Effects of the caudal fin morphology on the swimming performance of sharks

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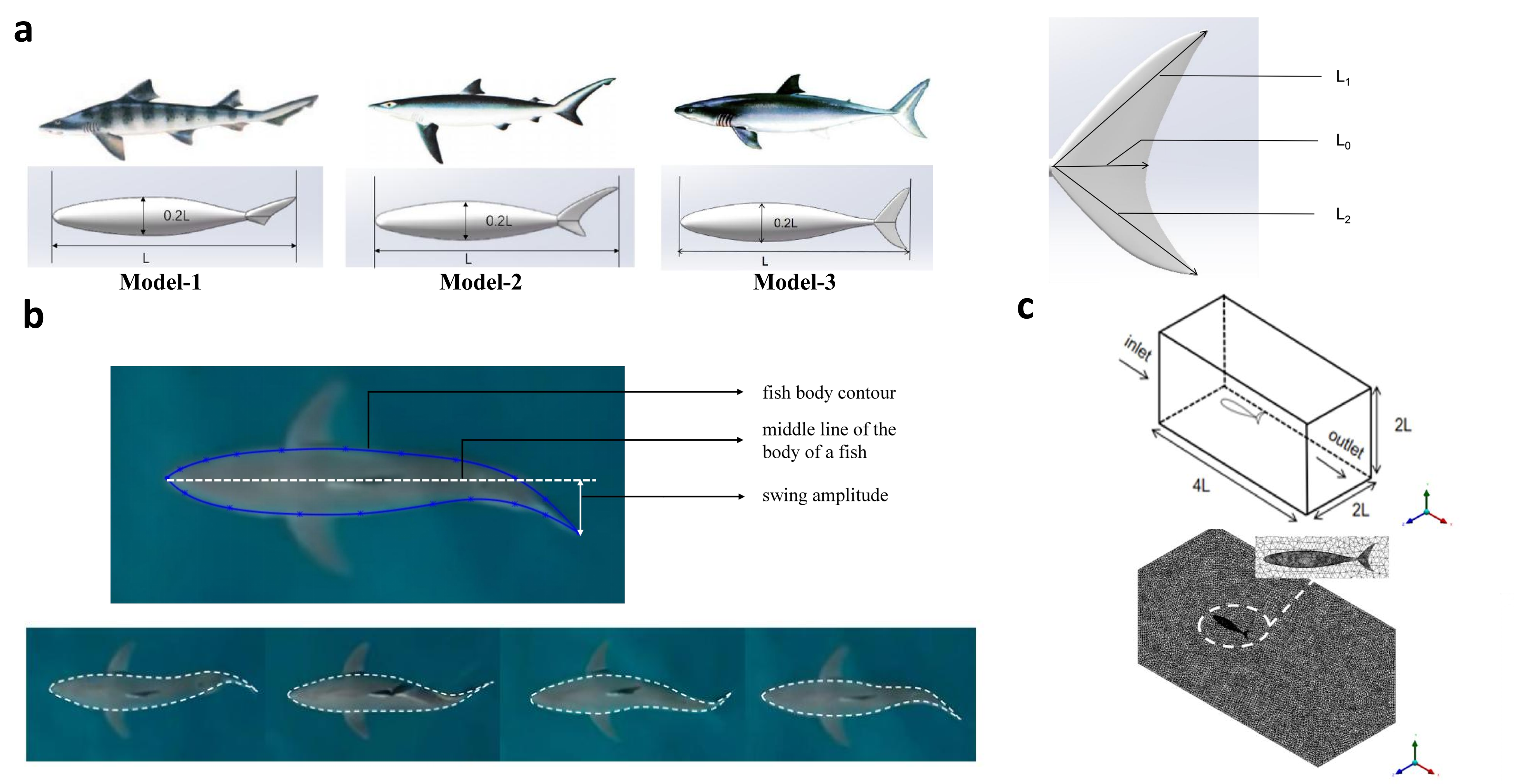
Introduction

- Through the processes of natural selection and evolution, fish have developed exceptional underwater maneuvering capabilities
- Despite significant efforts by scholars, the full implications of caudal fin shape on propulsion performance remain incompletely understood
- Investigating the relationship between caudal fin morphology and swimming performance in sharks not only elucidates the theoretical underpinnings for performance disparities among species, but also provides critical data for the design and optimization of propulsors in shark-inspired underwater vehicles.

