EFFECT OF GEOMETRIC DISTORTION ON THE FLOW FIELD AND PERFORMANCE OF AN AXISYMMETRIC SUPersonic intake

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ABSTRACT

Supersonic intakes are designed and used for reducing the speed of inlet air to the engine from supersonic to subsonic. In this case they must conduct the air with lowest loss and drag together with a given pressure and speed with best quality and uniformity to the engine. This is done based on flight Mach number, by an arrangement of shock waves in the inlet. Any distortion in the flow field and inlet geometry parameters may disrupt such arrangement and influence on the input efficiency and under critical conditions, it might unstable the intakes. This study aims to investigate the effects of geometric distortions on the surface of a spike. For this reason, there have been conducted some numerical simulations for air flow in a axisymmetric inlet. Initially the accuracy of results from simulation were compared with experimental results for no-distortion geometry and after verification of numerical solution characteristics, distortion has been added to simulation under different states. The effect of position and geometry of distortion was then analyzed on performance parameters of air intake. These studies indicated the considerable effect of position and size of distortion on arrangement of shock waves in front of an inlet and there have been observed different pressure loss and drag depending on locating the distortion in upstream or downstream of rear shock wave.

KEYWORDS: Axisymmetric Intake, Supersonic, Geometric Distortion, Numerical Simulation, Performance.

Most aircrafts and missiles designed and manufactured for operational missions in the supersonic flight system are equipped to air-breathing engines. These engines, mostly with supersonic combustion, must come with a flow with low speed and high pressure under related flight and mission conditions for combustion. Such increased pressure and reduced speed will be made in the air inlet and compressor depending on the type of engine used as well as flight Mach number. The supersonic air intake, designed and manufactured for reducing the flow speed from supersonic to subsonic, must come with lowest pressure loss and drag together with best quality and uniformity required for engine inlet.

In supersonic intakes, formation of shock waves, their impact and happening of phenomena such as interference of shock waves with boundary layer may make non-linear behavior and complexity in flow solution. Under some conditions, above mentioned cases together with instability in such inputs may complicate solving numerical problems (Kawai & Fujii, 2004). In the body fitted intakes, changes in the air mass flux and spillage air may increase such complexity. Intakes are designed such that they can provide the engine with mass flow rate with acceptable flow distortion and having lowest total pressure loss and external drag (Goldsmith & Seddon, 1993).

In supersonic intakes, shock waves and their interferences, simultaneous presence of internal and external fluxes and different flow regimes add the complexities of solution (Esenvein & Valerino, 1951).

Axisymmetric air inlets having better performance aerodynamically are better than other inlets (Seddon & Goldsmith, 1999). Axisymmetric inlets divided into two classes of spiked and non-spiked. Single-conical spiked air inlet is used to increase the pressure loss in normal shock wave for Maches higher than 1.5. Single-conical inlets are suitable and operational for flight ranges between 1.5 to 2.5 Mach, and for higher Maches, dual-conical and isentropic spikes are being used (Seddon & Goldsmith, 1999). In a propulsion system in supersonic flight, inlet is considered as an important part playing more roles in producing the thrust (Roskam, 1987).

Inlets with external compression have three operational states, sub-critical, critical and super-critical and optimal performance occurs by function under critical conditions, i.e. state that normal shock wave is placed by the inlet entry. In this state, oblique shock wave in front of spike passes from cowl lip resulting in less spillage air and reducing additional drag. These inlets practically function under sub-critical state; because critical conditions are‘n’t stable and by changing Mach number will be changed due to presence of environmental and geometrical distortions and position of shock wave and inlet will perform under sub-critical or super-critical conditions resulting in changes in the efficiency parameters such as mass flow rate (Macheret, Schneider & Miles, 2003). At the meantime, such instability may reduce the performance of engine and also pressure fluctuations may destruct the structure and providing many problems in the combustion chamber and engine stalling and rate of such effects depends on the ranges of fluctuations in such pressures (Trapier, Deck & Duvena, 2007). Pressure fluctuations might occur by changes in the flow parameters like mass flow rate and or occurrence of other fluctuations such as cross wind in the airflow entering to intake.

