Starting Characteristic of Supersonic Mixed Compression Air Intake with Cowl Porosity

N K Gahlot\textsuperscript{1,2}, N K Singh\textsuperscript{3}

\textsuperscript{1}Research Scholar, Department of Mechanical Engineering, NIT Kurukshetra, India
\textsuperscript{2}Assistant Professor, Department of Mechanical Engineering, SRM IST, Ghaziabad, India
\textsuperscript{3}Associate Professor, Department of Mechanical Engineering, NIT Kurukshetra, India

E-mail: \textsuperscript{1}neerajkumargahlot@gmail.com, \textsuperscript{3}kant.nirmal@gmail.com

Abstract. The present study is aimed towards the investigation of starting characteristic of supersonic air intake by adopting the cowl porosity. A computational study has been performed with k-omega turbulence model adopting the RANS solver. Air Intake shows the unstart phenomenon for the clean model case and this could be due to large shock wave boundary layer interaction near the throat. After implementing the cowl porosity, intake shows the starting behavior and there after a compression in the flow is observed. It also improves the quality of flow and performance of supersonic air intake. The obtained result have been validated with the previously published data. All the calculations were performed at design Mach no of 2.2 for free flow conditions.

1. Introduction

The main purpose of the supersonic air intake is to provide adequate air requirement for the combustion chamber of an air-breathing engine, especially at supersonic flow conditions. It plays a major role in evaluating the performance of an air-breathing engine by providing the desired mass flow rate, low distortion flow while operating at various operating conditions of supersonic flow regimes. In mixed compression supersonic air intake, a small part of flow compression takes place outside of the intake and rest of the flow is compressed while flow travels inside the duct. The major issues in flow compression arise due to shock wave boundary layer interaction (SWBLI) near the throat of the supersonic air intake, which could possibly lead the intake unstart. Various flow control methods such as flow injection, flow speeding, bleed, variable area duct and ventilation of the flow could be utilized to reduce the complexity of flow inside the duct and make the intake start.

For an understanding of the complex flow field existing inside the duct, various studies have been reported by the researchers in literature. (Das and Prasad 2010) conducted a two dimensional study on the starting characteristic of supersonic air intake with combined cowl deflection and bleed to improve the performance of the intake. Experimental studies were carried out for internal/external compression intake by implementing the variable duct, different bleed system and different diffuser shapes to overcome the starting problem at design Mach no of 2.2 by (Neale and Lamb 1962). The intake indicated starting behavior with adoption of cowl translation and bleed. Starting characteristics of intakes at supersonic speed were reported by (Kubota, Tani, and Masuya 2006) for a bent cowl with different contraction ratios. (Wie and Kwok 1996) performed experiments to study the starting behavior of intakes with variations in cowl height and length with emphasis on improvement of performance by...
fluid injection. (Trapier, Duveau, and Deck 2006) conducted experimental studies on supersonic inlet buzz due to unsteady unstart phenomenon. (Reinartz et al. 2003) have carried out the numerical and experimental studies with different isolator lengths of a hypersonic inlet to improve the flow quality. Use of conventional method of bleeding air to improve intake performance is reported in many articles. Numerical investigation of different bleed models for a mixed compression inlet has been reported by (Vivek and Mittal 2009). (Gawienowski 1961) conducted various experiments with different bleed slot size and mass flow rates to evaluate the performance of an external compression supersonic air intake. Performance parameters were projected and it was found that upon increment in bleed slot area and mass flow improves the performance of intake. (Syberg and Koncsek 1973) reported the effect of bleed hole geometry and its inclination for an effective bleed system to improve the flow field. The outcome of different bleed system at a variety of locations on hypersonic intake is calculated by (S Pandian 2001). Shock wave-boundary layer with bleed slot interaction studies were reported by (D. Kim, Hingst, and Davis 1997). Use of micro ramp vortex generators to control the boundary layer which improves the inlet performance is demonstrated by (Ogawa et al. 2008). Improvement of overall performance adopting a bump in intake is recently reported by (S. D. Kim 2009). This clearly shows that the flow control is necessary to improve the performance of air-intakes. The usefulness of passive, hybrid and active methods has been investigated and compared with one another experimentally by (Doerffer and Bohning 2003). An experimental assessment of two passive approaches for controlling the shock interaction with a turbulent boundary layer: low-profile vortex generators and a passive cavity (porous wall with a shallow cavity underneath) is conducted by (MCCORMICK 1993). Investigation shows an improvement in the flow filed.

