DESIGNING AND AERODYNAMIC ANALYSIS OF HYPERSONIC INLET INSPIRED BY PRAWN ROSTRUM ARCHITECTURE

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Keywords:

Bio-inspired design, computational fluid dynamics (CFD), hypersonic inlet, prawn rostrum, shock interaction

Introduction:

Hypersonic flight, defined as speeds above Mach 5, presents immense potential in aerospace but also introduces significant design challenges due to extreme thermal and aerodynamic stresses. Among critical components, the hypersonic inlet is essential for compressing incoming high-speed air to enable efficient combustion. Designing these inlets requires precise shockwave management, as improper control can lead to flow separation and unstart—causing severe performance losses. Traditional designs often struggle to maintain stability under varying conditions. This project takes a bioinspired approach, using the prawn rostrum—a naturally streamlined structure with excellent flow control properties—as the design basis. Its geometry helps in reducing drag and improving flow uniformity. The study aims to model and simulate this bio-inspired inlet using Computational Fluid Dynamics (CFD), analysing its pressure recovery, shock behaviour, and aerodynamic efficiency. The goal is to develop a more stable, efficient inlet suitable for hypersonic conditions through biomimicry and engineering innovation.

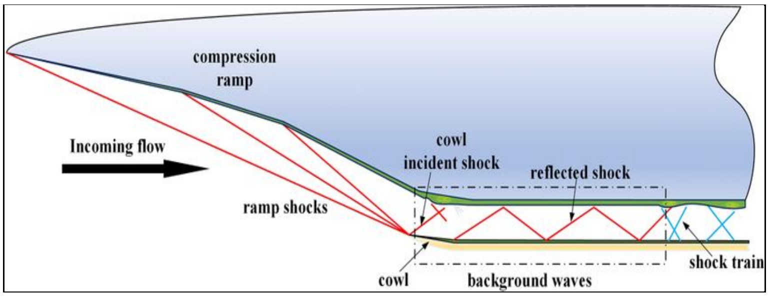

Fig 1. Hypersonic inlet

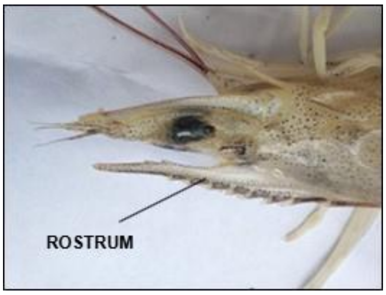

Fig 2. Prawn

Objectives:

- Develop an optimized hypersonic inlet inspired from the prawn rostrum architecture.
- Perform detailed aerodynamic analysis for the proposed designs and compare with the conventional inlet design using Computational Fluid Dynamics (CFD).
- To enhance the shock capturing capability at the inlet and pressure recovery at the throat region of the inlet.
- A scaled-down prototype of the optimized inlet will be constructed for the purpose of visual demonstration and presentation.

Methodology:

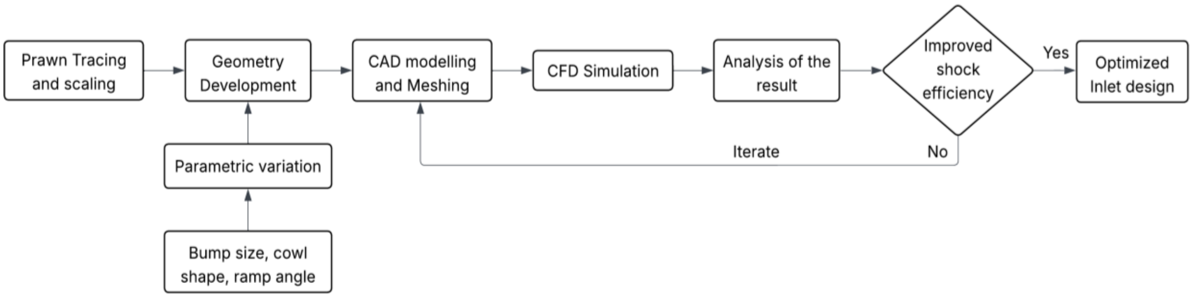

Fig 3. Flowchart of the project

This study begins with a comprehensive literature review focusing on hypersonic inlet configurations and bio-inspired aerodynamic principles, with particular interest in the structural characteristics of the prawn rostrum. To capture its geometry, the rostrum was traced from high-resolution images and subsequently scaled up to inlet-relevant dimensions while retaining its aerodynamic features.