Studying the distortions in the air intake flow can be done by different methods. Mass flow rate fluctuations can be studied...
by changes in the conditions of engine and making a distortion in the upstream flow. Authors couldn’t find any study previously conducted in the field of studying the distortions on air inlet flows related to influence of geometrical distortions; although there are similar studies on other cases such as fuselage perturbation (Heidari et al., 2010). Based on the importance of this subject, this study investigated the effects of geometrical distortions by using numerical simulations. For this reason, geometrical distortion that might be made by sticking external objects or ice on spike or damage is modeled in the front part of the spike and its effect was investigated on performance of a supersonic inlet by numerical solution.

As the speed is reduced to subsonic by an arrangement of oblique, normal and or combined shock waves in supersonic inlets, depending on the flight Mach number, therefore the arrangement of such shocks are very important and considerable. In the designed situation, such arrangement is in its best state and it is tried to not letting it to getting out of control in the out-of-design condition because any change due to distortion and or under external conditions of design may disarrange it and adversely influence on the performance as well as stability of supersonic air inlets.

As stated above, air inlet must make the best and highest quality flow in the inlet of engine with least pressure loss as well as minimum drag. Pressure recovery parameter is one of the most significant parameter indicating the pressure loss in the air inlets. Knowing the stagnation pressure of flow and stagnation pressure in the engine face, it can be calculated as below:

$$PR = \frac{P_{sf}}{P_{\infty}}$$  \hspace{1cm} (1)

This study investigated the effects of changes in the size and position of geometrical distortion in two different states of different mass flow rate. For this reason, by setting different pressures up in the ending part of inlet, mass flow rate will be changed. Parameter $\eta$ is defined as ratio of capture airflow to the ideal free-stream airflow (equal to zero overflow) $\eta = \frac{m_c}{m_{\infty}}$. Related inlet in 1.70 Mach (design point) has been studied for two mass flow rate ratios, $\eta=0.915$ and $\eta=0.544$.

### NUMERICAL METHODOLOGY

In this section important numerical solution parameters such as solver selection, grid generation, boundary and initial condition definition are discussed and verification of solution is done.

### GEOMETRY

According to figure (Fig. 1), the geometry used is related to the axisymmetric circular supersonic inlet that has been designed and manufactured for a ramjet engine (Esenevink & Valerino, 1951). Main parts of this air inlet includes an external shell making whole flow compression out of the intake and connected to a axisymmetric supersonic diffuser comprised from an internal shell. There are used of four struts for connecting the external shell to central part. By applying different geometrical distortions on spike, its influence on the parameters of inlet performance will be examined. Final length of geometry equals to 94cm and maximum diameter of frame is 20.7cm. figure (Fig. 2) indicates the position of geometric distortions applied in front of the spike and related geometric details. Distortion shape has been considered in a semi-circular with radius $R$ to include a wide range of common geometrical distortions. The origin of horizontal axis also put on cowl lip.

![Figure 1. Geometry of the intake](image1.png)

![Figure 2. Geometric details in front of spike](image2.png)

### COMPUTATIONAL GRID

Figure (Fig. 3) indicates boundaries selected for calculation field. Multi-block grid has been used for resolving the problem as indicated in figure (Fig. 4).
Selecting the Solver and Determination of Boundary and Initial Conditions

Simulation has been steady state and density based equations have been implicitly resolved. For modeling the effects of turbulence and viscosity, based on flow regime, there has been used of Sparlart-Allmaras turbulence model. Reynolds number in this problem is equal to 2130000 based on maximum diameter of used geometry. Free stream Mach number has been also selected equal to 1.79. In order for studying the mass flow ratio effects, simulation has been conducted in both low and high mass flow ratios. Boundary conditions for pressure therefore in the calculation field for both mass flow ratios indicated in table (Table 1).

