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Computational Analysis of a Multistage Nose Spike to Reduce Drag on a Conceptual Supersonic Transport Aircraft

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Abstract. Supersonic commercial aircraft have the potential to greatly reduce global travel times, but key challenges, such as high fuel consumption due to increased drag at supersonic speed, remain a barrier to commercial feasibility. In this study, a Concorde-like delta wing aircraft was modelled and analysed using ANSYS Fluent at different Mach numbers, such as Mach 0.8, 1.02,1.5 and 2. During supersonic flight, significant aerodynamic drag is generated primarily due to wave drag. A multi-stage nose spike was designed and tested to reduce the drag. Results indicate that a stage 4 spike reduced the total drag by 4.23% at Mach 1.5, and the Lift to Drag ratio has increased by 3.9%. The simulation results were compared and validated against results from a previous research paper It is recommended that at subsonic speed, the spike be retracted in position 1, position 2 is optimal for transonic speeds, and position 4 performs best at supersonic speeds.

Introduction

Commercial supersonic flight ended with the Concorde retirement in 2003 after nearly three decades of operation with British Airways and Air France. Despite its technological success, Concorde faced two major challenges the sonic boom, which restricted supersonic flight over land and high operating costs due to poor fuel efficiency. Both issues arise from the physics of supersonic flight, as an aircraft approaches and exceeds Mach 1, which is the speed of sound, the air in front of the aircraft begins to compress, resulting in the formation of shock waves. These shock waves not only produce a sonic boom but also introduce a component of drag known as wave drag, which can increase the total drag by more than 50% [1]. This significant increase in drag is responsible for the poor fuel efficiency of supersonic flight. There is renewed interest in the commercial supersonic market, with companies such as Boom Supersonic actively working to bring back supersonic commercial flight. The market is projected to be valued at USD 70 billion by 2034 [2]. However, aviation currently contributes approximately 2.5% of global carbon emissions, highlighting the need for a solution to make commercial supersonic travel environmentally viable [3].

Improving fuel efficiency and reducing drag in supersonic flight was greatly advanced by the development of the area rule in the 1950s[4]. This rule demonstrates that the significant increase in drag at transonic and supersonic speeds is heavily influenced by the longitudinal distribution of the cross-sectional area. A smooth and gradual change in cross-sectional area will minimise the increase in drag. [5]Supersonic fuselage designs often include a bottleneck section near the wings to reduce the change in cross-sectional area distribution. While it is effective at reducing drag, such a design compromises the cabin layout and limits the number of passenger seats [6] creating challenges for commercial aviation. [7]Variable sweep wings allow an aircraft to optimise performance at low and high Mach numbers. The wings sweep back to reduce the cross-sectional area change as the Mach number increases. However, the mechanisms are heavy, complex and difficult to maintain. [8]Extended nose designs, such as the NASA X-59, reduce the strength of the initial shock by distributing it along the length of the nose. Such a design does, however, limit pilot visibility, which is essential for certification in commercial applications. An alternative approach is the use of a slender retractable nose spike, [9] Gulfstream Aerospace has previously experimented with an extendable nose boom concept that extends in front of the fuselage at high speeds to break up the strong initial shock into subsequent smaller shocks, and the spike would be retracted at lower speeds, such as for take-off and landing. Gulfstream developed this concept to avoid impacting the internal cabin and cargo space. The concept was tested in an F15 platform, but its application for commercial supersonic aircraft has not been analysed. This study will examine the aerodynamic benefits of a multi-stage spike in reducing drag for supersonic transport aircraft. A simplified Concorde-type model will be analysed using computational fluid dynamics with baseline lift and drag values evaluated at Mach 0.8,1.02,1.5 and 2. Testing done by Gulfstream showed that while a single stage spike reduced the initial overpressure, multistage spikes effectively split the primary shock, lowering peak overpressure [10] .

