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Performance Enhancement of an External Compression Intake by the Boundary Layer Suction

Javad Sepahi-Younsi[1*], Safa Esmaeili[2], Behzad Forouzi Feshalami[2], Victoria Pellerito[3,4], Mostafa Hassanalian[5]

In this paper, the effects of boundary layer suction applied at the cowl surface on the performance of a supersonic air intake are investigated. A computational code developed by the authors is employed to simulate the compressible and turbulent fluid flow inside and around an external compression intake in the presence of a slanted slot bleed. Total pressure recover (TPR), flow distortion (FD), mass flow ratio (MFR), and drag coefficient (C_D) are considered as the performance parameters of the intake. Simulations are conducted at freestream Mach numbers of 1.8, 2.0 and 2.2 at zero degrees angle of attack. For every freestream Mach number, the intake flow field has been computed for different back pressures to study various operating conditions of the intake. Results show that intake with boundary layer suction has less distortion compared to the base intake. In addition, applying the bleed causes the critical back pressure of the intake to be increased and consequently the intake with bleed has a wider operating range.

I. Introduction

Supersonic air intake (SAI) is the first component of an air-breathing engine. Providing required amount of airflow with the minimum drag, flow distortion and maximum total pressure recovery are the main contributions of SAIs. However, boundary layer separation that is caused by the interaction of shock waves with boundary layer seriously affects the performance of SAIs[1]. Recently, there has been a significant interest in the reduction of the separated flow. Many methods, such as boundary layer suction[2], injection of high energy flow[3], plasma actuators[4], and bumps[5] have been exploited by engineers to mitigate undesirable effects of the flow separation. Among these techniques, boundary layer suction or bleeding has been widely used. Simultaneous use of the bleed with other methods has been interest of many researchers. For instance, effects of using boundary layer suction together with the blowing on the flow pattern and performance parameters of a supersonic intake studied by Rolston and Raghunathan[6]. Furthermore, integration of bleed and vortex generators was the aim of some studies[7, 8]. However, it has been deduced that collaboration of bleed with other flow control methods increases the complexity of the intake while proper utilization of bleed solely can improve the intake performance considerably[1].

Many researchers used boundary layer suction individually as the best flow control method. They used bleed in different sizes, types, and positions to attain the best performance. Syberg and Koncsek[9] showed that slanted bleed results in the higher overall performance than the normal bleed. Gawienowski[10] pointed out that total pressure recovery (TPR) is enhanced and Flow Distortion (FD) is reduced when

[1]Assistant Professor, Mechanical Engineering Department, Faculty of Engineering, Ferdowsi University of Mashhad, Azadi Square, Mashhad, 9177948974, Iran, Email: jsepahi@um.ac.ir
[2]Master of Science, Mechanical Engineering Department, Faculty of Engineering, Ferdowsi University of Mashhad, Azadi Square, Mashhad, 9177948974, Iran, Email: jsepahi@um.ac.ir
[3]Undergraduate REU student, Department of Mechanical Engineering, New Mexico Tech, Socorro, NM 87801, USA.
[4]Undergraduate student, Department of Mech. Engineering, Lawrence Technological University, Southfield, MI 48075, USA
[5]Assistant Professor, Department of Mechanical Engineering, New Mexico Tech, Socorro, NM 87801, USA.

bleed mass flow rate increases. Sanders and Cubbison[11] stated that bleed exit area plays crucial role in performance of SAIs. Reduction of the bleed exit area which increases the bleed back pressure results in the reduction of bleed mass flow rate and consequently degrades the intake overall performance. Soltani et al.[12] manifested that intake performance is deteriorated with increment of the bleed slant angle and entrance width.

Bleed position is of great importance from engineering design point of view since it can effectively change the performance. Cubbison et al.[13] showed that when the bleed is placed just downstream of the last cowl and spike shock reflection point, the overall performance of a mixed compression intake is improved. Herrmann and Triesch[14] showed that applying a bleed at the throat of the hypersonic intakes only affects the flow structure at the shock reflection location. Soltani et al.[12] applied a slot bleed upstream of the throat outside the intake over the spike tip cone of a mixed compression intake and showed that intake performance enhances with moving the bleed location downstream toward the intake entrance. Effects of the boundary layer suction on the performance and stability of supersonic intakes have been comprehensively reviewed by Sepahi-Younsi et al.[1].

Literature review shows that the previous studies are most about the mixed compression intakes. Present research investigates the effects of boundary layer suction applied at the cowl surface on the performance parameters of an external compression intake. Simulations are performed at zero degrees angle of attack for different back pressures and freestream Mach numbers in the supercritical, critical and subcritical operating conditions before buzz phenomenon onset. By comparing the performance parameters of the base intake with the intake equipped by bleed, the effectiveness of applying boundary layer suction over the cowl surface of an external compression intake is studied.

II. Operating Conditions, Performance Parameters, and Numerical Methodology

Performance curve and operating conditions of a supersonic intake are shown in Fig. 1. According to this figure, the difference among supercritical, critical and subcritical operating conditions is due to position of the normal shock relative to the intake throat. When the normal shock is located downstream or upstream of throat, the intake operating condition is called supercritical or subcritical, respectively. Normal shock in critical condition is very close to the throat section.

