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Design and Optimization of Supersonic Intake

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Abstract. The ideal supersonic intake was designed using the Theta-Beta-Mach relations and a CAD modelling software. After the design was done the optimization part was carried out. Initially the easy method of cowl deflection angle variation was used to get the optimum results at a particular angle and then the pressure recovery was maximized using the intake bleed technique. The bleed technique was optimized by fixing the best location of bleed according to the shock reflections in the intake and then maximizing the results analyzing the problem for various bleed diameter values. The mesh resolution for all the analyses was taken constant along with the turbulence model and solution methods. The analyses were carried out completely considering the free flow exit condition in the intake and the back pressure condition was not taken into account due to time constraints. Therefore, the pressure recovery or the efficiency of the intake is judged solely on the minimum velocity achieved in the intake. This value was used to maximize the intake too.

Index Terms—Supersonic intake, bleed, cowl deflection angle, optimization

1. Introduction

With the advent of modern CFD techniques it has become quite easy to design analyze and optimize everything. Out of all the components involved in supersonic flight, engine intake is the most important one whose operation affects the overall performance of the engine to a great extent. The basic use of it, simply being to slow down the incoming flow or increasing the pressure of the flow to make it eligible for combustion. Simple as it sounds, it is done by a neat arrangement of shockwaves which are formed by the supersonic flow interacting with the ramp and the cowl tip. The shockwaves further keep reflecting after interacting with the cowl tip to form a final normal shock downstream in the back pressure condition. When the incoming flow interacts with these shockwaves, the flow properties change abruptly. The changes which we are concentrating on are, increase in pressure and decrease in velocity, which is exactly what is needed for a good combustion.

There are various types of supersonic intakes which are currently used depending on the Mach operation range and operating conditions for which the vehicle is designed. The ramp is intentionally designed in such a way that it creates strong shock which further reflects to form numerous others downstream. It is preferable for an intake with same pressure recovery to have numerous weak shocks than having one strong shock. The reason being, a strong shock can largely increase the total drag which in a way decrease the performance even when it is performing well in terms of pressure recovery. In addition to increasing the drag, strong shocks are also not preferred when it comes to integrity of the structure of the intake. Stronger the shocks, stronger the intake structure will have to be to bear the forces exerted by strong shocks which in turn will increase the weight of the overall intake and thus the efficiency will decrease too. A hypothetical intake which has infinite shockwaves is known as isentropic intake.

In modern designs, the researchers are trying to achieve maximum number of shockwaves by changing the ramp contour. Each downstream ramp is steeper than the previous one, which helps in increasingthe number of reflected shockwaves and in turn, increases the efficiency of the intake. The efficiency of intake can also be increased by changing the cowl deflection angle and adding a bleed downstream. These two techniques are used in this project to maximize the pressure recovery for an intake design using ANSYS Fluent.by considering the free flow exit condition in all the analyses and a Mach number of 2.2. The intake design was taken as mixed compression which means the compression takes place upstream of the cowl tip and also by the shock trail inside the intake.

There are different methodologies developed for increasing the pressure recovery at various flight regimes and attitudes. Some of them are variable geometry intake which includes cowl deflection angle change, bleeding, perforation and diffuser length variation out of which variable geometry intake is one of the handiest method to achieve a good pressure recovery at varying attitudes. Bleeding the intake is always a second priority as there will be a loss of mass flow rate through the bleed thus, controlling the bleed diameter or the bleed mass flow is very essential while incorporating this method as excessive bleeding can overrule the advantage of this method and lead to pressure loss. In this project two methods, cowl deflection angle change and the bleeding of intake have been used to optimize the designed intake for zero-degree angle of attack.

2. Design Procedure

The intake design was initiated by the 15-degree wedge shock analysis and the result of the shock angle was verified using the Theta-Beta-Mach graph. The shock angle achieved was 45 degrees which was exactly the result from the graph as well. After this the ramp intake diameter was chosen from Reference-I the cowl tip was accordingly positioned to take the first shock from the ramp approximately at its tip. Initially a single shock generating ramp was used to achieve proper reflections throughout downstream as shown in figure-1.