Materials and Methods

- This study employs numerical simulations to investigate the differences in swimming performance among three shark models with distinct caudal fin structures. It further examines the effects of the caudal fin area (S=0.0155, 0.0165, 0.0175, and 0.0185 L^2) and the caudal lobe asymmetry ratio (CLAR = 1.05, 1.15, 1.4, 1.65) on thrust and lateral forces.
- Based on authentic video footage of shark swimming, the kinematic equations were formulated.
- Set up the computational domain, perform mesh generation, and select the appropriate turbulence model to simulate shark swimming behaviour via a UDF (user-defined function) .



Results

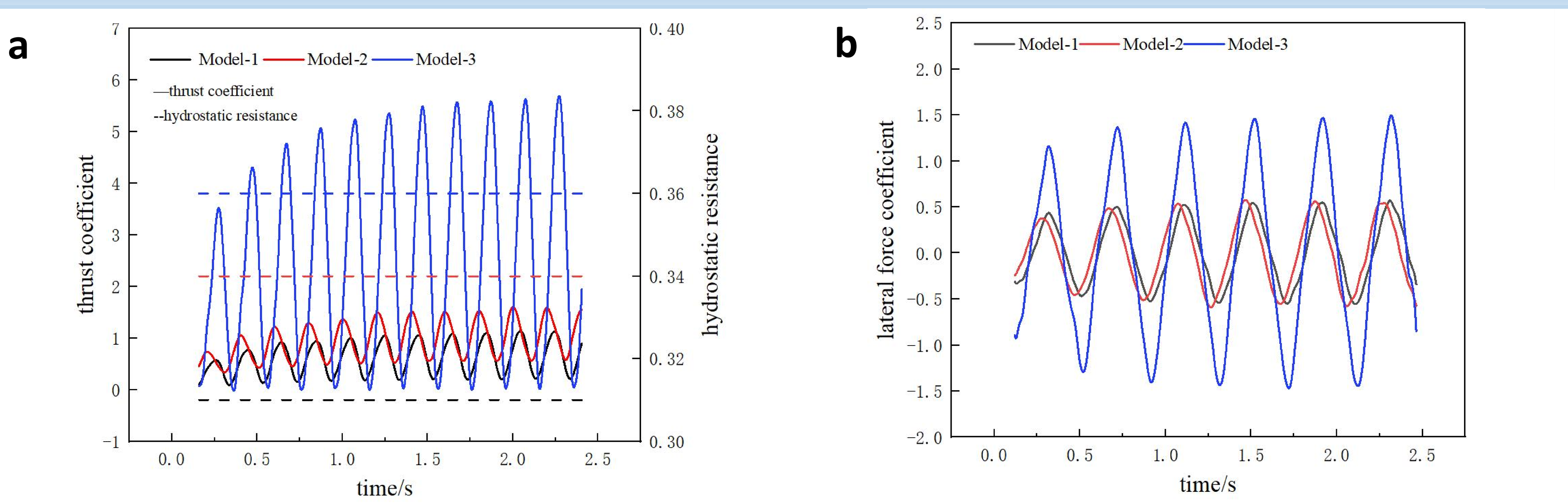


Fig.1 Resistance coefficients and lateral force coefficients for different sharks models.
a) Variation of thrust coefficient with time and hydrostatic resistance. b) Variation of lateral force coefficient with time

For Model-1, Model-2, and Model-3, $\overline{Cx}$ are 0.67, 1.05, and 2.73, respectively. In terms of Cz, the peak values for Model-1 and Model-2 are relatively close, at 0.54 and 0.56, respectively. The peak Cz for Model-3 is 1.45, representing an increase of 63.5% and 61.5% compared to Model-1 and Model-2, respectively.