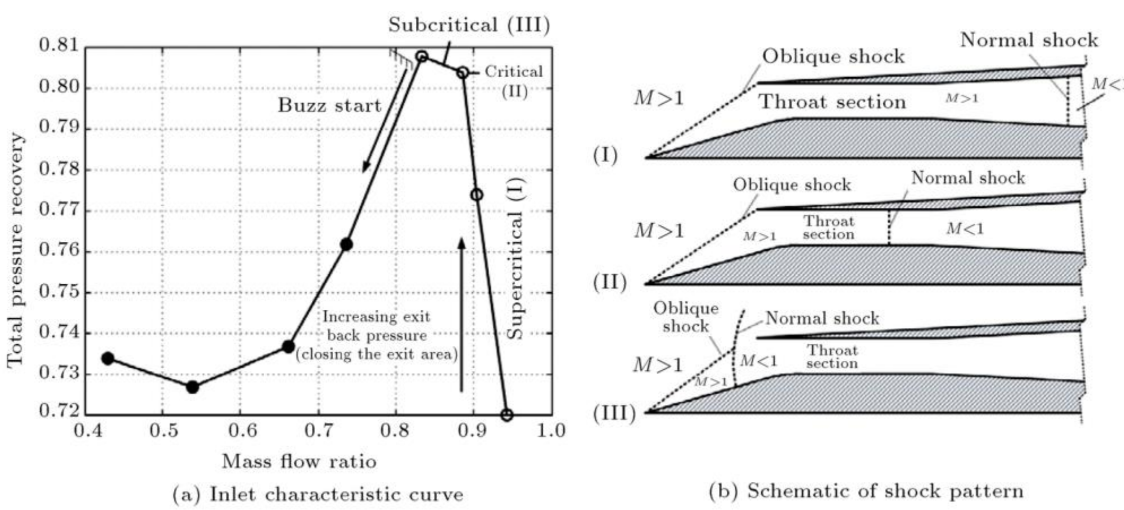


Figure 1. Performance curve and operating conditions of a supersonic intake.

As seen from Fig. 2, an axisymmetric external compression air intake designed for the freestream Mach number of two was used in this study. Shock pattern for this intake at the design condition is also presented in Fig. 2. To investigate the role of boundary layer suction in the intake performance, a slot flush-type bleed is designed with slant angle of 32.78°. This bleed is placed at X/D=0.96, where X is measured from the cowl lip and D is the maximum exit diameter of the intake. Additionally, the bleed duct width is fixed, W/D=0.055.

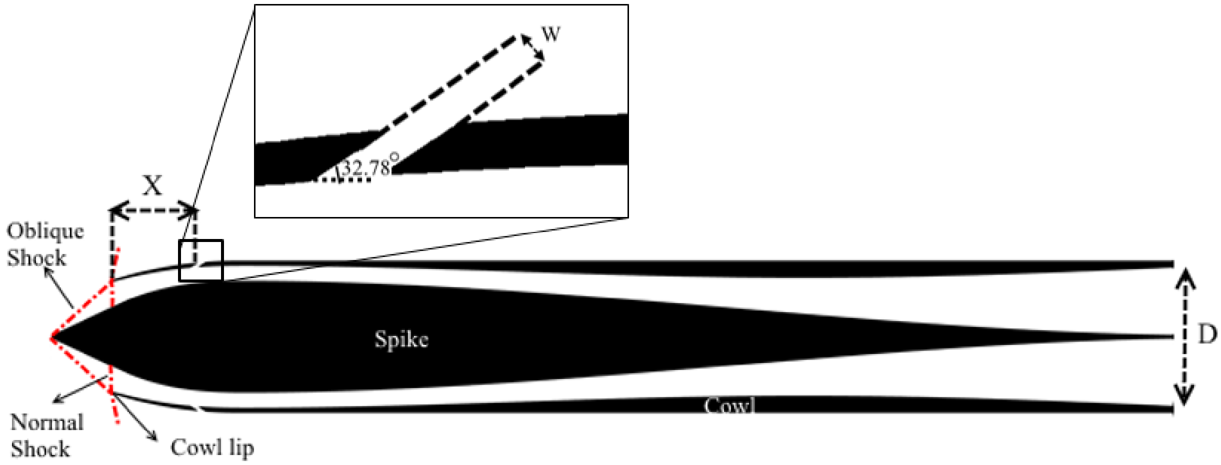


Figure 2. External compression intake used in this study.

In this study, TPR, MFR, C_D and FD are considered as the intake performance parameters[15]. TPR is the ratio of the total pressure at the intake exit plane to that of freestream:

$$TPR = \frac{P_{0e}}{P_{0\infty}} \tag{1}$$

P_{0e} is computed by the area-weighted averaging of the total pressure at outlet. Higher TPR indicates less total pressure loss and more thrust for the vehicle. According to Fig. 3, MFR is defined as the ratio of the actual mass flow rate passing through the intake (A_{01}) to the maximum mass flow rate that the intake can capture at every freestream Mach number (A_1):

$$MFR = \frac{A_{01}}{A_1} \tag{2}$$

It is worth mentioning that intakes should be designed to capture higher MFR. Maximum value of MFR at supersonic speeds is unity.

