Design and Modelling of TorsioSquid: A squid-inspired underwater bot

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Abstract: Underwater soft robotics is an emerging field due to the increased need for underwater exploration and surveillance, which requires blending with natural habitats. Although previous work has been done mimicking fishes and octopuses, only a few have tried to imitate the mantle movement of squid. Mimicking the mantle's propulsion mechanism could lead to a compact design, which we have presented through the TorsioSquid, a bio-inspired robotic system. Its unique propulsion is achieved through a synergy of torsional buckling [1] and Bowden cables arranged in a helical pattern around a semi-ellipsoidal Ecoflex shell. At its heart, a linear actuator drives the system by pulling on the cables, inducing controlled buckling and mimicking the squid's mantle movement to generate thrust. In previous similar works, rigid components like motors and gears have been used to mimic squids [2]. These components often fail under cyclic loads. Our design of TorsioSquid prioritises using softer components like bowden cables and torsional buckling to mimic squids. We have simulation results specifically and have estimated the mass of TorsioSquid to be 800 g and length of 540 mm through its CAD model. Using Ansys, we concluded that TorsioSquid achieves a notable mass ejection rate of 0.4 kg/sec, contributing to significant thrust force.

Keywords: Underwater soft robotics, squid, mantle movement, torsional buckling, Ansys, mass ejection

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1. Introduction

The quest for effective underwater exploration and surveillance has driven significant advancements in robotics, particularly in soft robotics. Traditional underwater vehicles, often characterised by rigid structures and mechanical components, struggle with the demands of complex underwater environments and the need for minimal disruption to marine ecosystems. Soft robotics offers a promising alternative, leveraging the flexibility and adaptability of natural organisms to create more resilient and efficient machines.

Squids are particularly noteworthy for their unique and efficient propulsion mechanism among marine animals. Squids move by contracting and expanding their mantle, expelling water to generate thrust. This biological process provides an excellent model for developing underwater robots that can navigate swiftly and efficiently. However, while substantial research has focused on replicating the movements of fish and octopuses, the intricate mantle movement of squids has received comparatively less attention. Existing attempts to mimic this movement often rely on rigid components such as motors and gears [2], which are prone to failure under the cyclic loading conditions typical of underwater propulsion.

Mechanical instability and buckling have recently been used for structural and motion applications. These have also been used to actuate soft robots like soft gripper [3] and soft pump [1]. Hence, we prioritise using softer components to overcome the challenges of failure under cyclic loading. Hence, we have used torsional buckling as an actuation mechanism to model an underwater soft robot bot, TorsioSquid.

In the subsequent sections of the paper, we have explained the background of squid propulsion, working, and design of the TorsioSquid, modelling, simulation and analysis using Ansys and the performance metrics derived from our simulations. We aim to demonstrate the feasibility and advantages of this bio-inspired approach, highlighting its potential applications in underwater exploration and surveillance. By drawing inspiration from the natural world, we aim to contribute to the advancement of underwater robotics and broaden the scope of soft robotic technologies.

