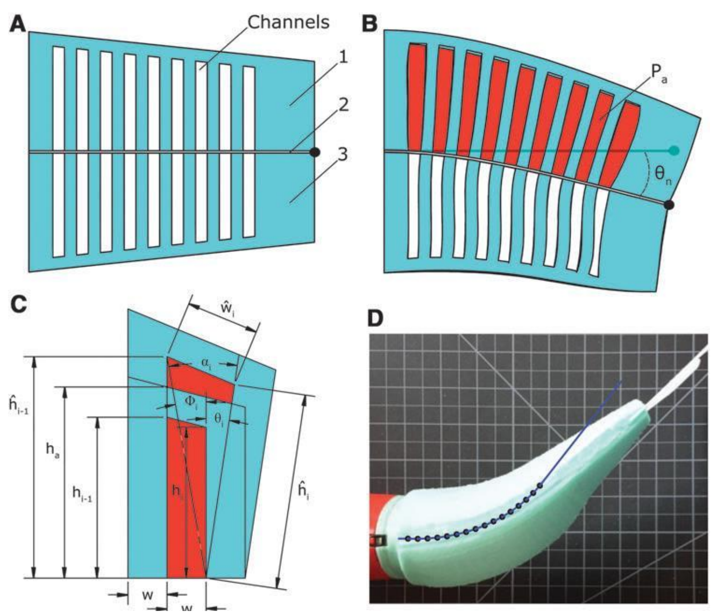

Fig. 15 Pneumatically controlled fluidic elastomers [22]

Robert K. Katzschmann (Katzschmann, Marchese, Rus - 2016) developed hydraulically actuated an autonomous soft-bodied robotic fish which possessed the capability of sustained swimming in all three dimensions. A rib structure (fig. 16) was developed from fludic elastomers for expansion and contraction of the thin exterior skin influenced by positive and negative hydraulic pressure respectively and total of these expanding or contracting movements lead to deflection of the inextensible central constraint layer.

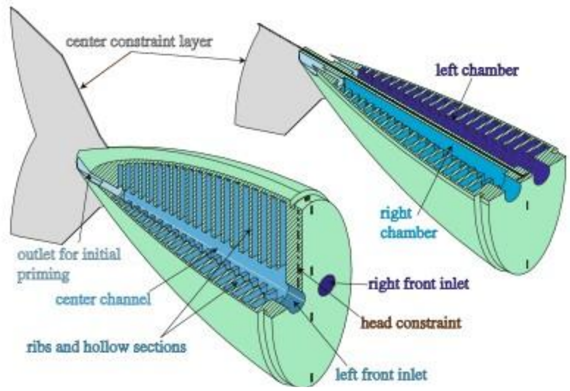

Fig. 16: hydraulically actuated soft robotic fish body features [23]

Jun Shintake [24] developed a soft biomimetic robotic fish (fig. 17) based on dielectric elastomer actuators (DEAs). The robot consisted of laminated silicone layers on which two DEAs were placed in an opposing arrangement, which generated undulating fish-like movement. The design of the robot was governed by a mathematical model based on the Euler–Bernoulli beam theory which takes in to consideration, the non-uniform geometry of the robotic fish and the hydrodynamic effect of water [24].

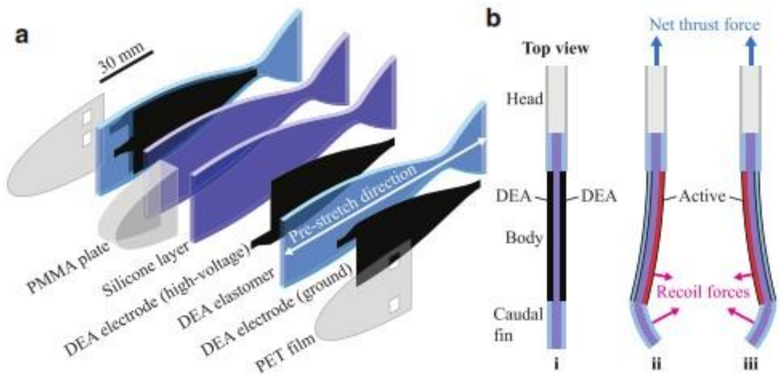

Fig. 17 Soft automated robotic fish utilizing dielectric elastomer actuators (DEAs) [24]

Li Wen [25] found that erecting the soft dorsal/anal fins significantly enhanced the linear acceleration rate by 32.5% over the folded fin state using an undulatory Biorobotic model with soft fluidic elastomer actuated by Morphing Median fins. Median fins was found to enhance axial force produced by the biomimetic robotic fish during the initial acceleration stage.