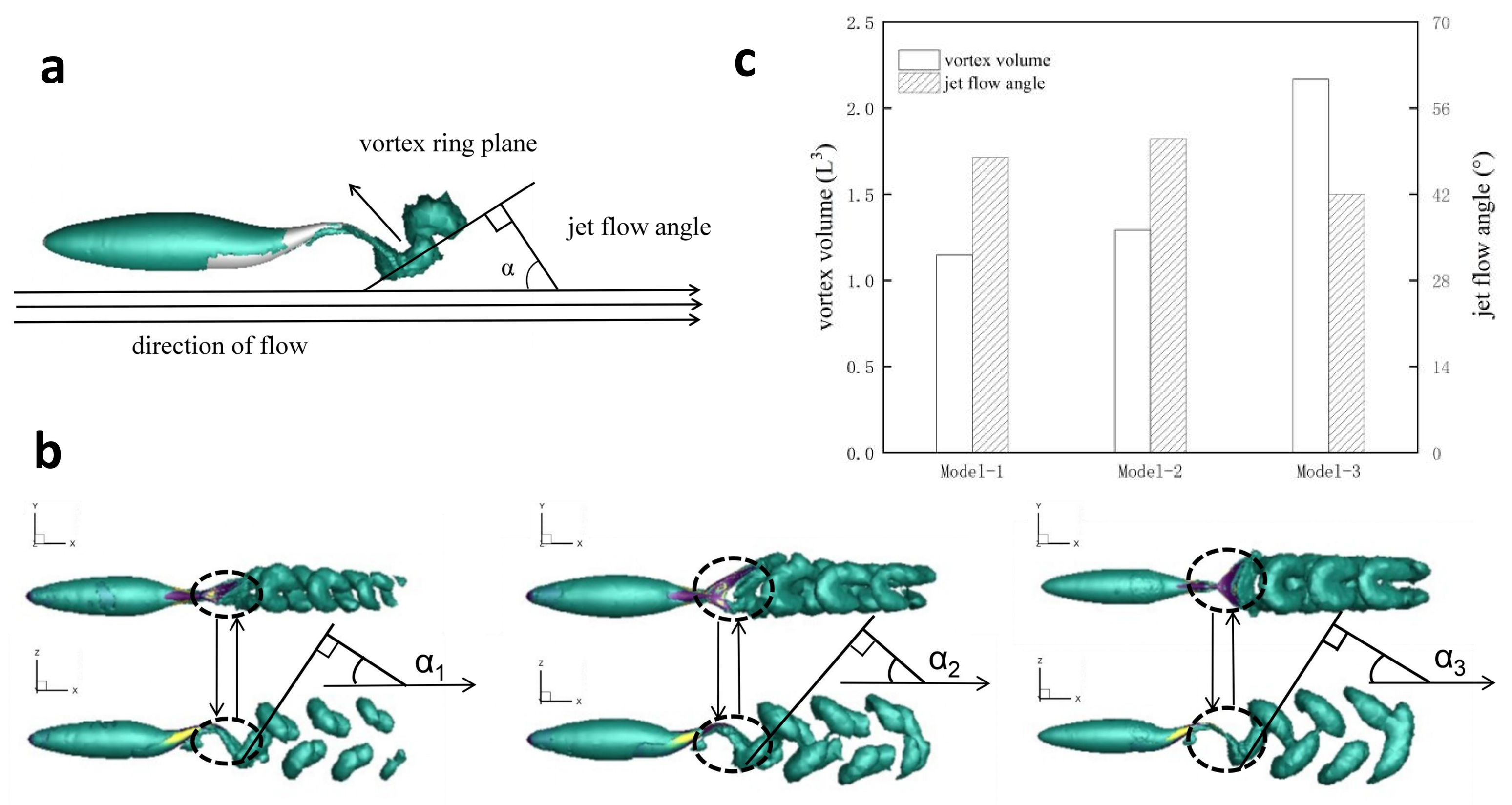


Fig.2 Schematic diagram of jet flow and vortex ring.
a) Schematic diagram of the jet flow. b) Propulsion vortex structure of different sharks. c) Changes in vortex volume and jet flow angle

Model-3 generates the largest vortex volume and smallest jet angle among the three models, resulting in the strongest axial jet component and optimal thrust performance. Although Model-2 shows a moderately improved jet angle over Model-1, its larger vortex volume yields higher thrust. The substantial vortex volume of Model-3 enables maintained vortex alignment distance even with a lower y-component ratio.