2. Background of squid propulsion

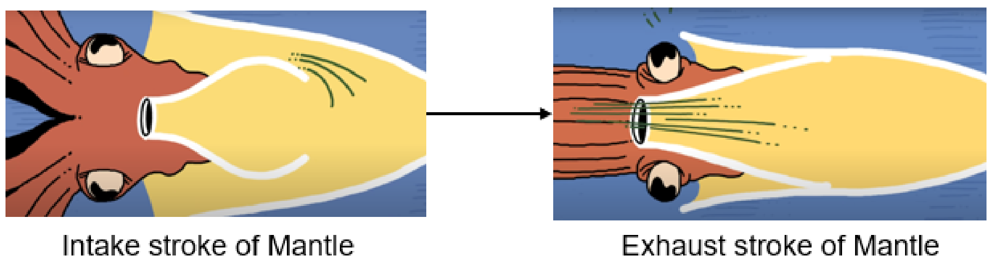


Figure 1: Working of mantle

Squid performs locomotion in two ways: - slow jetting and fast jetting. Slow jetting is performed by fins for intricate movements, while fast jetting is an escape response performed by the mantle. In fast jetting, during the intake phase, the squid's mantle muscles relax, allowing the mantle cavity to expand and fill with water. This expansion is made possible by the contraction of radial muscles within the mantle, increasing the cavity's volume. In the exhaust phase, the circular muscles contract, squeezing the mantle cavity and forcing the water out through the funnel or siphon. This expelled water creates a powerful jet of thrust that propels the squid forward. During this means of locomotion, some squid similarly exits the water to flying fish, gliding through the air for up to 50 m (160 ft) and occasionally ending up on the decks of ships [4]. This natural propulsion system is highly efficient and highlights the incredible adaptability and ingenuity of biological systems, which we strive to emulate with the TorsioSquid in our robotic design.

3. Working and Design

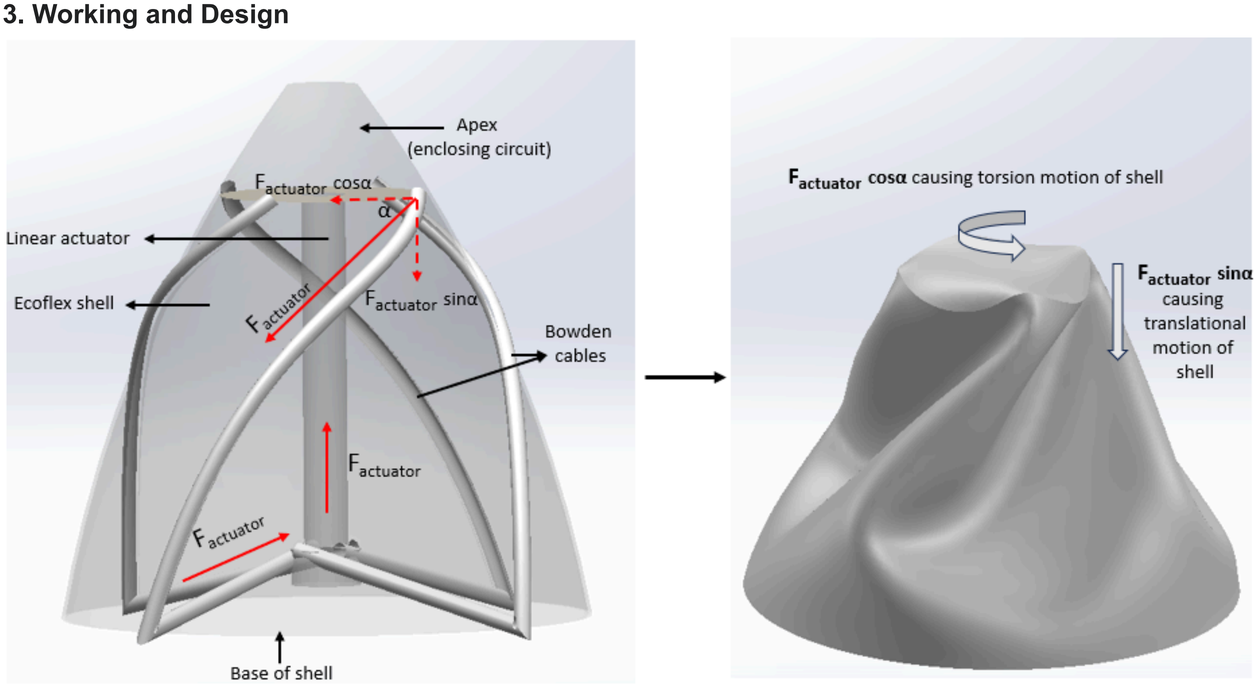


Figure 2: FBD and working of the TorsioSquid during backstroke of linear actuator

Key to TorsioSquid's actuation is a unique combination of torsional buckling and Bowden cables. Torsional buckling, a form of mechanical imperfection, is induced in the system through carefully engineered Bowden cables arranged in a specific helical geometry. We have kept all electronics and mechanisms in a semi-ellipsoidal shell of Ecoflex.