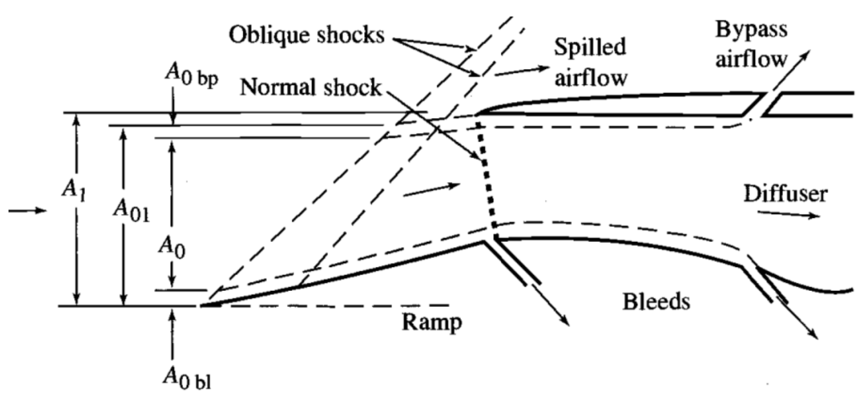


Figure 3. Definition of MFR for supersonic air intakes[18].

Other important performance parameters that should be taken into account is flow distortion at the exit surface which is calculated as follows:

$$FD = \frac{(P_0)_{max} - (P_0)_{min}}{(P_0)_{avg}} \quad (3)$$

Small values of FD are favorable for the operation of the subsequent component of the intake in the engine. In addition, BPR is defined as the ratio of the outlet static pressure to the static pressure of the freestream.

Fluid flow inside and around the intake is simulated by employing a computational fluid dynamics (CFD) code. In this code, discretization of RANS (Reynolds-averaged Navier Stokes) equations is performed based on an explicit finite volume method[16, 17]. The second-order accurate Roe scheme is used to compute the convective fluxes. Laminar viscosity coefficient is computed using the Sutherland equation. The eddy viscosity coefficient is computed by the SST *k*-*ω* turbulence model. Boundary conditions used in the current simulations are illustrated in Fig. 4[19].

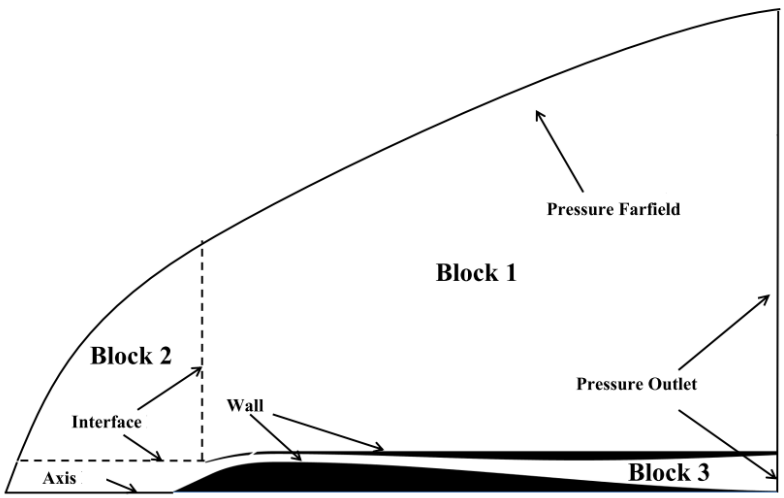


Figure 4. Computational blocks and boundary conditions.

As can be seen in Fig. 5, an elliptic grid generator was used to produce high-quality structured mesh inside and around the intake. Mesh independency study was carried out to guarantee that the results are independent of the mesh size and consequently a grid with total cell numbers of 30500 was selected.