Table 1. Boundary condition values for both mass flow ratios

<table>
<thead>
<tr>
<th></th>
<th>( \eta=0.915 )</th>
<th>( \eta=0.544 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Far-Field Pressure [pa]</td>
<td>25571.1</td>
<td>25571.1</td>
</tr>
<tr>
<td>Outlet Pressure [pa]</td>
<td>133323.31</td>
<td>120263.15</td>
</tr>
</tbody>
</table>

Second order method has been used for discretization of equations of flow and first order method used for discretization of equations for turbulence model. Simulation has been conducted for geometry related to boundary conditions as well as simulation conditions and after reviewing the simulation independency of computational grid and evaluation of results by experimental data, there has been studied the influence of disturbance on performance parameters of flow detailed as below.

Validation of Numerical Solution for No-Distortion Geometric State

Figure (Fig. 5) indicates the arrangement of shock waves related to Mach number in the non-distortion state in both different mass flow ratios and it has been compared to experimental results as provided in reference (Esenevein & Valerino, 1951) with considerable conformity. Because conditions of \( \eta=0.915 \) is in sub-critical state, besides oblique shock wave on the tip of the spike, a normal shock wave is formed before inlet entry which by impact of an oblique shock wave makes a bow shock and due to the type of design a normal shock wave in the diffuser throat section as indicated in figure (Fig. 5).

By reduction of mass flow rate to \( \eta=0.544 \), resulted from increased pressure of engine face in the same Mach number, equal to 1.79, it can be seen that normal shock wave isn’t formed into the diffuser and existing normal shock wave moves towards the upstream in front of the inlet entry and resulting in high spillage air and finally increased total pressure loss and reduced inlet efficiency as indicated in figure (Fig. 5).
As indicated, simulation results are accurately conformed to numerical results. The difference that can be seen in the state of $\eta=0.915$ in the diagram of pressure distribution between position of about 0.75 to 1.5 as well as position of formation of a normal shock wave into the diffuser is due to the presence of struts in the same positions in experimental tests, but not considered in numerical simulation. In this mass flow ratio, flow in the position of installing the struts is in supersonic form resulting in formation of weak shock waves considerably influencing on internal flow that not considered in numerical solution.

**RESULTS**

In the previous section, the accuracy of numerical solution has been studied and verified for clean or no-distortion geometry; unfortunately there wasn’t found any result or data related to distortion geometry in the references to be used for validation; therefore, according to the similarity of this issue with clean
model, one can use the conditions and methods the same as previous solution method.

**Numerical Results for State of Applying Geometric Distortion**

Ensuring properly using the problem, results are being examined in the mass flow ratio of $\eta=0.915$ for both states dent and nub in both radius ratios of $R/R_s=2.59\%$ and $R/R_s=5.17\%$.

a. **Numerical Results for State of Applying Geometric Nub**

Figure (Fig. 9) compares the pressure distribution on the spike in the state of nub with clean state indicating the abrupt pressure changes close to the nub site.

![Figure 9. Effect of nub on the Pressure distribution over the spike](image)

Abrupt increase and decrease in the pressure occurs due to presence of nub on the spike in a distance between oblique shock wave stick to the tip of the spike and normal shock wave of inlet entry where the flow is still supersonic. After oblique shock wave, because flow is still supersonic, presence of any barrier (distortion) may make a shock wave and abrupt increase in the pressure. In this case, due to the geometry of distortion and deflection angle higher than maximum deflection angle of local Mach number ($0>\theta\max$), it can be seen that a shock wave is formed of bow shock type detached from the tip of the nub and immediately after bow shock the flow is turned into subsonic and by beginning the movement on the nub, it will be increased again proportional to its geometry and in a point it will attain to supersonic again and then by expansion waves made due to presence of negative surface gradient on distortion, the flow speed will be increased and expansion continues to a pressure lower than clean state pressure. By making a not so strong compression by a few other shock waves resulted from surface gradient in the site of reconnection of distortion to spike, the pressure will be increased to a value close to the pressure in clean state. Due to the flow from a few additional compressional waves than clean state, total pressure will be more reduced and due to direct relation between mass flow rate with $P_p$ , $\eta$ will be reduced and spillage air will be increased; therefore, normal shock wave in this state is formed ahead of clean state to let more spillage air. In addition, bow shock forming before distortion impacts with oblique shock wave stick to the tip of the spike and slightly distorts it and this will also increase the spillage air than clean state.

b. **Numerical Results for State of Applying Geometrical Dents**

Figure (Fig. 10) compares the pressure distribution on the spike in the state of presence of dent with clean state indicating the abrupt pressure changes close to the dent site.