VII. WAKE STRUCTURE OF CAUDAL FIN AND AFFECTING PARAMETERS

The wake structure behind a fish fin is consists of vortices lagging behind, walking falteringly with alternating sign. As shown in fig. 19(a), Karman Vortex Street is formed by vortex shedding in wake behind blunt objects for a particular range of the Reynolds number. The rotational direction of vortices in the wake of fish caudal fin is the opposite of the one displayed by vortices within the Karman Vortex Street back of blunt objects, as it is shown in Fig. 18.

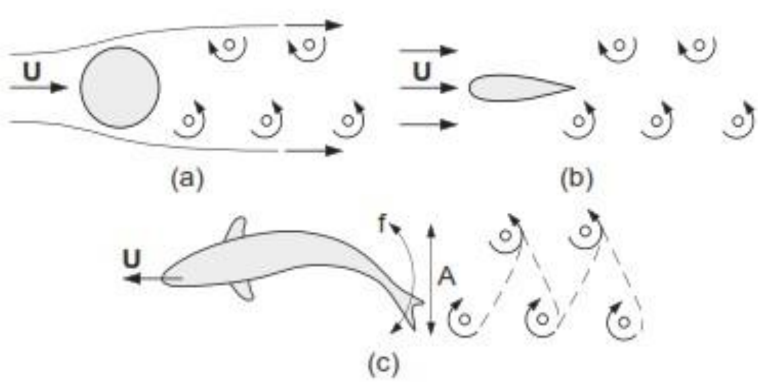

Fig. 18 Wake structure of a swimming fish caudal fin and a blunt object or a streamline object [2]

In Fluid dynamics, the Strouhal number St is a non-dimensional parameter used for defining oscillating flow mechanisms. It represents a major of ratio of inertial forces due to unsteadiness of flow or local acceleration to the inertial forces due to change in velocity from one point to another point. Mathematically it is described as

$$St = \frac{f}{U} A$$

where f is fin frequency, U is average swimming speed/flow speed and A is amplitude of oscillation. Heathcote, S., Gursul [26] based on their water tunnel experiments on chord-wise flexible flapping aerofoil, showed that if laminar flow at Reynolds number 2000 is assumed then results on experimental mapping of propulsion parameters of a oscillating foil compare agreeably against simulation results. Also thrust coefficient and propulsive efficiency were found to be functions of Strouhal number. Tryantafyllou (Triantafyllou, & Yue, 2000),Anderson [5] found that thrust production in flapping foils is maximum for a particular range of St, given as 0.25 < St < 0.35. D. Costa et al.[28] performed numerical analysis of an oscillating foil and developed an ostraciiform fish model with the foil hinged to it by a revolute joint. The obtained results showed that foil propulsive thrust and efficiency could be anticipated and appropriately set in bio-inspired thruster design, as a function of the Strouhal number and flapping amplitude. Thus strouhal number becomes an important parameter for analysing biomimetic propulsion.

Kai Zhou, Junkao Liu and Weishan Chen [29] conducted numerical simulations to reveal the hydrodynamic mechanism of caudal fin propulsion. In the modelling of a bionic caudal fin, a universal kinematics model with three degrees of freedom was adopted and the flexible deformation in the spanwise direction was considered. The results showed that the caudal fin can get thrust force due to the self-motion and vortex rings existing in the wake. Borazjani and Daghooghi [30] presented the first evidence of the vortex reattachment at the leading edge of the fish tail using three-dimensional high-resolution numerical simulations of self-propelled virtual swimmers with different tail shapes. The results showed that the evolution of the LEV drastically alters the pressure distribution on the tail and the force it generates. They had also found that LEV creation is seen in the wake of rectangular fins and that trapezoidal shapes are superior considering the stabilization of LEV's for thrust generation. At Strouhal numbers at which most fish swim in nature (approx. 0.25), an attached LEV is formed, whereas at a higher Strouhal number of approximately 0.6 the LEV does not reattach [30].