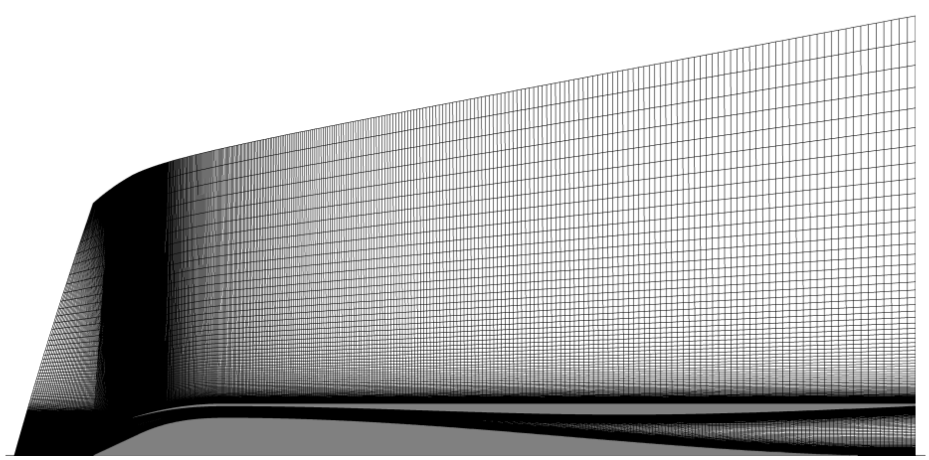
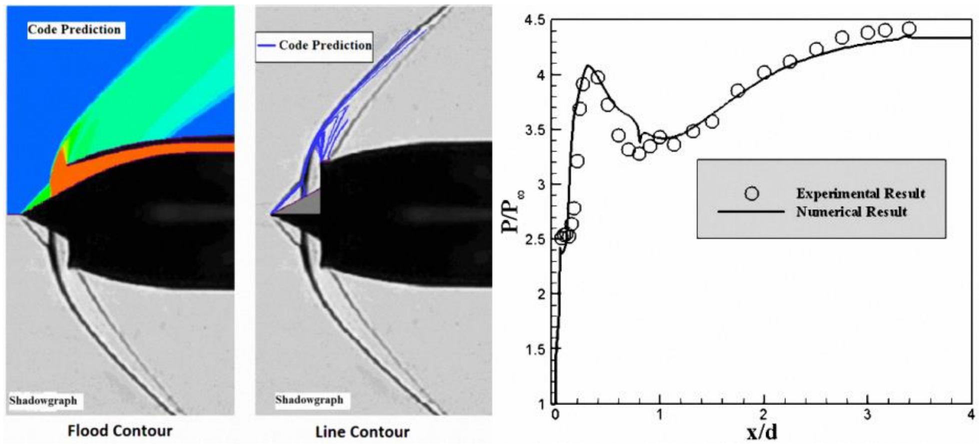


Figure 5. The generated mesh inside and around the intake.

The numerical results are compared to the wind tunnel data of a similar external compression intake in order to validate the numerical methods. As can be seen from Fig. 6, there is an acceptable agreement between the results.



(a) (b)

Figure 6. Comparison of the numerical and experimental results for an external compression intake at M_∞=2.0, (a) shadowgraph picture against the numerical simulation, and (b) distribution of the static pressure ratio over the spike[20].

III. Results and Discussion

Fluid flow at freestream Mach numbers of 1.8, 2.0 and 2.2 is simulated once without the bleed which is called "primary intake" and then it is equipped and simulated with previously described bleed which is named "Intake with bleed". Performance parameters of the intake for two cases are compared with each other to highlight the effects of boundary layer suction. It should be noted that both intakes are at supercritical operating condition at the beginning of the simulation when BPR is equal to 2.0. However, increasing the back pressure ratio causes the normal shock to move upstream and stand in the throat (critical condition) and finally stand upstream of the throat (subcritical condition).

In this study, the back pressure ratio in which intake reaches critical and subcritical condition is a function of freestream Mach number and type of the intake (primary intake or intake with bleed). Generally speaking, the BPR that makes intake to be in critical condition increases with increment of freestream Mach number. Furthermore, the critical and subcritical BPRs of the primary intake are less than those for the intake with bleed.

Variations of total pressure recovery with back pressure are shown in Fig. 7 for different freestream Mach numbers. According to this figure, TPR of both intakes increases as BPR increases because normal shock inside the intake moves upstream toward the throat and stands in a region with smaller area. The flow after the throat is supersonic and it has a smaller Mach number at a position with smaller area. As a result, the internal normal shock is weakened in the new position and causes less total pressure loss. Moreover, TPR of the primary intake is a little more than the intake with bleed because, as shown in Fig. 8, a barrier shock wave is formed around the bleed entrance that causes additional losses as compared with the primary intake. However, the discrepancy between TPR of two cases is reduced when BPR increases. On the other hand, TPR of both intakes reduces with increment of the freestream Mach number because the shock waves are strengthened at higher freestream Mach numbers and the interaction between these stronger shocks and boundary layer leads to more flow separation and more total pressure losses.