Design

The baseline configuration was derived from a Concorde-type design from a previous analysis [11]. The long and slender fuselage, along with the ogive delta, was designed on Fusion 360 with the NACA 64A210 aerofoil being utilised. The Fuselage section was generated from longitudinal and cross-sectional sketches, which were mirrored about the centreline. The final base model measured 62 m in length. The wing geometry was produced by lofting the aerofoil section with the leading and trailing edge curves. The final wingspan measures 25.46 m Finally, the vertical stabiliser and the engine inlets were modelled. For computational fluid dynamics (CFD), all components were unified into a single body and uniformly scaled down by a factor of 1:10. The scaled-down dimension measures 6.2 m in length and a span of 2.54 m. This was done to reduce the computational time and allow for a denser mesh. A multistage nose spike consisting of four different stages was designed with the modification beginning from the approximate location of the bulkhead in front of the cockpit. The retracted stage measures 0.69 m in length with a radius of 224mm, while the fully extended stage measures 2.59 m in length. The spike proportions were based on a ratio derived from Gulfstream Aerospace. Figure 1 show the base and the multistage spike configurations and figure 2 shows the four different spike stages.

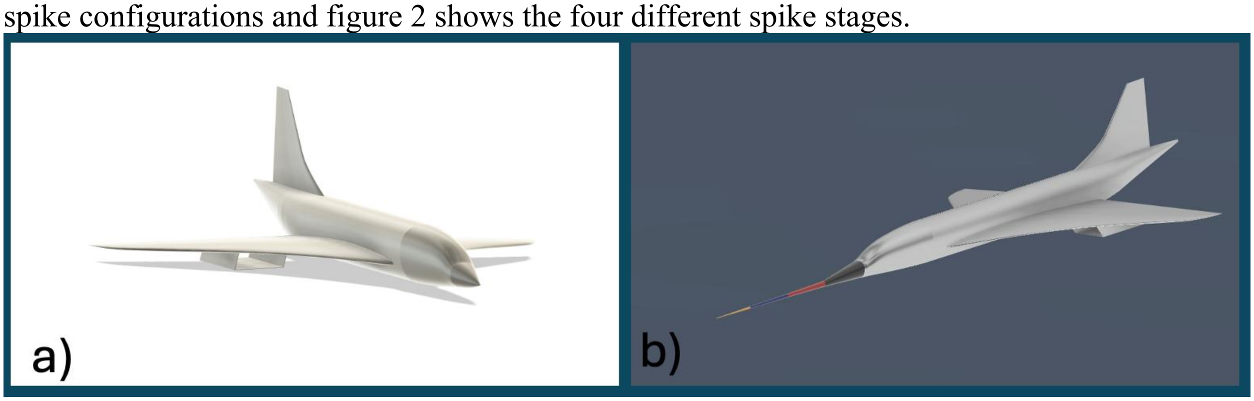

Figure 1 a) Base configuration b) Multi-Stage spike configuration

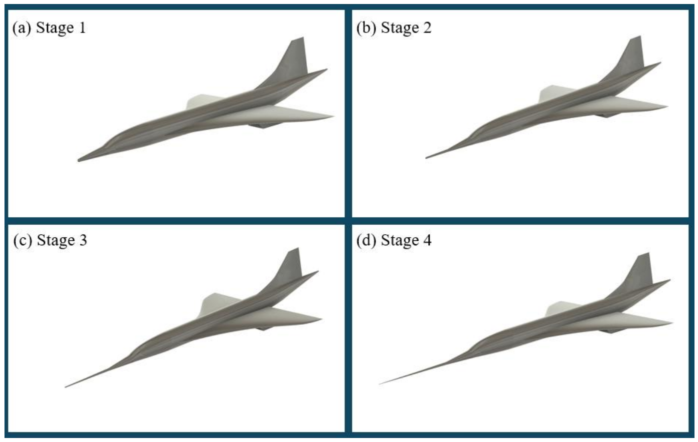

Figure 2 Four different Spike Stages

Computational Analysis

ANSYS Fluent was used to conduct the CFD simulation. The aircraft model geometry was imported into Design Modeller, and a C-Type domain was generated 40 m upstream and 60 m downstream. The aircraft model was subtracted from the domain using a Boolean command. The mesh generation was carried out using Fluent's watertight meshing. A poly hexacore mesh was used, and an inflation layer with 20 layers and a target wall y+ of 5 was applied to accurately resolve the boundary layer. The final mesh contained approximately 800,000 cells with an average orthogonal quality and skewness of 0.97 and 0.0024, respectively. A mesh-independent study was performed to ensure the accuracy of the results. The simulations were performed using a steady-state density-based solver. The K -ω SST turbulence model was employed as it is good at capturing the boundary layer Curvature correction and compressibility effect were enabled to improve accuracy[12]. The ideal gas model and Sutherland viscosity model were used to model the air properties. The Boundary conditions include a pressure far field and a pressure outlet based on the simulation setting from a base reference paper. The aircraft surface was defined as a no-slip wall. The operating conditions were based on standard atmospheric data at four Mach numbers 0.8,1.02,1.5 and 2. All cases were analysed at a 5-degree angle of attack. The implicit solver was used along with Solution steering to improve convergence and stability. The lift and drag coefficient was analysed and compared against the base reference paper to validate the results, following which the multi-stage spike was implemented and analysed under the simulation conditions from table 1 .