At the core of TorsioSquid is a linear actuator housed within the apex of the shell, whose circuit has been isolated from water to prevent damage. All the bowden cables have been arranged in a helix around the shell, one end of which has been connected to the linear actuator while the other end has been fixed to the apex of the shell. As the linear actuator retracts, it pulls on the Bowden cables arranged in a helix around the shell. The helical geometry imparts axial and tangential forces on the shell, inducing a combined axial and torsional movement. By optimising the helix angles and cable configurations, we induce controlled buckling of the shell, which will lead to the volumetric reduction of the shell, mimicking the squid's mantle movement and generating thrust for propulsion.

4. Modelling, Simulation and Analysis

The **Finite Element Method (FEM)** stands out as our chosen approach for the modelling of Soft Robotics due to its adaptability in handling complexities without intricate analytical models. FEM accommodates deformations and material complexities within Soft robots, aiding in predicting performance and identifying weak areas. Thus, We have used the Ansys Workbench tool, which works on FEM [5].

The following steps have been followed for modelling: -

4.1.) Material Assignment - We chose the **Yeoh 3rd order model** [6] and its parameters for Ecoflex for the material assignment. The Yeoh model is chosen because it only needs a small amount of experimental data to get reasonable numerical results. It can also describe a wide range of deformation. The reason for choosing Ecoflex material is the abundance of its experimental material data, and it is biocompatible and flexible.

Properties of Outline Row 3: Elastomer Sample (Yeoh)

	A	B	C	D	E
1	Property	Value	Unit		
2	Material Field Variables	Table			
3	Density	1030	kg m^-3		
4	Uniaxial Test Data	Tabular			
5	Scale	1			
6	Offset	0	Pa		
7	Biaxial Test Data	Tabular			
11	Shear Test Data	Tabular			
15	Yeoh 3rd Order				
16	Material Constant C10	0.35944	MPa		
17	Material Constant C20	-0.14221	MPa		
18	Material Constant C30	0.26112	MPa		
19	Incompressibility Parameter D1	0	MPa^-1		
20	Incompressibility Parameter D2	0	MPa^-1		
21	Incompressibility Parameter D3	0	MPa^-1		

Figure 3: Ecoflex properties and parameters [1]

4.2.) Meshing parameters - We choose **Nonlinear Mechanical** and large deflection while meshing to capture the nonlinearities of a soft robot. The element order was kept linear, and the **element size was 3.75 mm**. The **Automatic meshing method** has been used, which generally creates a tetrahedral mesh for 3D models, which balances computational efficiency and accuracy. Thus, we get an average **element quality of 0.78 with nodes <50000**.