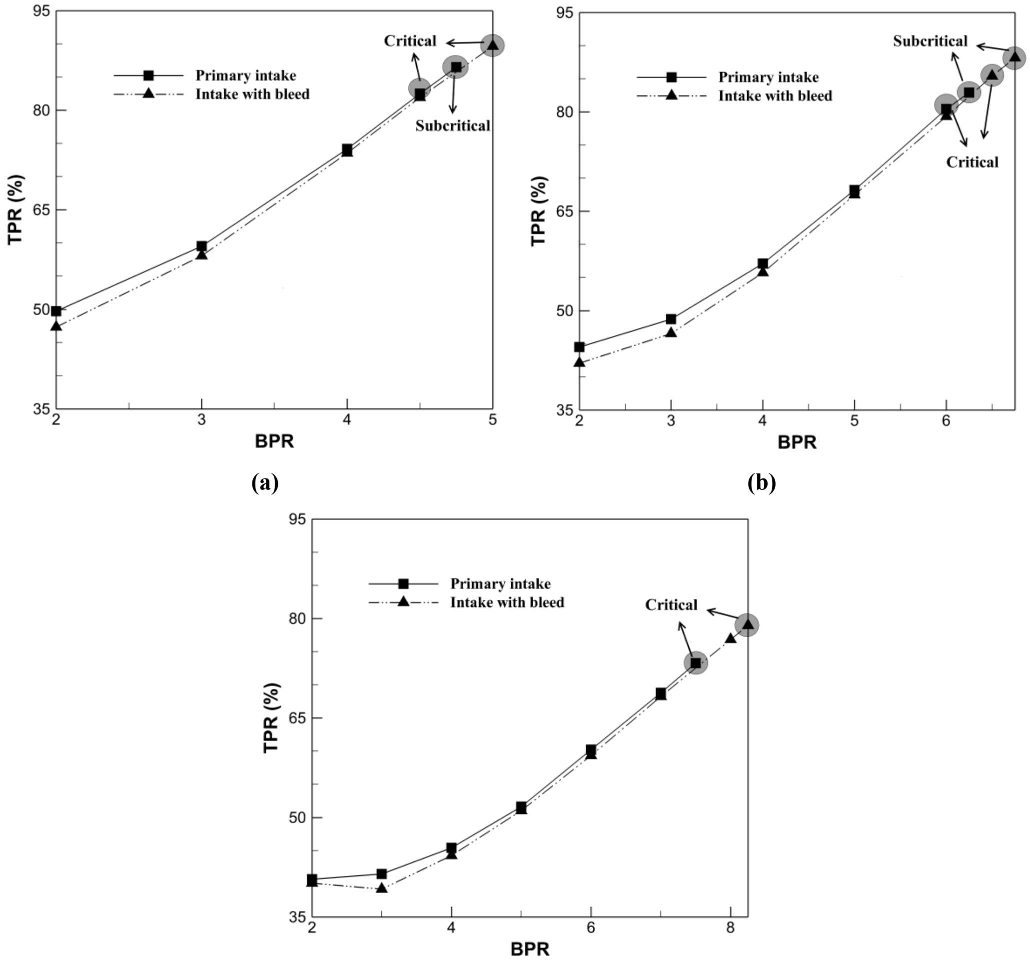


Figure 7. Variations of the total pressure recovery with back pressure ratio; (a) M_∞=1.8, (b) M_∞=2.0, and (c) M_∞=2.2.

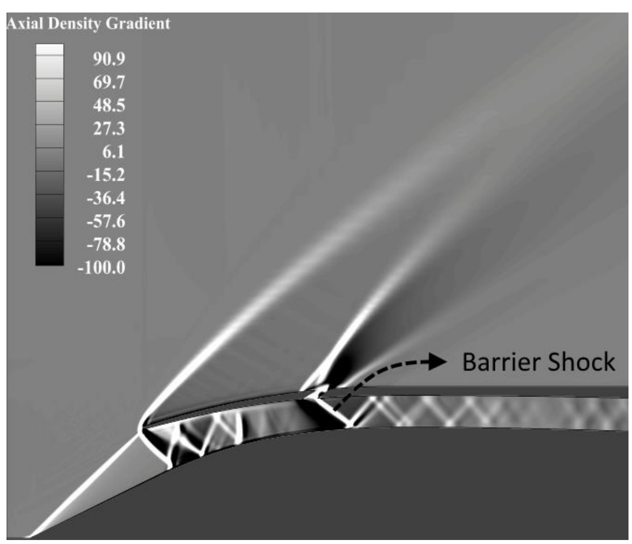


Figure 8. Contours of axial density gradient for the intake with bleed at M_∞=2.0 and BPR=3.0.

Variations of flow distortion with back pressure and freestream Mach number for both intakes are presented in Fig. 9. As can be seen from this figure, the amount of FD is considerably reduced with BPR increment for both intakes at all freestream Mach numbers. This behavior can be attributed to the declined interaction of the internal normal shock wave with boundary layer due to movement of the normal shock upstream and because it is weaker in the new position. In addition, intake with cowl bleeding has less FD than the primary intake for all BPRs that shows that the bleed slot sucks the flow separation and makes the flow more uniform. Furthermore, FD considerably increases when freestream Mach number increases. This is due to the formation of stronger shock waves at higher freestream Mach numbers that result in the more separation. As a result, an upgraded bleed system is required for higher freestream Mach numbers to keep FD in the acceptable range.