From the literature, it can be inferred that various techniques has been adopted by various researcher to make the intake start and cowl porosity might be one of them. An effort has been made in the present study to analyze and visualize the effect of porosity in the cowl on the performance of the supersonic air intake (Especially on the starting characteristic). All the simulations were conducted at Mach 2.2 for supersonic exit flow and results obtained are compared with the results available in the literatures.

Till now the starting behavior of supersonic air intake is reported by using the active methods in most of the literature. In the present work, passive technique (cowl porosity) is used, which is not reported yet.

2. Intake geometric details

Figure 1 shows the geometrical details of the supersonic air intake. Two ramps have been used to compress the flow. Ramp 1 and 2 are having the angles 7 and 14 degree respectively. The divergent portion of the intake are deflected to 2.5 and 6 degrees respectively. The cowl inner surface is parallel to the free-stream direction. The overall length (L) of the model is 130.98 mm with a capture height (h_c) of 63.5mm.

![Figure 1. Intake geometry details](image-url)
3. Methodology
Three-dimensional simulations were performed to simulate the flow inside the mixed compression supersonic air intake. All the simulations were performed for Mach no 2.2. The computations were performed in ANSYS. Fluent to solve the RANS for compressible flow by adopting the finite volume technique with standard turbulence model K-Omega turbulence model was adopted for the present case. A structured mesh was created with minimum spacing in the y-direction near the wall of 0.1 mm. Three different grids (500000 cells, 600000 cells and 700000 cells) were created for the base geometry and based on the result Grid 2 of 600000 cells was chosen for the further computations for all the geometries. Figure 2 shows the meshing of the supersonic air intake with cowl porosity (various rectangular and square shapes holes have been made on the cowl surface) along with extended chosen domain & adopted boundary conditions. A symmetry boundary condition was adopted to minimize the computation time due to the symmetry of the geometry. All the computations were made for the supersonic exit condition. Residual of density and turbulent kinetic energy were monitored during the simulations and a suitable convergence criteria ($10^{-3}$) was set for the convergence of the solutions.

![Figure 2: Showing the details of mesh with extended domain along with boundary conditions.](image)

4. Results and discussion
Computations were performed to get an understanding of the flow field around a rectangular mixed compression supersonic air intake with and without porosity. Computations using the commercially available software FLUENT, were carried out at Mach number of 2.2.

Figure 3 shows the similarity of obtained density contours of current computation with results (computational and experimental) published in literature. Figure 3 a, and b clearly show the bow shock over the cowl tip with huge spillage. Here the bow shock impinges over the second ramp and interacts with the boundary layer, leading to the separation zone and expelling the shock out of the throat. We observe the spillage over the cowl tip and no internal reflection inside the duct which shows the unstart condition of the intake. Figure 3 c and d show the shocks emanating from the first and second ramps very noticeably. The reflected shock from the cowl tip impinges on the ramp surface just downstream of the shoulder. The reflected shock waves in the diffuser and the expansion waves from the outer side of the cowl and inside the duct are seen clearly. It can be seen that by
implementing the bleed\textsuperscript{1} and cowl porosity (present computation) intake can be seen in starting condition. However the flow seems to be very complex near the throat area due to the implementation of cowl porosity.

Figure 3: Density contour at Zero-degree cowl deflection for Mach no of 2.2, (a) Clean model (present computation), (b) Ref Experiment\textsuperscript{1}, (c) Cowl with porosity (Present Computation), (d) Bleed Computation\textsuperscript{1}

Figure 4: Density contour for 2-degree cowl deflection

Figure 4 shows the density contours for 2 degree cowl deflection at Mach no 2.2. It also shows a similar behavior of shock pattern inside the duct but the intensity and strength of the reflected shock seems to be a little less as compared to zero degree cowl deflection (with porosity in near the cowl tip).
Figure 5: Ramp pressure distribution at Mach 2.2