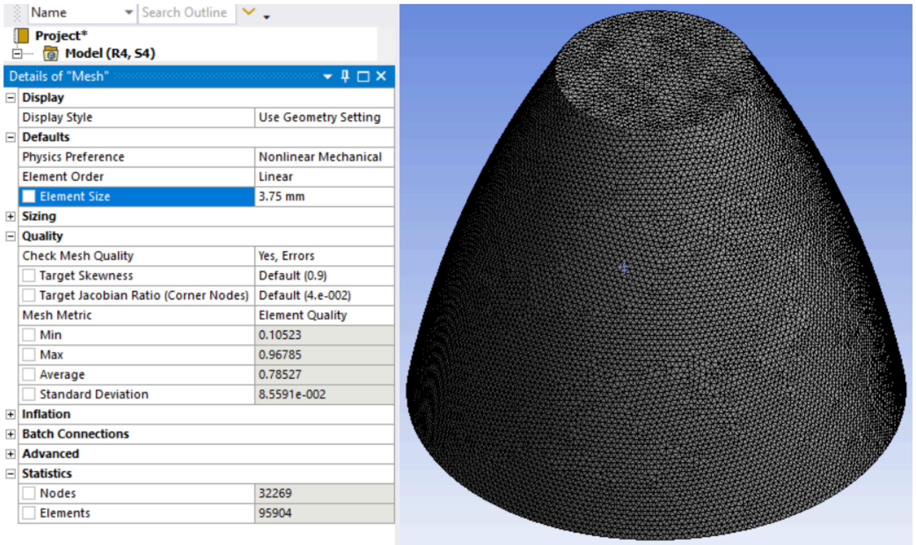
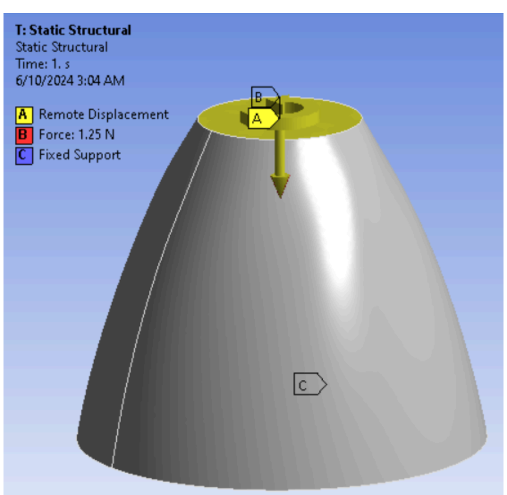


Figure 4: Meshing parameters

4.3.) Equations and Boundary conditions - The base of the shell has been kept fixed while all the forces and remote displacement have been provided at the top of the apex. A Force of 1.25 N has been applied at the centre of the apex to consider the weight of the electronics enclosed within the apex of semi ellipsoidal shell. The following are the equations used to calculate the loads and perform further analysis.

- Thrust force = Exit velocity * Mass ejection rate
- Mass ejection rate = Density of water * $\triangle V$
- Translation load [1] = $(A+w)*(\sin\alpha_f - \sin\alpha_0)$ = 37 mm
- Rotational load [1] = (Helix parameter)*$(\alpha_f - \alpha_0)$ = 45 degrees

Where $\triangle V$ = Volumetric deformation
A = Major axis = 298 mm
w = Shell thickness = 2 mm
α_f = Final helix angle = 56.25 degree
α_0 = Initial helix angle = 45 degree
Helix parameter = 4*n = 4
n = no. of turns of the helix around the semielliptical surface