![Figure 10. Effect of dent on the Pressure distribution over the spike](image)

The flow entered into dent site, when exiting impacts with external flow and due to its angle, it acts as a barrier against main flow and forms a bow shock before barrier and increases the pressure. It must be mentioned that a similar shock wave is formed in the inlets with boundary layer suction at the beginning of suction inlet. And then the flow is expanded and passing through another shock wave at the end of hole for recirculation. On the other hand, it can be stated that a confined circulation flow is formed in the hole that must be accelerated in the front lip of distortion encountering the external flow to adapt itself with external flow; this requires momentum conduction from high-speed layers of external flow towards low-speed layers of internal flow resulting in reduced speed followed by increased pressure of flow passing on the distortion. By continuing the momentum conduction between
this layers, the external flow speed will be reduced followed by reduced pressure in the flow. Finally, by approaching the flow to the ending lid of distortion, internal flow will be negatively accelerated and reduces its speed and this results in reduced speed of external flow and increase in its pressure again.

Results for Change in the Position of Geometrical Nub

Here, by putting a distortion with radius ratio of \( R/R_a = 2.59\% \) on positions \( L/L_{lip} = 0.25 \), \( L/L_{lip} = 0.5 \) and \( L/L_{lip} = 0.75 \), the changes in the position of nub will be studied on pressure distribution on the spike.

Generally, by distance of distortion from the tip of spike, by development of boundary layer, passage speed will be reduced on the nub and power of bow shock will be reduced followed by reduction in the range of abrupt pressure changes.

\[ a. \text{ Change in the Position of nub in the state of } \eta = 0.915 \]

As indicated in figures (Fig. 11) and (Fig. 13), by distancing the distortion from the tip of spike, the throat shock wave will be moved towards downstream and closes into clean state.

The more the distortion towards the tip of spike, due to its increased power, the arrangement of shock waves in the intake entry will be more influenced caused by interference of bow and normal shock waves. Such distortion together with more total pressure loss is due to increased shock wave power, will increase the spillage air.

\[ b. \text{ Change in the Position of nub in the state of } \eta = 0.544 \]

Comparing figures (Fig. 12) and (Fig. 13), by distance of distortion from the tip of the spike, the effect of position of distortion depends on its placing in the subsonic site (downstream of the normal shock wave) or supersonic (upstream of normal shock wave). In the position of \( L/L_{lip} = 0.25 \) because distortion is located in the upstream of the normal shock wave and flow is supersonic, it can be seen a behavior like results from state \( \eta = 0.915 \).

In the position of \( L/L_{lip} = 0.5 \) however, distortion is located after normal shock wave of the inlet entry in the subsonic site; therefore, first, when impacting to distortion, flow reduces its speed with increased pressure, and then by passing through the distortion, it increases its speed with reduced pressure. Since distortion is close to shock wave and flow Mach number after shock wave is more than critical Mach number of distortion geometry, the Mach number in a point on the distortion attains to one and makes a small supersonic region on the distortion. Since flow should adapt itself with downstream that is a subsonic region, it requires a normal shock wave resulting in abrupt increased pressure. Then flow enters into diffuser and continues to increase its pressure to the end of inlet.