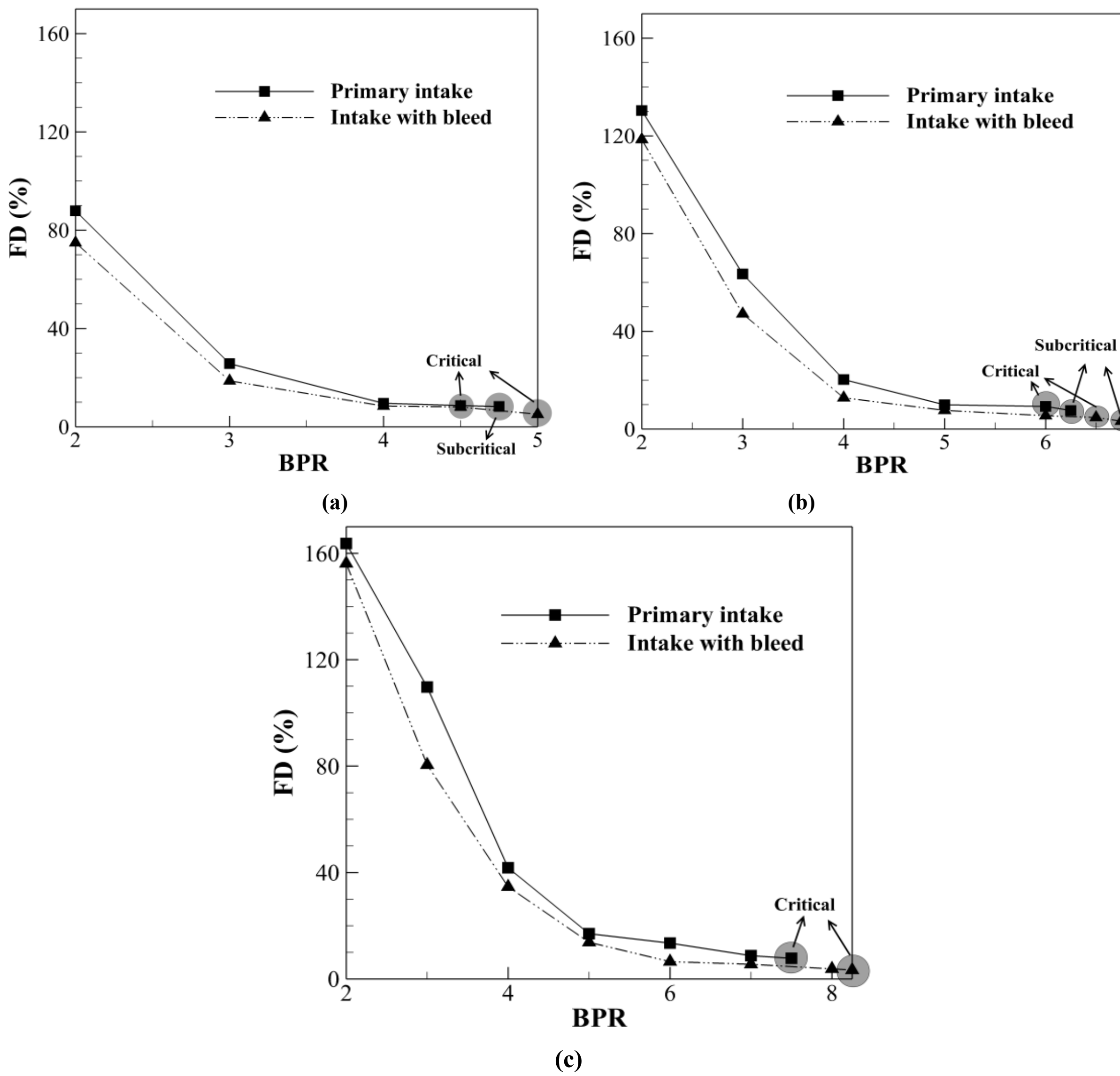


Figure 9. Variations of the flow distortion with back pressure ratio; (a) M_∞=1.8, (b) M_∞=2.0, and (c) M_∞=2.2.

Another performance parameter investigated in this study is MFR which is illustrated in Fig. 10. According to this figure, MFR remains almost constant for both intakes in supercritical and critical conditions. This is because MFR is related to the distance between the spike conical shock and cowl lip and consequently to the flow spillage in this region. By increasing the back pressure at the supercritical and critical operating conditions, shock pattern ahead of the intakes is unchanged. Therefore, MFR is constant. However, when both intakes become subcritical, the normal shock stands outside intake and flow spillage increases as seen from Fig. 1 that finally results in the significant reduction of MFR. In addition, it is seen that MFR of both intakes increases as the freestream Mach number increases because the angle of conical shock and the distance between this shock wave and cowl lip decrease.

Fig. 10 further shows that the intake with bleed has more MFR for all freestream Mach numbers than the primary intake since the bleed which is applied near the throat increases the effective area of the intake throat and consequently increases the mass flow rate passing through the intake. However, both intakes have the maximum value of MFR which is unity at the freestream Mach number of 2.2 because the conical shock of both intakes impinges the internal surface of the cowl, Fig. 11, and the flow spillage vanishes completely in this Mach number.