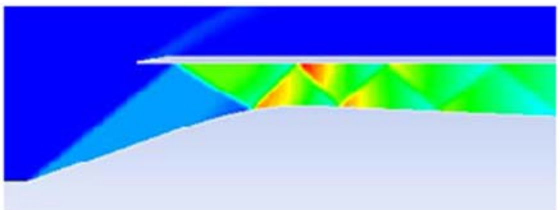

Figure-1: Initial design with simple ramp contour

After this the ramp contour was modified to produce two shocks meeting at the cowl tip without changing the lateral or longitudinal dimensions of the cowl tip with respect to the ramp to check the location where shock intersects. The pressure recovery will not be increased much by this but the gradual

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compression through two weak shocks and further reflections will increase the overall structural integrity of the intake as there won't be any strong shock directly impinging on the structure to damage it, thus the cost on material can be reduced to a great extent. After proper positioning of the shock on the cowl tip the optimization process was started. To position the shock exactly on the tip with the two shock ramp, the cowl was moved laterally towards the shock intersection so that both the shocks from the ramp intersect and impinge the cowl at the tip as shown in the figure-2. The first shock is the weak one due to the lower ramp angle which is 7 degrees and a stronger shock due to the 14-degree ramp after that. These two shocks exactly meet at the cowl tip and gets reflected from there further downstream and weakens with each reflection due to interaction with the boundary layer.

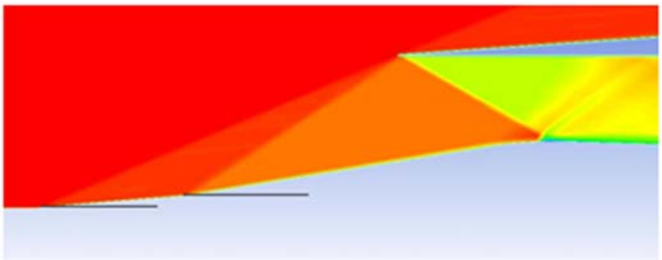

Figure-2: Final design with two angles on the ramp

3. Mesh and Setup

The boundary layer had to be captured in this problem so the mesh resolution was high at the inside boundaries of the intake with the first cell size being 0.0004m progressively increasing to coarse mesh. Overall the mesh was kept coarser than it should actually be to account for the limitations of the academic version of ANSYS. But, all the analyses were carried out for the same mesh resolutions so the results may not be accurate but the results can surely be compared with the previous ones to carry out the optimization process. The mesh at top part of the cowl was coarsely done as that was not the area of interest here. The complete geometry was divided into four blocks out of which two blocks were meshed with higher resolution and inflation on the edges and the other two blocks were coarsely handled. The preview of the mesh with the quality at intake cowl area is shown in the figure-3. Number of nodes were 4 lakhs 50 thousand.

Analysis was carried out for 5 lakh nodes by further refining the mesh at the regions where shocks are formed and the results were found similar to the previous mesh but there was a difference in the results of the 4 lakh mesh and the 4 lakh 50 thousand mesh so the later was chosen for all the further analyses to make sure that the solutions are independent of the increase in mesh density.

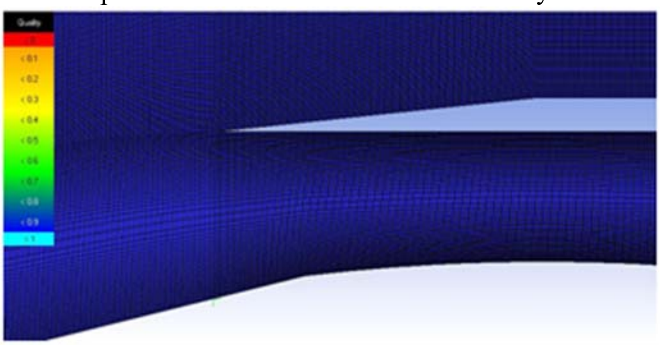

Figure-3: Mesh for the region near the cowl tip

4. Cowl Deflection Angle Variation

Cowl deflection angle is the angle between the inner line of the cowl tip and the horizontal line touching the cowl tip. In this project the deflection angle was varied from 1 degree to 6 degrees and the minimum velocities achieved were documented for each angle. The pressure recovery increases up to 5 degrees and then experiences a sudden drop after increasing it more than 5 degrees. The minimum velocity plot is shown in the figure-4 with respect to the cowl deflection angle.