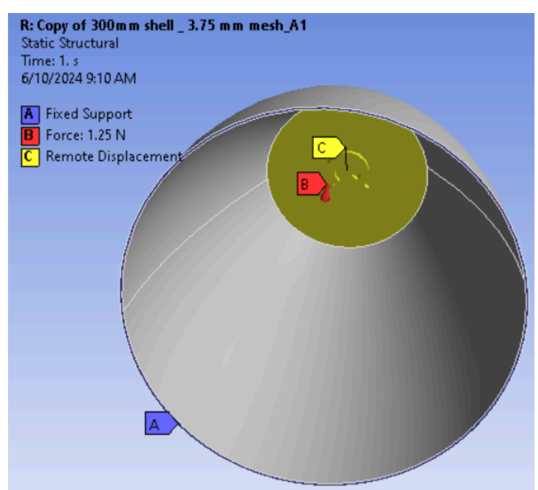


Figure 5 and 6: Loads and Boundary conditions

4.4.) Simulation and Analysis

4.4.1) Nonlinear buckling and eigenvalue buckling to find△V

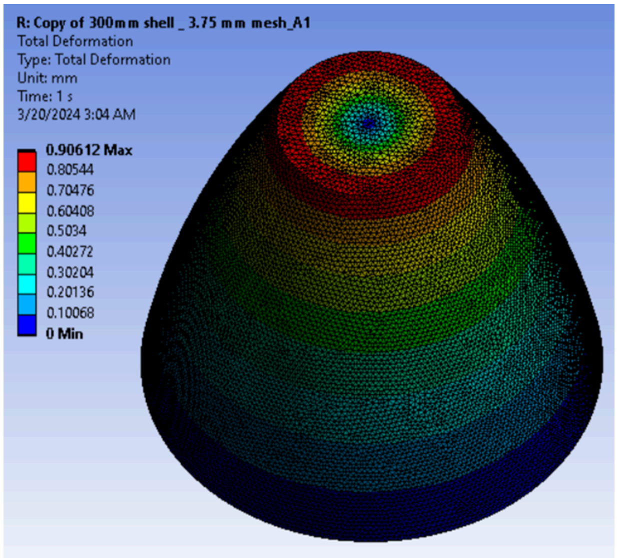


Figure 7: Analysis A1

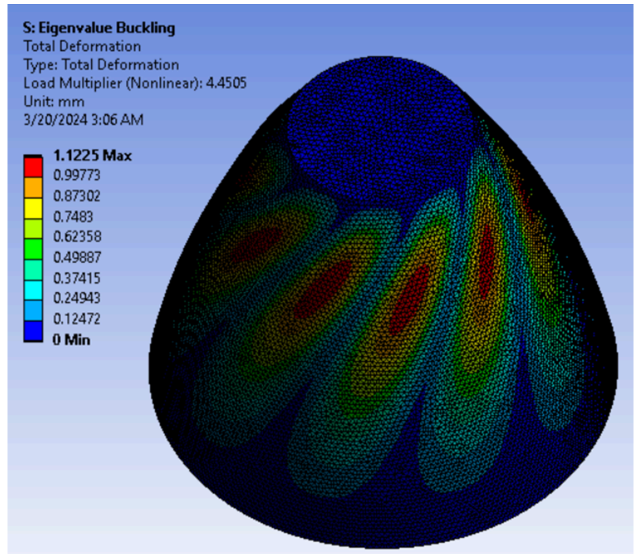


Figure 8: Analysis A2

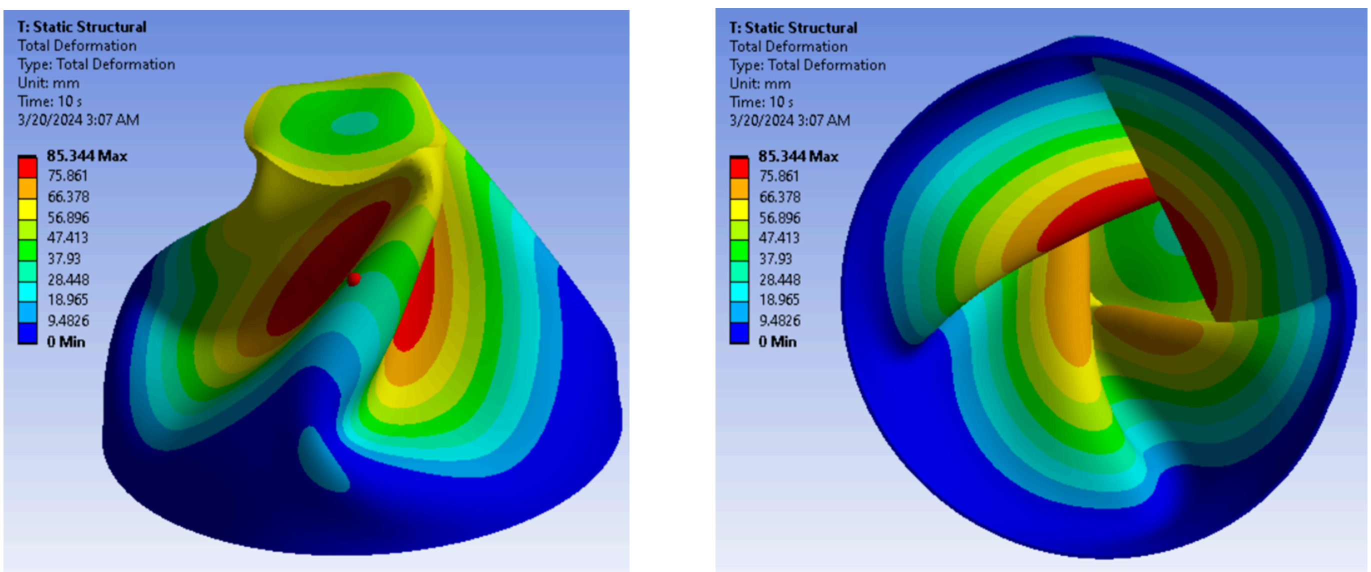


Figure 9: Analysis A3

- **Analysis A1**: A 1-degree rotation has been applied to give Pre-stress to the shell.
- **Analysis A2**: Eigen buckling analysis to create geometrical imperfections in the shell.
- **Analysis A3**: Translational and rotational load are applied in steps of t = 10 secs on the geometrically imperfect shell to generate folds in the semi-ellipsoidal shape, replicating the volumetric deformed state.