Table 1 Simulation conditions

Mach number	Angle of attack (degrees)	Altitude (m)	Temperature (K)	Pressure (Pa)	Density (Kg.m^{-3})
0.8	5	5090	255.09	53402	0.7359
1.02	5	7940	236.60	35961	0.5248
1.5	5	18288	216.65	7231.20	0.1206
2	5	18288	216.65	7231.20	0.1206

Results

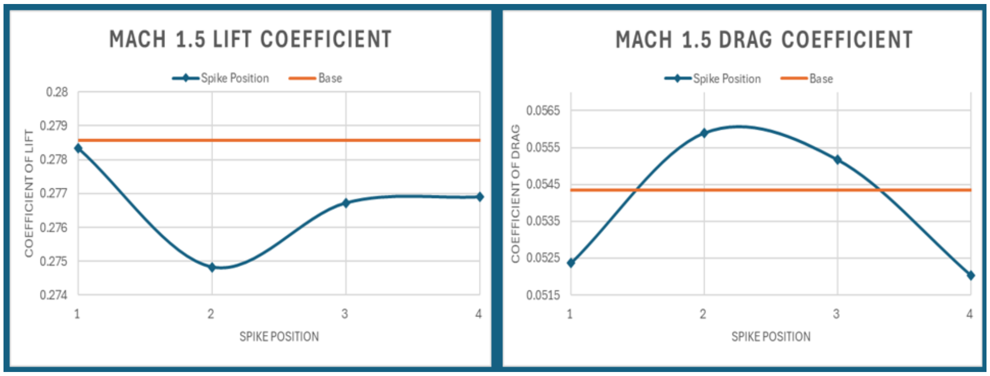

Figure 3 Lift and Drag Coefficient

At Mach 1.5, the baseline configuration produced a lift coefficient of 0.2786. With spike position 1, lift decreased marginally to 0.2783, a 10% decrease. The lowest lift was observed at position 2, while positions 3 and 4 had only a 0.6% decrease in lift relative to the baseline
In terms of drag, the baseline coefficient was 0.0543. Spike 1 reduced drag to 0.524, representing a 3,6% improvement. Position 4 achieved the greatest drag reduction with a 4.2% decrease in the drag coefficient. Considering both lift and drag, position 4 produced the most favourable lift-to-drag ratio. Thus, spike position 4 was identified as the most aerodynamically effective configuration at Mach 1.5