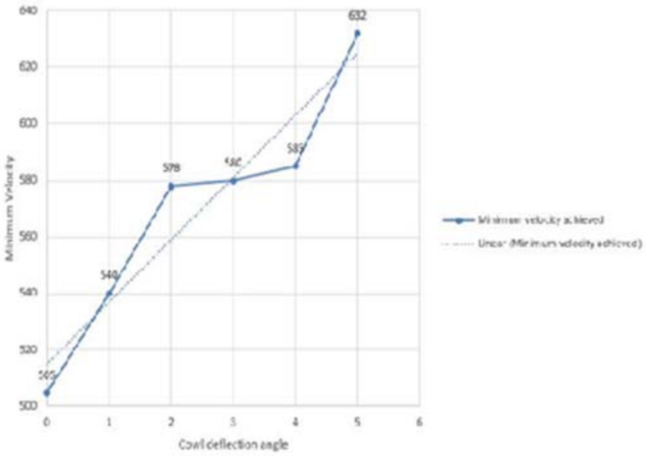

Figure-4: Minimum velocity vs. Cowl deflection angle plot

From the plot we can observe that as the cowl deflection angle increases, the pressure recovery that can be achieved from the intake decreases substantially. The reason for this is that as we increase the cowl deflection angle, the shock impinging on the cowl tip will reflect at a much lower angle downstream compared to low cowl deflection angle or zero angle where the shock directly reflects at a steep angle. We know that when the shock angle is high or the shock is near normal it is much stronger than the slant shocks that are formed due to high cowl deflection angles. Thus, property changes through the strong and weak shock will obviously differ and there will be less compression occurring through the weaker shock which is formed at higher cowl deflection angles than the stronger shocks formed at the lower or zero cowl deflection angles. When there is less compression the overall pressure recovery will decrease. This is why the minimum velocity achieved at higher cowl deflectionangles are high and thus the pressure recovery is low at high angles. The figure-5 shows the above explained reason with 1 and 5-degree cowl deflection angle. As shown in the figure, the shock reflects and impinges the cowl further downstream in 5 degree compared to the 1-degree cowl which increases the compression in the 1-degree cowl deflection angle intake.

So, as the cowl angle keeps increasing, the pressure recovery will decrease and then suddenly fall after a point at which the two initial shocks are no longer able to impinge at the cowl tip due to large increase in cowl deflection angle.

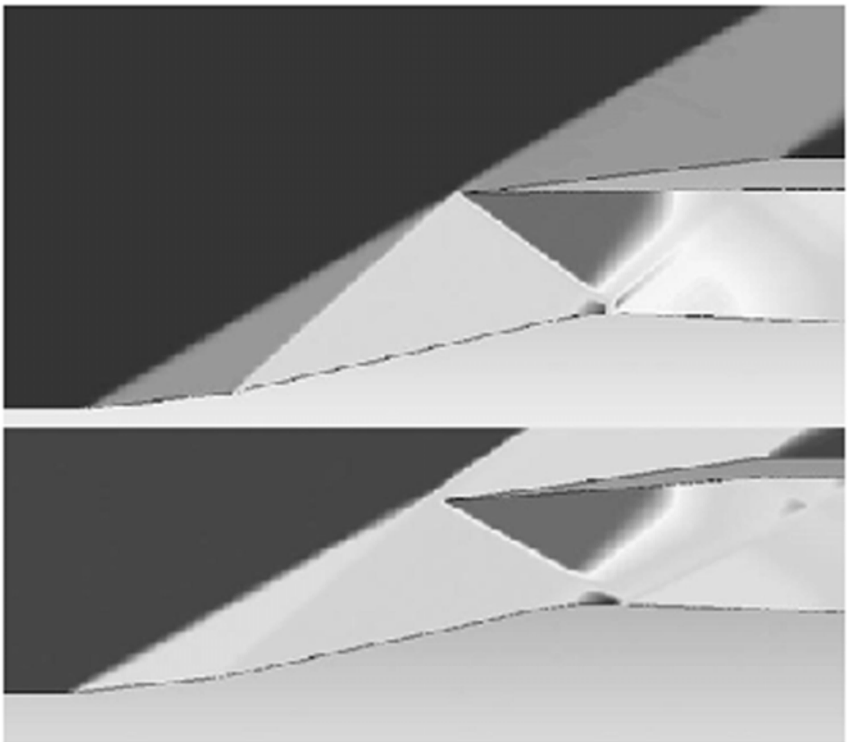

Figure-5: Cowl deflection angle 1degree-steeper shock, 2. Cowl deflection angle 5degree-decreased shock angle

The figure-6 shows results of pressure recovery v/s cowl deflection angle and it is clear that as the cowl deflection angle increases the pressure recovery decreases. Above figure shows highest pressure recovery at 1-degree and lowest at 5-degree cowl deflection angle. Similar to the results that we have achieved in terms of minimum velocity which is with the increase in cowl deflection angle the minimum velocity achieved in the intake increases which in turn means that the pressure recovery is reduced. Variation in cowl deflection angle can only be done up to certain angle as after a certain angle the pressure recovery will abruptly drop due to sudden decrease in mass flow rate which is due to decrease in frontal area. It is a good method to control the pressure recovery while the aircraft attains high angle of attacks.