In the position of \( L/L_{lip} = 0.75 \), a behavior similar to state of \( L/L_{lip} = 0.5 \) can be seen except that due to distancing the distortion from normal shock wave and reduced speed due to development of boundary layer, supersonic region on the distortion will be smaller followed by reduced pressure gradient.

\[ \text{Figure 11. Pressure distribution over the spike in presence of nub: (a) Effect of change in position of nub at } \eta = 0.915 \text{ & } R/R_a = 2.59\%; \text{ (b) details of pressure variations near the distortion.} \]
Figure 12. Pressure distribution over the spike in presence of nub: (a) Effect of change in position of nub at $\eta=0.544$ & $R/R_a=2.59\%$; (b) details of pressure variations near the distortion.

Figure 13. Effect of the position variations of nub on the shock system of the inlet at $R/R_a=2.59\%$.

Results for Change in the Position of Geometrical Dent

Here, by putting the distortion in positions $L/L_{lip}=0.25$, $L/L_{lip}=0.5$ and $L/L_{lip}=0.75$, the influence of change in the position of distortion of dent type on pressure distribution on the spike has been investigated.

In this state, by distance of distortion from the tip of the spike due to reduced Mach of the flow by development of boundary layer, the range of abrupt pressure changes will be reduced.

- Change in the Position of dent in the state of $\eta=0.915$

As indicated in figures (Fig. 14) and (Fig. 16), by distancing the distortion from the tip of the spike, due to developed boundary layer, the shock waves around the dent site will become weaker with no considerable changes observed in the position and power of shock wave of the inlet entry and diffuser throat.

b. Change in the Position of dent in the state of $\eta=0.544$

Figures (Fig. 15) and (Fig. 16) indicate that in this state, presence of distortion may move the shock wave towards downstream of the flow. In the position of $L/L_{lip}=0.25$, since the distortion is in the upstream of the normal shock wave of the inlet entry, shock waves from dent may reduce the flow speed and causes the shock wave to become closer to the cowl lip.

In the position of $L/L_{lip}=0.5$ also presence of distortion, displaced the shock wave of inlet entry to such extent that it located in the downstream of the distortion; therefore, it has a behavior like previous position, except that than position of $L/L_{lip}=0.25$ due to increased thickness of boundary layer in this state, the range of abrupt pressure changes due to distortion is lower and distortion has lower effect on the flow speed, so the displacement of normal shock wave is lower.

In the position of $L/L_{lip}=0.75$, distortion is after normal shock wave; therefore, it has no considerable effect on the position of shock wave and slightly reduces its power.
Figure 14. Pressure distribution over the spike in presence of dent: (a) Effect of change in position of dent at $\eta=0.915$ & $R/R_a=2.59\%$; (b) details of pressure variations near the distortion.

Figure 15. Pressure distribution over the spike in presence of dent: (a) Effect of change in position of dent at $\eta=0.544$ & $R/R_a=2.59\%$; (b) details of pressure variations near the distortion.

Figure 16. Effect of the position variations of dent on the shock system of the inlet at $R/R_a=2.59\%$.
Results for Changes in the size of Geometrical distortion

After studying the influence of distortion (dent and nub) on the pressure distribution on the surface of spike, behaviors similar to previous state observed by increasing size of distortion ($R/R_a=2.59\%$). The main difference obtained in this state is closing the dimensional scale of distortion to the dimensional scale of main body, and under specific conditions, i.e. putting the distortion along with the shock wave; it can change the general pattern of flow and arrangement of shock wave and extremely effect the intake performance.

In the state of higher mass flow ratio ($\eta=0.915$) according to figures (Fig. 17) and (Fig. 18), there is seen a behavior similar to previous state except that intensity of changes and its ranges of effect will be increased, such that compressional waves of nub are stronger than normal shock wave.

In the low mass flow ratio ($\eta=0.544$) however, as indicated in figures (Fig. 19) and (Fig. 20), since shock wave of the inlet entry moves to upstream, its interference with shock waves resulted from distortion will be increased and this results in more changes in the arrangement of shock waves. In the position of $L/L_{lip}=0.75$, the shock wave of the inlet entry is displaced such that it located on the distortion and combined with shock waves of the distortion. distortion has almost influenced the pressure distribution of the whole spike in its downstream, In both mass flow ratios.