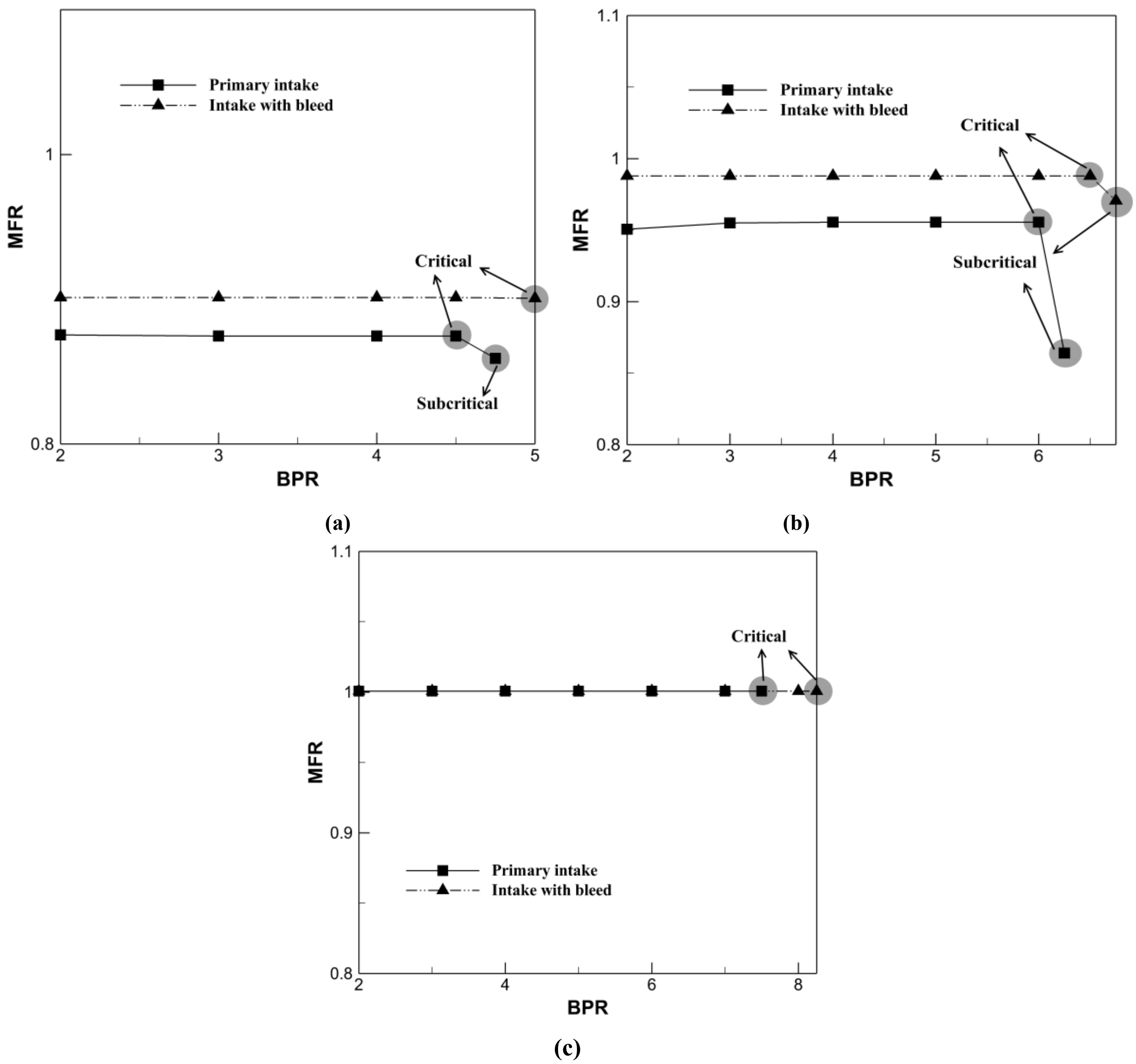


Figure 10. Variations of the mass flow ratio with back pressure ratio; (a) M_∞=1.8, (b) M_∞=2.0, and (c) M_∞=2.2.

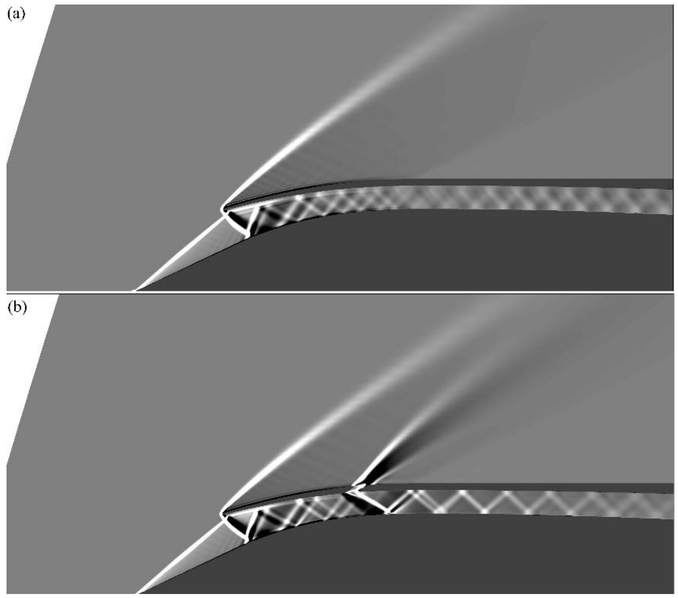


Figure 11. Contours of axial density gradient at M_∞=2.2 and BPR=3.0; (a) primary intake, and (b) intake with bleed.

Variations of the bleed mass flow ratio (BMFR) which is defined as the ratio of the bleed mass flow rate to the mass flow rate entering the intake, A_{0bl}/A_{01} in Fig. 3, is shown in Fig. 12 for different freestream Mach numbers. According to this figure, mass flow passing through the bleed slot is constant in the supercritical conditions and variation of back pressure does not change it because the internal normal shock stands downstream of the bleed slot in these conditions. However, as the back pressure increases the internal normal shock moves upstream and stands upstream of the bleed slot in the critical and subcritical operating conditions. At these conditions the bleed slot sucks the separated flow behind the normal shock and the bleed mass flow rate increases drastically.