Using CAD software, like CATIA two primary inlet configurations were developed: a conventional baseline and a bio-inspired design incorporating the scaled rostrum geometry. In addition, several variants were generated by systematically modifying key geometric parameters such as bump size, cowl shape, and ramp angle. This allowed for a parametric exploration of design sensitivities and performance optimization.

High-fidelity meshes were created for each model, with localized refinement in regions expected to experience high flow gradients and shock interactions. Computational Fluid Dynamics (CFD) simulations were carried out using an appropriate solver like the ANSYS Fluent, with boundary conditions mentioned in below table and turbulence modeling (i.e SST k-ω) chosen to reflect realistic hypersonic flow scenarios, particularly at Mach number range of 6-10.

Parameter(s)	Value(s)
Mach number	6
Total Pressure (P0)	18.5E+5 Pa
Total Temperature (T0)	1858.5 K
Gamma	1.4
Gas constant	287 J/Kg K

The flow behavior and performance of each inlet design were evaluated based on criteria such as shock wave interaction, pressure recovery, total pressure loss, and flow uniformity. The variations were compared to identify optimal configurations that enhance shock-capturing capability and overall aerodynamic performance.

Results & Conclusions:

To investigate the impact of cowl inclination on flow behaviour and shock control, four inlet configurations were created with varying angles. Design 1 featured a 26° inclination, targeting effective shock compression while preserving attached flow. In Design 2, the angle was reduced to 18° to promote gentler shock interactions and reduce flow irregularities. Design 3 utilized a minimal 8° inclination along with a straight internal cowl, aiming to minimize aerodynamic drag and support steady flow. Design 4 introduced a 10° inclination, offering a well-balanced configuration that demonstrated improved shock management and aerodynamic efficiency.

The resulting shock formed on the cowl was at an angle of 15° (in modified design 4), compared to a 65° shock angle in the conventional design. This significant difference led to a drastic reduction in drag, from 0.04 in the conventional inlet to just 0.0015 in Design 4.