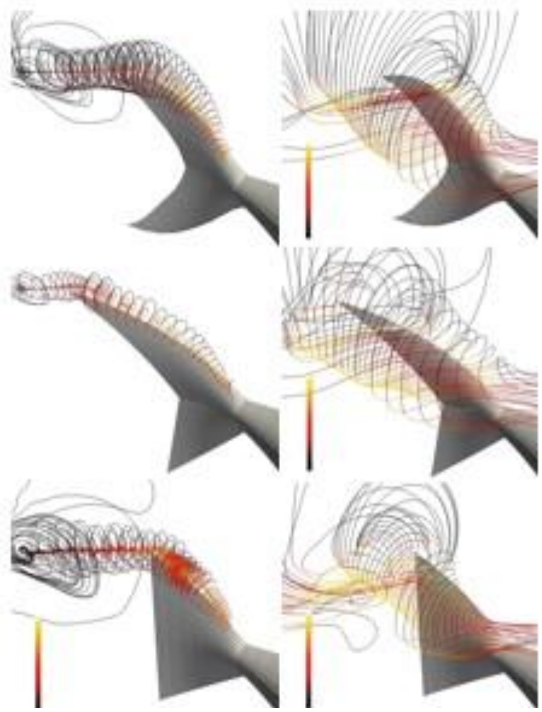

Fig. 19 the flow near the tail in the inertial regime (St 0.25); the flow near the tail in the transitional regime (St 0.6)[30]

The presence of a leading-edge vortex is also strongly influenced by the angle of attack [5]. Given the amplitude-to-chord ratio h_o/c, when the angle of attack crosses a inception value, leading-edge vortices are formed. Region C in fig. 20, (region of optimal efficiency) hold by the boundaries $7 < \alpha_{max} < 50$ and 0:2 < St < 0.5, forms clear reverse Karman street. A leading-edge vortex is formed for angles of attack greater than about 10 degrees, which grows in terms of strength with increasing angle of attack [5].

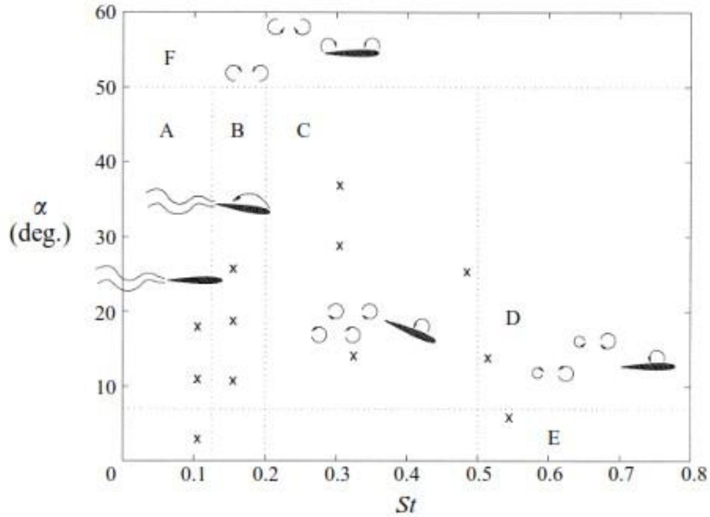

Fig. 20 Wake patterns as function of the Strouhal number and angle of attack for h/c=1 [5]

VIII. CONCLUSION AND FUTURE PROSPECTS

This paper presents detail insights of fish locomotion, the effects of caudal fin geometrical shapes and flexibility on propulsion, the effect of span-wise variable fins, recently developed biomimetic technologies and the parameters affecting wake structure and vortex generation. The propulsive efficiency of automated underwater robots can definitely be increased by studying swimming modes of fish, optimizing caudal fin parameters and utilizing advances of soft robotics technologies. As fish fin has a major influence on thrust production and performance of the caudal fin propulsion system, study for the optimization of the caudal fin parameters for optimal propulsive efficiency needs to be carried out. So far flexibility of caudal fin is studied numerically and experimentally, while very limited study is found on shapes of caudal fin and that are also numerical studies. Experimental studies relating geometrical features of caudal fin shapes directly to propulsive efficiency are yet to be carried out. Also vortices shedding has found to have a major effect on thrust production but few results relates caudal fin parameters to low-pressure vortex generation and shedding in the wake region of caudal fin and thus needs further study.

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