Figure 6: Cowl pressure distribution at Mach 2.2

The ramp surface pressure distribution is shown in Figure 5. For clean model, it can be seen from the ramp pressure distribution that the pressure is constant along the first ramp. There is an increase in pressure from the first ramp to second ramp due to the presence of the second oblique shock emanating from the second ramp. There is huge pressure rise over the second ramp which is due to bow shock. But for other cases (2 degree cowl, zero degree cowl with porosity and zero degree cowl with bleed) it is observed that the pressure is constant along the first ramp and second ramps with an increase in pressure from the first to second ramp due to the oblique shock emanating from the second ramp. There is a sudden decrease in pressure at the shoulder of the intake due to the expansion corner. The pressure starts to increase in the diffuser part of the intake due to the presence of reflected shock waves. The fluctuation in pressure near the throat area (because of the porosity) is also observed. This pressure fluctuation will be more on the cowl side and less on the ramp side. It can be validated from the cowl pressure distribution as shown in figure 6. It may produce an adverse effect on the performance of the supersonic air intake.

Figure 7: Exit total pressure distribution at (a) Z/W=0 (b) Z/W=0.5

Figure 7 shows the total pressure distribution at the intake exit for various Z/W (ratio of location along z axis to the total width of the supersonic air intake). Only a small amount of variation in total pressure is observed for all the cases at Z/W=0 but the total pressure distribution at the intake exit at
Z/W=0.5 shows significant improvement. This clearly indicates the improvements in the flow field condition by implementing the cowl porosity or cowl bending.

Pressure recovery (PR), an important performance parameter of an intake, was calculated by using the following equation

$$\text{PR}=\frac{1}{n}\sum_{j=1}^{n}\left(\frac{P_{o_j}}{P_{o_0}}\right)$$

Table 1. Estimated Pressure recovery and flow distortion for the free exit flow.

| Cases                          | Pressure Recovery % | Flow distortion % |
|-------------------------------|--------------------|-------------------|
| Clean model                   | 80.74              | 0.85              |
| Cowl bending of 2 degree      | 83.41              | 0.90              |
| Zero degree cowl porosity     | 74.31              | 0.97              |

For the better performance of the supersonic air intake the pressure recovery should be high. Table 1 shows the comparison of pressure recovery for the three cases (clean model, 2 degree cowl bending and zero degree with cowl porosity). It can be seen that the PR is high in the case of 2 degree cowl deflection, because it is the design condition. As mentioned earlier, due to the pressure fluctuations near the throat area the PR is not up to the mark. Similarly the lesser the flow distortion (FD), better will be the performance of the supersonic air intake. But for the current case flow is getting distorted and it might be because of the complexity of flow inside the duct due to the disturbance produced by porous cowl surface. FD can be calculated by using the following relation.

$$\text{FD}=\left(\frac{P_{o_{\text{avg}}}-P_{o_{\text{min}}}}{P_{o_{\text{avg}}}}\right)$$

Figures 8 and 9 show the Mach no and total pressure distribution at the throat of supersonic air intake. Highest value of the Mach no recorded is 2 for the current case which is larger as compared to the other two cases. Similarly the improvement in total pressure distribution can be observed by implementing the cowl porosity.
5. Conclusions
Investigation of flow field around supersonic mixed compression air intake with cowl porosity has been made using computations at supersonic speed. Three dimensional turbulent simulations show interesting features with cowl porosity. Intake shows the unstarting characteristic for zero degree cowl deflection without porosity which might be because of the bow shock appearing just before the throat and might partially be because of an interaction of shock wave boundary layer near the throat area. Results show that this issue can be resolved to some extent by utilising the porous cowl and intake shows the starting characteristic. However the flow physics seems to be complex and performance parameters can be improved by incorporating the active and passive methods of flow control for the current case.