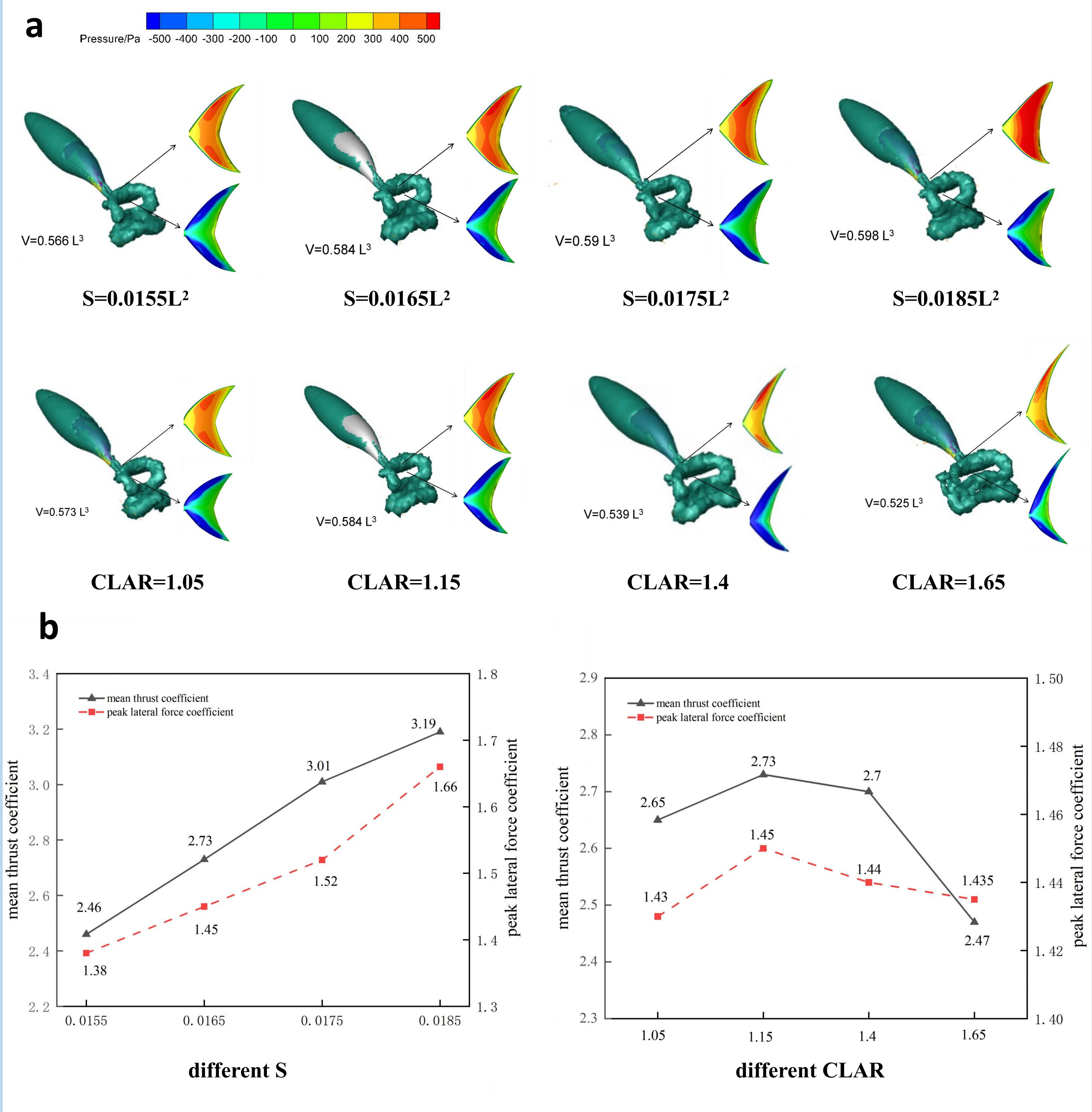


Fig.3 a) Caudal vortex structure and caudal fin pressure contour. b) Trends in mean thrust coefficient and peak lateral force coefficient .

- The Cx,Cz, cadual fin pressure difference and vortex ring volume both exhibit a positive correlation with S, though the rate of increase gradually diminishes.
- When CLAR=1.15, the caudal fin exhibits the maximum pressure difference. With increasing CLAR, the vortex ring volume initially expands before decreasing. Furthermore, the rise in CLAR causes the vortex ring shape to elongate, reducing the jet's x-component velocity. Consequently, this diminishes the Cx during the fish's swimming motion.

Conclusion

- The white shark's crescent-shaped caudal fin demonstrated superior swimming performance by generating optimal vortex dynamics and thrust efficiency among the three modeled species.
- Whilst thrust typically increases with enlarged caudal fin area, the growth rate diminishes markedly when S ≥ 0.0175 L^2 due to trailing edge curvature effects.
- CLAR=1.15 represents the optimum value for tail fin blade asymmetry; exceeding this threshold leads to vortex distortion and reduced pressure differential, thereby diminishing propulsive efficiency.