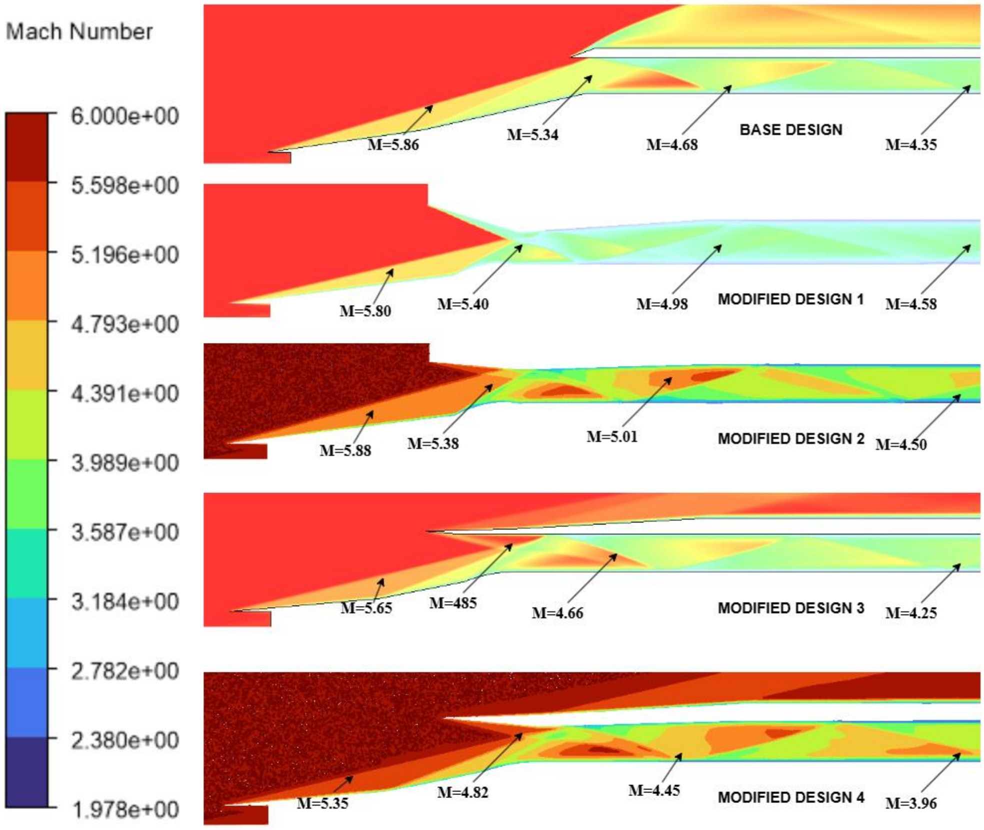

Fig 4. Comparison of Mach number contours

The Mach number at the inlet throat, measured after the compression process, varied across the different designs. Design 1 recorded a Mach number of 4.58, followed by Design 2 at 4.50, Design 3 at 4.25, and Design 4 at 3.96, while the conventional inlet showed a value of 4.35. Among these, Design 4 exhibited the most significant reduction in Mach number, suggesting enhanced energy dissipation and more effective flow compression. This characteristic is particularly important for maintaining engine stability and performance in hypersonic flight conditions.

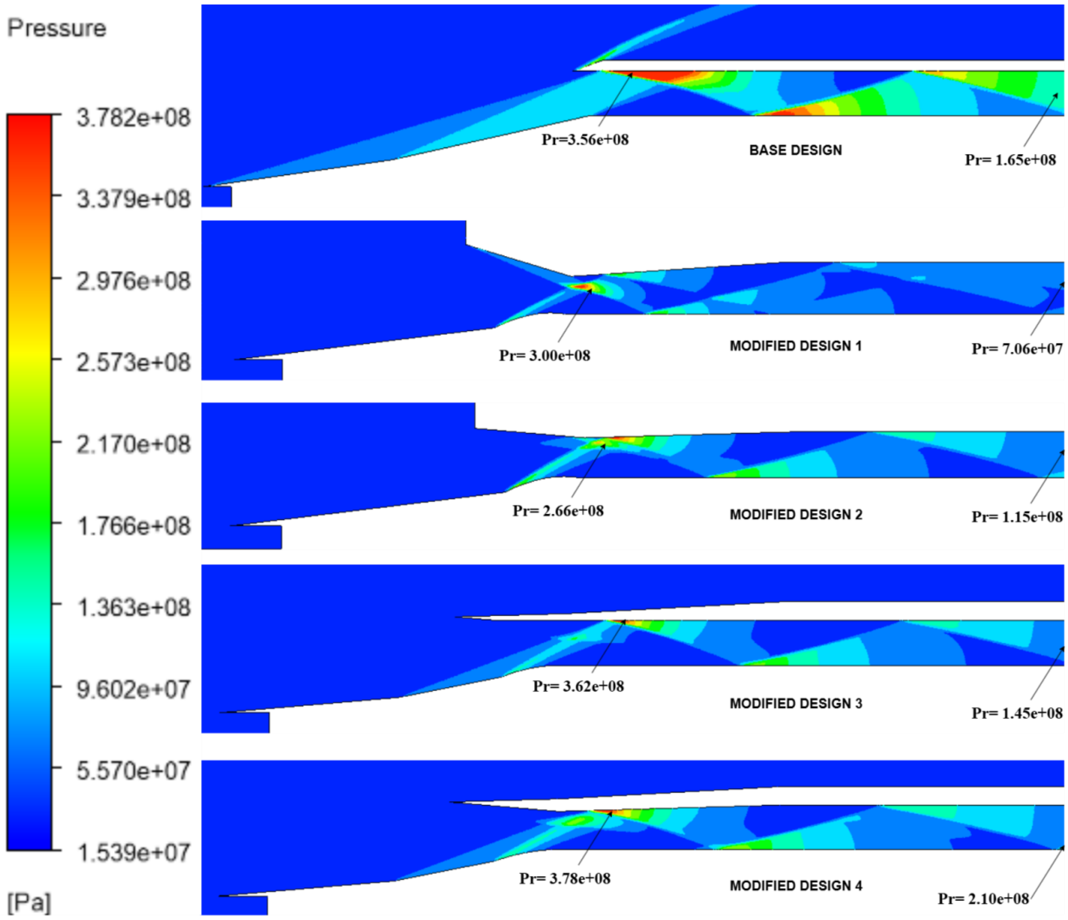

Fig 5. Comparison of pressure contours

As illustrated in Figure 5, Design 4 recorded the highest pressure at the inlet throat, which can be attributed to its well-managed shock structure and relatively lower shock angle. Design 3 achieved the second-highest pressure, benefiting from a longer and more gradual compression pathway that allowed for smoother flow deceleration. In contrast, the conventional inlet showed lower pressure recovery, ranking third among the designs, largely due to its steeper shock angle and associated increase in drag and flow losses.