![Graph](image1.png)

**Figure 17.** Pressure distribution over the spike in presence of nub: (a) Effect of change in position of nub at $\eta=0.915$ & $R/R_a=5.17\%$; (b) details of pressure variations near the distortion.

![Graph](image2.png)

**Figure 18.** Pressure distribution over the spike in presence of nub: (a) Effect of change in position of nub at $\eta=0.544$ & $R/R_a=5.17\%$; (b) details of pressure variations near the distortion.
Effects of making Geometric Distortion on Performance Parameters and Comparison under Different States

Here, two parameters, pressure recovery and drag coefficient have been considered as performance parameters for intake and turned dimensionless to have more comprehensive comparison with similar results in the clean state. Figures (Fig. 21) and (Fig. 22) indicate that despite what expected, presence of distortion always doesn't result in increased pressure loss. Although air inlets are designed such that they have minimum loss, however, most of the time, some considerations like weight of the structure may prevent accessing to the design with minimum loss. Therefore, in some cases, presence of distortion may improve the arrangement of shock waves and result in reduction in total losses. But usually, distorting such arrangement may increase the percentage of losses.
Figure 21. Variations of inlet Pressure Recovery versus distance of nub from tip of spike: (a) \( \eta = 0.915 \); (b) \( \eta = 0.544 \)

Figure 22. Variations of inlet Pressure Recovery versus distance of dent from tip of spike: (a) \( \eta = 0.915 \); (b) \( \eta = 0.544 \)

Figures (Fig. 23) and (Fig. 24) indicate changes in the dimensionless drag coefficient with clean state versus changes in the position of distortion in two different mass flow ratios.

Generally, by increase in the deviation of oblique shock from the cowl lip, the spillage air will be increased followed by increase in the additional drag; in comparison, by acceleration of spillage air when passing through the cowl lip, the pressure will be reduced around the cowl lip resulting in reduced pressure drag. Because of high effect of pressure drag on total drag, it can neutralize the influence of increased additional drag and reduce total drag.

Figure 23. Variations of inlet Drag coefficient versus distance of nub from tip of spike: (a) \( \eta = 0.915 \); (b) \( \eta = 0.544 \)

Figure 24. Variations of inlet Drag coefficient versus distance of nub from tip of spike: (a) \( \eta = 0.915 \); (b) \( \eta = 0.544 \)

CONCLUSION

This study investigated the effects of change in the position and size of geometric distortion by two forms, nub and dent on pressure distribution and performance of a supersonic axisymmetric intake. These studies conducted numerically in the Mach number of inlet design, \( M_{\infty} = 1.79 \) and in two different mass flow ratios, \( \eta = 0.915 \) and \( \eta = 0.544 \). The accuracy of calculations were verified by experimental data of pressure distribution and profile of boundary layer, and the same settings of clean geometry were used for solving distortion state. Predictions indicated that position of distortion considerably influences the change in the arrangement of inlet external shock waves and indicates different behavior depending to this whether it has been located in the upstream or downstream of the normal shock wave of the inlet entry. In addition, due to the development of boundary layer, by closing the distortion to the cowl lip, pressure changes will be reduced next to the distortion. For distortion with small size, there was no considerable effect on pressure distribution into the diffusor, while increased radius of geometric distortion may almost influence on total internal flow. In low mass flow ratio, \( \eta = 0.544 \), presence of distortion may change the position of shock wave of the inlet entry and by closing the site of distortion to this wave, it will displace it towards itself, because interference of compressional waves of distortion with entry shock wave changed the boundary condition in its downstream and moving it to setup new boundary condition.
Performance parameters of total pressure recovery and drag coefficient indicated different behavior before disturbance. Total pressure loss wholly depends on how to change the arrangement of external shock wave of inlet resulted from distortion and this change in the structure of waves influences more on total drag and particularly component additional drag. Additionally, in high mass flow ratio, $\eta=0.915$, that is closer to design conditions, presence of distortion will increase both pressure loss and drag coefficient and this isn’t a desirable condition.

REFERENCES