- **Obtaining volumetric reduction** - Importing the volumetric deformed state in Analysis A3 of the shell in Solidworks and comparing it with the initial one gives us the volumetric deformation△V.

4.4.2) Usage of the nozzle to increase the exit velocity

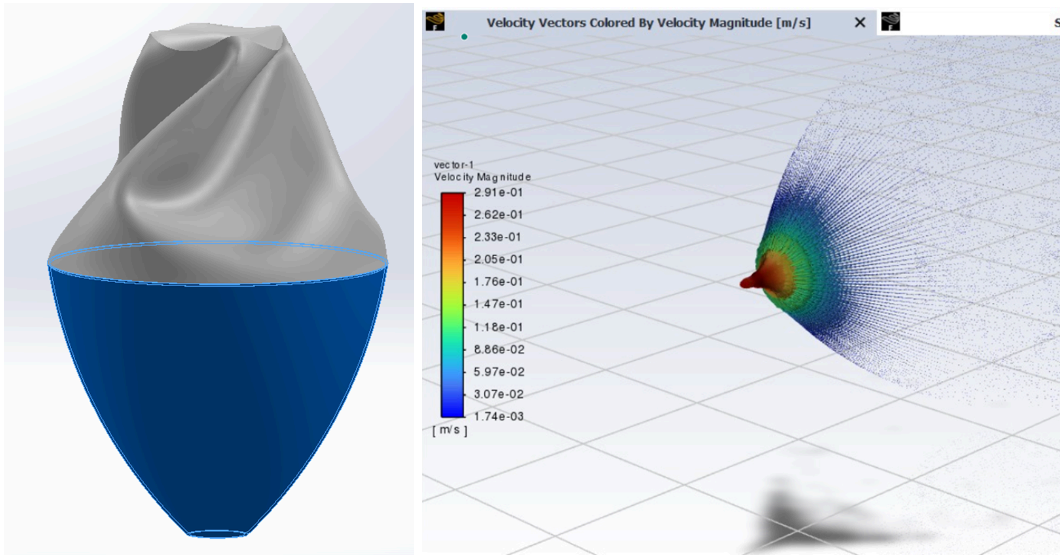


Figure 10: A semi-ellipsoidal-shaped nozzle with an exit diameter of 50 mm can increase the exit velocity, thus increasing the thrust force

5. Performance metrics and conclusion

ΔV (cm^3)	Mass ejection rate ($kg.s^{-1}$)	Exit Velocity ($cm. s^{-1}$)	Thrust Force (N)	Acceleration (ms^{-2})
4077.032	0.4077	20.76	0.0846	0.105

We calculate the mesh convergence error to verify our simulation results. We get a **0.7 % mesh convergence error**, which gives our simulation results reasonable accuracy.

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