References
[1] Das, S., and J. K. Prasad. 2010. “Unstart Suppression and Performance Analysis of Supersonic Air-Intake Adopting Bleed and Cowl Bending.” Journal of the Institution of Engineers (India): Aerospace Engineering Journal 91(MAY): 27–35.
[2] Neale, M C, and P S Lamb. 1962. “Tests with a Variable Ramp Intake Having Corn Bined External/Internal Compression, and a Design Mach Number of 2.2.” Aeronautical Reasearch Council (CP-805): 1–35.
[3] Kubota, Shinji, Kouichiro Tani, and Goro Masuya. 2006. “Aerodynamic Performances of a Combined Cycle Inlet.” Journal of Propulsion and Power 22(4): 900–904. http://arc.aiaa.org/doi/10.2514/1.17777.
[4] Wie, D M Van, and F T Kwok. 1996. “AIAA , ASME , SAE , and ASEE , Joint Propulsion Conference and Exhibit , 32nd , Lake Buena Vista , FL , July 1-3 , 1996.” (July).
[5] Trapier, Simon, Philippe Duveau, and Sébastien Deck. 2006. “Experimental Study of Supersonic Inlet Buzz.” AIAA Journal 44(10): 2354–65. http://arc.aiaa.org/doi/10.2514/1.20451.
[6] Reinartz, Birgit U., Carsten D. Herrmann, Josef Ballmann, and Wolfgang W. Koschel. 2003. “Aerodynamic Performance Analysis of a Hypersonic Inlet Isolator Using Computation and Experiment.” Journal of Propulsion and Power 19(5): 868–75. http://arc.aiaa.org/doi/10.2514/2.6177.
[7] Vivek, P., and Sanjay Mittal. 2009. “Buzz Instability in a Mixed-Compression Air Intake.” Journal of Propulsion and Power 25(3): 819–22. http://arc.aiaa.org/doi/10.2514/1.39751.
[8] John J. Gawienowski. 1961. “The Effects of Boundary-Layer Removal Through Throat Slots on the Internal Performance of a Side Inlet at Mach Numbers of 2 and 2.3.” NASA Technical Memorandum, NASA TM-X-502.
[9] Syberg, Jan, and Joseph L. Koncek. 1973. “Bleed System Design Technology for Supersonic Inlets.” Journal of Aircraft 10(7): 407–13. http://arc.aiaa.org/doi/10.2514/3.60241.
[10] S Pandian, J Jose, M M Patil and P Srinivasa. 2001. "Hypersonic Air-Intake Performance Improvement Through Different Bleed Systems." ISABE-2001-1039.
[11] Kim, D, Warren R Hingt, and O Davis. 1997. “Experimental Investigation of Crossing Shock Wave-Turbulent Boundary Bleed Interaction.” Nasa Technical Memorandum (January).
[12] Ogawa, H., H. Babinsky, M. Pätzold, and T. Lutz. 2008. “Shock-Wave/Boundary-Layer Interaction Control Using Three-Dimensional Bumps for Transonic Wings.” AIAA Journal 46(6): 1442–52. http://arc.aiaa.org/doi/10.2514/1.32049.
[13] Kim, Sang Dug. 2009. “Aerodynamic Design of a Supersonic Inlet with a Parametric Bump.” Journal of Aircraft 46(1): 198–202. http://arc.aiaa.org/doi/10.2514/1.37416.
[14] Doerrfuer, Piotr P., and Rainer Bohnning. 2003. “Shock Wave - Boundary Layer Interaction Control by Wall Ventilation.” Aerospace Science and Technology 7(3): 171–79.
[15] McCormick, D. C. 1993. “Shock/Boundary-Layer Interaction Control with Vortex Generators and Passive Cavity.” AIAA Journal 31(1): 91–96. http://arc.aiaa.org/doi/10.2514/3.11323.
**Nomenclature**

| Symbol | Definition                                      |
|--------|-------------------------------------------------|
| L      | Total length of the intake                      |
| M      | Local Mach number                               |
| P      | Static Pressure                                 |
| $P_c$  | Intake exit pressure                            |
| $P_{\text{inf}}$ | Free stream pressure          |
| $P_{\text{oi}}$ | Free stream total pressure             |
| $P_{\text{oe}}$ | Intake exit total pressure             |
| SWBLI  | Shock wave boundary layer interaction          |
| W      | Width of the intake                             |
| X      | Location of a point along the length of intake from the leading edge of ramp |
| Y      | Location of a point along height of intake      |
| Z      | Location of a point along span of intake        |