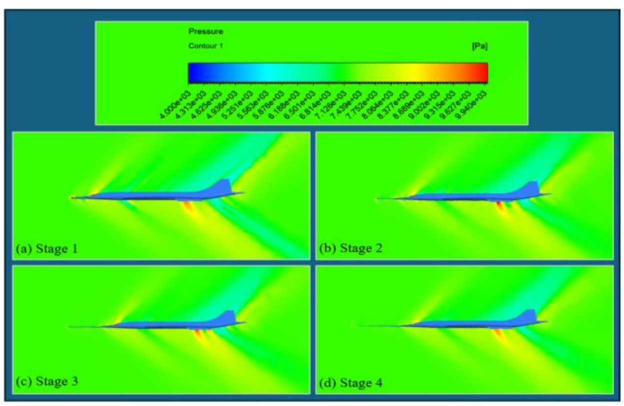

Figure 4 Spike stages pressure contours

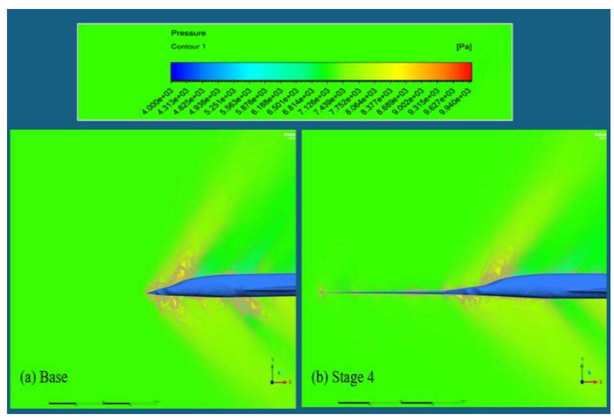

Figure 5 Nose Close-up Pressure Contours

The pressure contours in figure 4 further support these results. Across all supersonic cases, shock waves originated at the nose of the aircraft, with the shock deflection angle increasing as the Mach number increased. However, their intensity diminished progressively with the extension of the spike. The stage 4 configuration displayed notably weaker and more diffuse shocks, indicating improved shock mitigation at higher Mach numbers. Pressure distribution ranged between 4000 Pa and 9000 Pa. Overall, the analysis demonstrates that a multistage spike can efficiently reduce drag and improve aerodynamic efficiency at supersonic speeds.

A more detailed comparison in figure 5 of the baseline configuration with the stage 4 spike configuration clearly shows the representation of the shockwaves. The colour scale ranges from 4000 Pa in blue to 9000 Pa in red, with the green corresponding to approximately 7000 Pa, the atmospheric pressure at an altitude of 18000 m. In the base configuration, a strong singular shock was observed at the nose of the aircraft. The pressure contour in this region reaches close to 8800 Pa, significantly above the standard atmospheric pressure. This concentrated rise in pressure is a characteristic of wave drag due to the formation of a strong supersonic shock. By contrast, in the stage 4 spike configuration, instead of a single strong shock, there are multiple weaker shocks distributed along the length of the spike. These shocks appear to not coalesce, resulting in a lower intensity. This diffusion of the shock strength indicates improvements in reducing the wave drag and the overall total drag on the aircraft. Analysing the Lift to drag ratio across 4 different Mach numbers and spike positions, at Mach 0.8, the baseline achieves the highest L/D However, using a spike reduces the efficiency in subsonic Mach numbers. In the transonic regime, Mach 1.02 spike position 2 provides a 1.5% increase in the L/D. At supersonic Mach numbers, spike position 4 increases the L/D by 3.9% at Mach 1.5 and 0.38% at Mach 2. Based on these results, the spike should remain retracted at subsonic speeds, partially extended to position 2 at transonic speeds and fully extended at position 4 in supersonic flight to maximise aerodynamic efficiency and reduce drag, which will contribute to lower fuel consumption and emissions.

The results were validated against values from a previous study. Comparing the values at Mach 1.5, the coefficient values from the analysis deviated by only 3.77% and 5.54 % for the lift and drag coefficient values, respectively, from the reference study. Additionally, a mesh-independent study was conducted to ensure that the mesh quality did not affect the results, as can be seen in figure 6

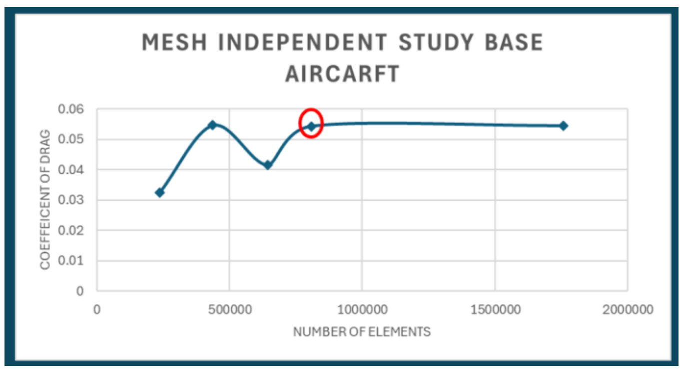

Figure 6 Mesh Independent Study

Conclusion

This study investigated the aerodynamic performance of a supersonic transport aircraft using a multi-stage nose spike to reduce total drag. Using CFD simulation in Ansys Fluent at Mach numbers 0.8,10.2,1.5 and 2, the lift and drag coefficients were analysed along with pressure contours. Results indicate that while the spike reduces efficiency in subsonic conditions. At Mach 1.5, the stage 4 position reduces drag by 4.23% and improves the lift to drag ratio by 3.9%. Pressure contours indicate that the spike diffuses the strong nose shock into multiple weaker shocks, reducing the drag. These results highlight the potential of a multistage nose spike for enhancing the aerodynamic performance and reducing drag and fuel consumption for future supersonic passenger aircraft.

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