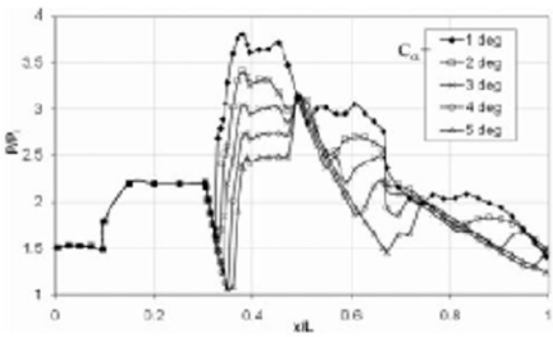

Figure-6: Results from reference [1]

5. Bleed Diameter Variation

Bleeding the intake is a very complex and expensive technique used to increase the pressure recovery by bleeding the boundary layer which reduced the effects of weakening of shock after interacting with boundary layer and thus improves the pressure recovery which in our case decreases the minimum velocity value for free flow exit analysis. Bleeding the intake has a considerable disadvantage too, the performance of the engine can go down as a part of the mass flow is directed to the bleed duct which decreases the mass flow of air reaching the combustion chamber. Working a way out between the disadvantage of reduced mass flow and the advantage of bleeding the boundary layer is a challenge for every intake design engineer. The initial task was to choose a proper location for the bleed.

When the shockwave impinges the boundary layer formed due to the ramp, there is a sudden increase in the boundary layer thickness which in turn decreases the mass flow rate that can be allowed through the intake by decreasing the effective intake area. So, the perfect location for the bleed for this intake will be exactly after the location where the strongest shock impinges downstream of the ramp. This will reduce the sudden bump in the boundary layer which will increase the effective intake area and thus increase the mass flow rate going in the engine. It also affects the strength of the reflecting shock. If the boundary layer is bleeded, the shock that reflects will be much stronger than the shock reflected without the bleed so the compression will be more in the intake with bleed and thus the pressure recovery will also be more in the bleeded intake. The figure-6 shows how bleeding the intake increases the reflected shock strength and the bump in the boundary layer after the impinging point.

From figure-7 it is clear that the second diagram with bleed added shows higher strength of shock wave after reflection because of the reason explained previously.After considering and verifying the bleed advantages the optimization of the bleed duct can be done. Here the bleed duct diameter is considered as the variable that can be adjusted to achieve maximum performance from the intake at design Mach numbers and zero angle of attack.Initially, the intake was analyzed with 2mm bleed diameter and with a similar mesh analysis was done for 3, 4 and 5mm bleed diameter and the results were documented. The figure-8 shows the plot of minimum velocity with respect to bleed diameter.

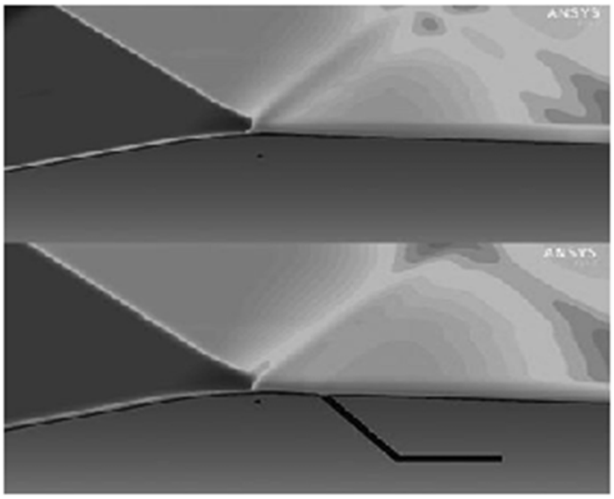

Figure-7: With and without bleed respectively for an intake with 5-degree cowl deflection angle