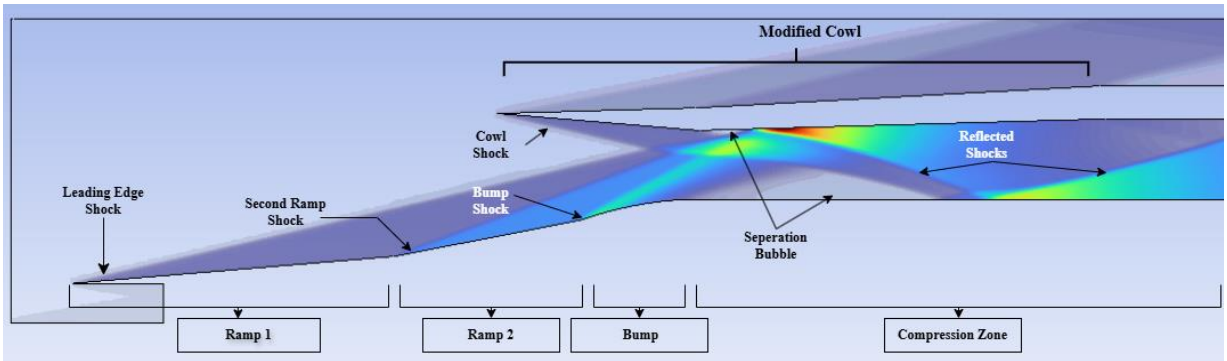

Fig 6. Modified design 4

Industry Relevance:

In line with industry-standard practices, the development process involved high-fidelity analysis using advanced Computational Fluid Dynamics (CFD) tools to evaluate aerodynamic performance under hypersonic conditions.The results have significant implications for the missile and aerospace industries, particularly in advancing hypersonic missile technology. Improvements in inlet efficiency could lead to better propulsion, greater maneuverability, and enhanced survivability of hypersonic missiles, increasing their range and precision.

This work supports the broader industry trend toward creating more efficient and resilient defense systems, capable of operating at extreme speeds. Bio-inspired design offers a new approach to overcoming challenges in high-speed flight and missile technology.

Working model vs simulation study:

A detailed simulation study was conducted using Computational Fluid Dynamics (CFD) to evaluate the aerodynamic performance of both conventional and bio-inspired hypersonic inlet designs. Various configurations were tested under hypersonic flow conditions, focusing on parameters such as Mach number, pressure distribution, and shock behaviour. The study incorporated turbulence modeling and high-resolution meshing to ensure accuracy. Performance comparisons helped identify the most effective design in terms of shock control, pressure recovery, and flow stability.

Project Outcomes and Learnings:

Among all the configurations analyzed, Design 4 demonstrated the most favorable results in terms of both Mach number reduction and pressure recovery. The flow entering the inlet was decelerated to a Mach number of 3.96, indicating effective compression. Additionally, the pressure at the throat reached 3.78×10^8 Pa, with a downstream pressure of 2.1×10^8 Pa at the exit of the inlet. These values reflect superior shock management and energy dissipation, making Design 4 the most efficient configuration for hypersonic flow conditions.

One of the core takeaways was the effectiveness of biomimicry in solving challenges inherent to hypersonic flight. The prawn rostrum-inspired shape facilitated better airflow control, leading to improved pressure recovery and overall flow demonstrating the power of evolutionary design in engineering contexts.

The study revealed that even small geometric changes significantly impact hypersonic inlet performance, underscoring the need for precise meshing and turbulence modeling. The results validate the potential of biomimetic designs in advancing next-generation hypersonic and defense systems.

Future Scope:

- Future work could involve creating a detailed 3D model of the optimized inlets and conducting high-resolution CFD studies to explore airflow behavior under diverse operating conditions.
- A scaled-down physical prototype may be produced to carry out wind tunnel experiments, offering real-world insights into the aerodynamic characteristics of the design.
- The experimental outcomes can be systematically compared with simulation and theoretical predictions to ensure consistency and design reliability.
- Additional studies could focus on the potential application of the developed inlet configurations in missile platforms, evaluating their practical advantages in terms of performance, efficiency, and system integration.