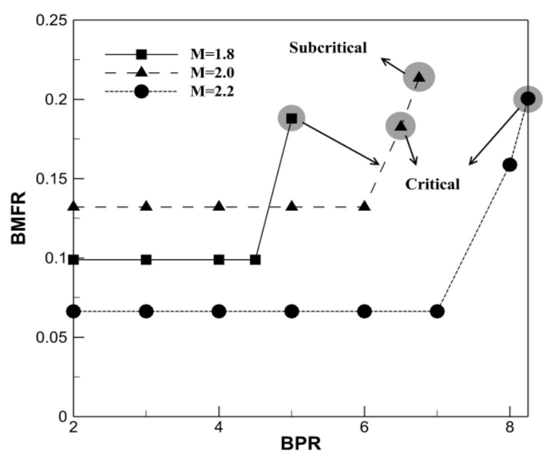
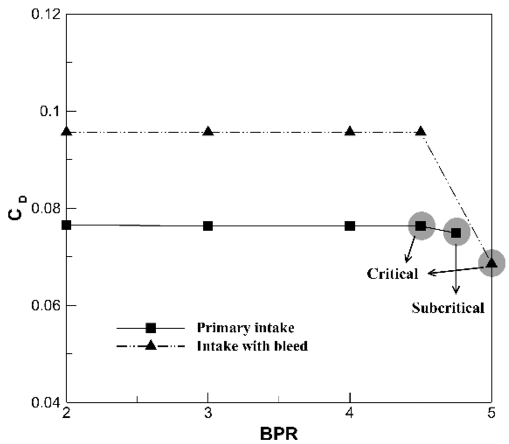
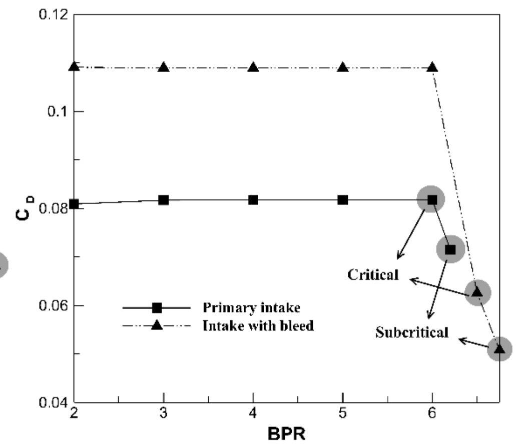


Figure 12. Variations of the bleed mass flow ratio with back pressure ratio.

Variations of the intake drag coefficient with back pressure and freestream Mach number for both intakes are demonstrated in Fig. 13. It should be mentioned that the drag force is computed over the upper surface of the cowl and for the intake with bleed the bleed duct surfaces are further added to this surface. According to Fig. 13, the drag coefficient remains constant with BPR for the primary intake in the supercritical and critical operating conditions. However, it reduces in the subcritical condition. This decrement is sharp for the design Mach number of two. This reduction is also observed for the intake with bleed when it moves from supercritical to critical and subcritical conditions. In fact, when the normal shock stands outside of the intake at subcritical condition, the flow which travels over the first part of the upper surface of the cowl accelerates and a pressure drop takes place in this position that decreases the drag coefficient. Moreover, Fig. 13 shows that the intake drag coefficient increases after applying the bleed which is mainly due to the extra drag force over the walls of the bleed duct.



(a)



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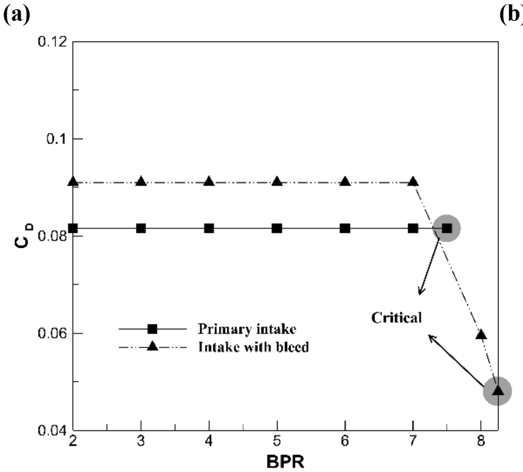

(c)

Figure 13. Variations of the intake drag coefficient with back pressure ratio; (a) M_∞=1.8, (b) M_∞=2.0, and (c) M_∞=2.2.

IV. Conclusions

Effects of the boundary layer suction applied at the cowl surface of an external compression intake were studied on the performance parameters of the intake. A computational code was used to simulate the intake flow filed at various freestream Mach numbers and operating conditions. Intake performance parameters including total pressure recovery (TPR), mass flow ratio (MFR), flow distortion (FD), and drag coefficient (C_D) were assessed for different back pressures in the supercritical, critical and subcritical operating conditions. Results showed that applying the bleed decreases the flow distortion and increases the critical back pressure significantly. However, as the freestream Mach number increases, the bleed system should be modified to be beneficial for the higher freestream Mach numbers. In addition, the intake with bleed has a larger drag coefficient as compared with the primary intake.

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