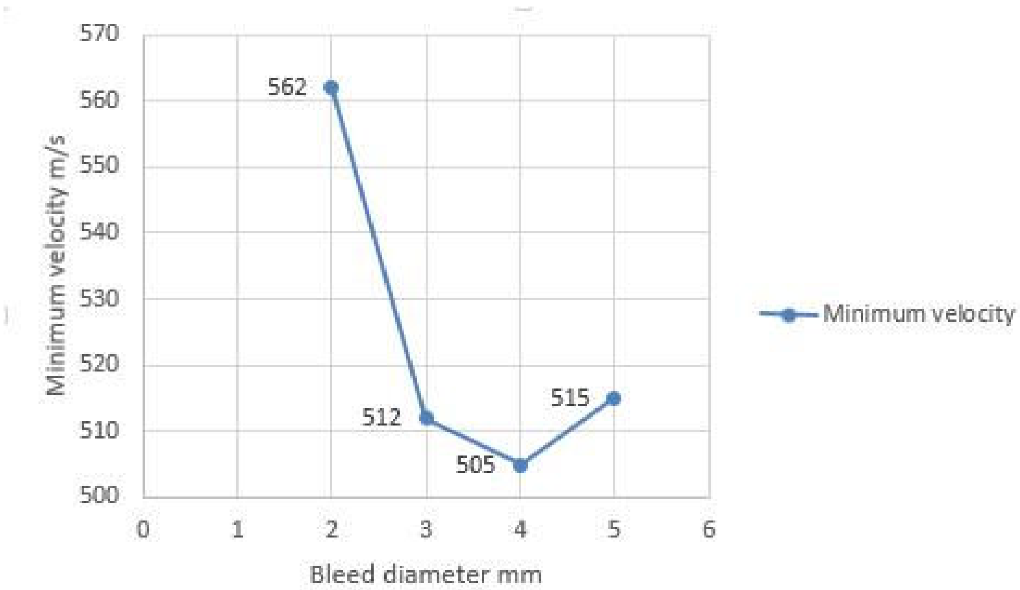

Figure-8: Plot of minimum velocity vs. bleed diameter

When the intake is bleeded and the end of the bleed is declared to be as pressure far field the pressure inside the intake will be much higher due to compression than the pressure at pressure far field or outside the intake. This will create a force on the boundary layer pushing it through the bleed duct. This is how the boundary layer is bled from the intake to increase the performance. As the bleed diameter is increased up to a certain point the performance of the intake is increased or the minimum velocity achieved will decrease but after a point say 4mm the minimum velocity suddenly increases which shows that the bleed diameter is exceeding its optimum value. When the bleed diameter exceeds this value the mass flow rate escaping through the bleed air duct increases a lot which will disrupt the flow uniformity and also weaken the shocks reflecting in the intake which is why the minimum velocity increases in the free flow exit condition which means the pressure recovery will decrease after this point for the intakes with back pressure acting on them. Due to these reasons for maximizing the pressure recovery for this design a bleed duct diameter of 4mm was chosen.

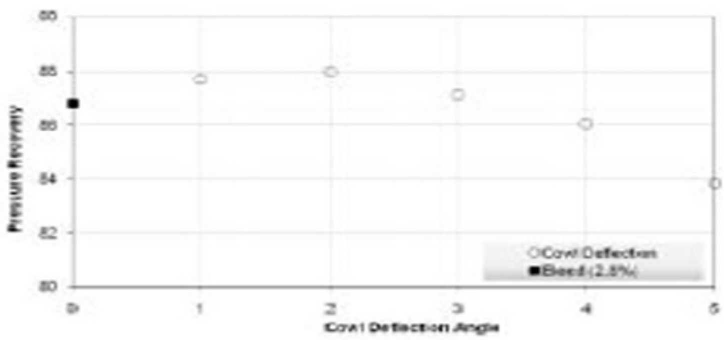

Figure-9: Bleeded intake results from reference [1]

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It can be observed from figure-9 that bleeding the intake by withdrawing 2.8% of mass flow given almost same pressure recovery as obtained by cowl deflection angle of 3-degree.

6. Conclusion

A supersonic intake is designed using the Theta-Beta-Mach relations and is optimized by using two techniques. First one being the cowl deflection angle change wherein the angle can be varied according to the operating conditions and attitude of the aircraft. It can be varied accordingly and a trend was obtained which shows that the pressure recovery decreases as the cowl deflection angle increases. Secondly the bleed duct was added to improve the performance of the intake and through various analyses a 4mm bleed just after the shock reflecting location was found to be most effective for this design with cowl deflection angle of 5 degrees and a Mach number of 2.2. Also, a simpler methodology was created to predict the increase and decrease in pressure recovery and it was found that predicting the behavior through minimum velocity achieved also does well in studying the trend through various parameters while optimizing the intake

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