The Impact of Ramp Deflection on the Jet Inlet Flow Properties of a Supersonic, Variable-Geometry Intake Concorde Engine

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This project focuses on analyzing the essence of the various parts and series of waves present at the intake of Concorde engine at supersonic speed. Different waves exhibit different impacts on the flow properties which is well leveraged on by the variable intake design of the Concorde engine to build up the air pressure and feed this pressurized air to the jet engine at desirable flow speed. Precisely, the impact of oblique shock wave, expansion wave, normal shock wave, and diverging nozzle on the flow properties are investigated. The impact of various ramp deflection on flow properties is also studied, with more focus on the behavior of static and stagnation pressures across the shock waves at different ramp deflection angles. The relevant nonlinear equations were solved using SciPy and a Python program is developed to solved this problem.

I. Introduction

A crucial component of supersonic transport is the supersonic inlet. To achieve higher net thrust in a propulsion system, the inlet design should prioritize a higher inlet pressure ratio while minimizing external drag [1]. High inlet pressure ratio is desired for several reasons which includes higher net thrust, engine performance, pressure recovery, etc. In supersonic flows, pressure recovery depends on the number of shock waves generated by the intake: more shock waves lead to higher pressure recovery [2]. The Concorde inlet geometry is designed such that there are a couple of shock waves which builds up to high pressure at the jet inlet.

The design of the Concorde engine intake got its application and importance due to the jet engines limitation from taking supersonic flow into the compressor. The compressors are optimally performant at subsonic speed of about Mach 0.4 - 0.5 [3]. For supersonic speed through the jet engines compressors, shock waves would be inevitable which could potentially damage the compressor blades and break down the engine. Therefore there is need to slow down the flow to subsonic speed before the jet engine inlet. Since shock waves, especially normal shock waves, are effective ways to slow down the flow to subsonic speed, the variable geometry Concorde inlet, as in Fig 1 is designed to create these shock waves which both slows down the flow to subsonic speed and build up the pressure toward the jet engine inlet which enhances the jet engine performance.

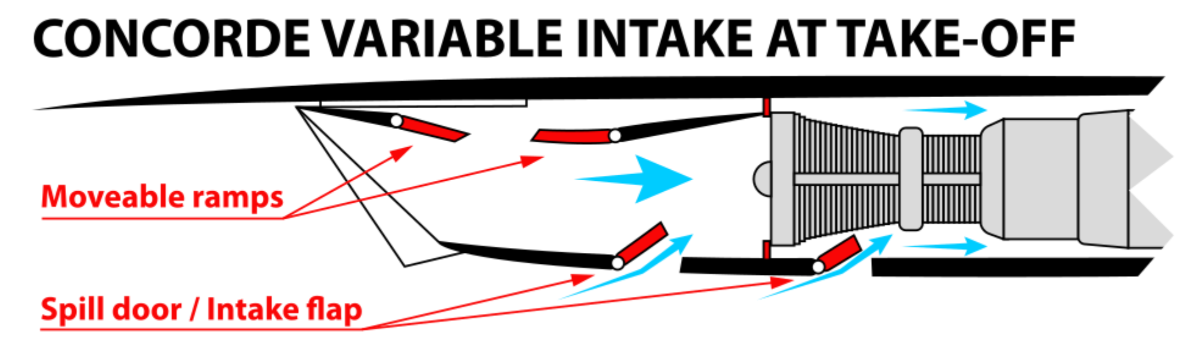

Fig. 1 Concorde engine engine with variable intake geometry

The focus of this study is to analyze the impact of ramp deflection on the flow properties at the jet inlet. In addition, the variation of the flow properties across the various waves (shock and expansion waves) that occurs at the intake at

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supersonic speed as shown in Fig 2 is also investigated. It is noteworthy to highlight that this study doesn't analyze flow through the gap in-between the ramps. Neither does it consider the effects of boundary layer or friction in the analysis.

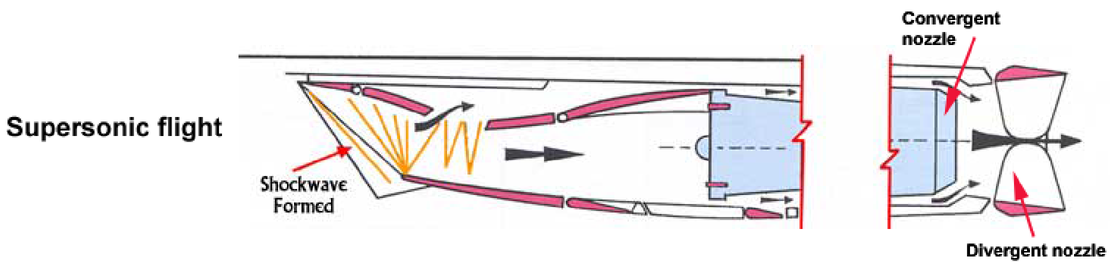

Fig. 2 Shock waves and expansion wave at the Concorde engine inlet

II. Methodology

In determining the flow properties across the regions, various compressible flow relations were employed. The relationships employed are dependent on the kind of shock or flow nature present in that region. Typically, from the Concorde inlet to the jet engine inlet, there are oblique shocks, expansion wave, normal shock, and isentropic diverging flow nozzle, in this order. The atmospheric flow before the Concorde engine, at the flight altitude is also isentropic.

A. Isentropic Flow

This study and analysis is done for a Concorde flight with a flight altitude of 18.3km. The standard atmosphere relationships were used to estimate the atmospheric conditions (air pressure, density, and temperature) at this altitude. The atmospheric stagnation pressure, stagnation temperature, and stagnation density at the flight altitude are estimated through the following isentropic flow properties relations [4]:

$$\frac{T_o}{T} = 1 + \frac{\gamma - 1}{2} M^2 \tag{1}$$

$$\frac{P_o}{P} = \left(\frac{T_o}{T}\right)^{\frac{\gamma}{\gamma-1}} = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{\frac{\gamma}{\gamma-1}} \tag{2}$$

$$\frac{\rho_o}{\rho} = \left(\frac{T_o}{T}\right)^{\frac{1}{\gamma-1}} = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{\frac{1}{\gamma-1}} \tag{3}$$

where T is the static temperature, T_o is the static temperature, P is the static pressure, P_o is the stagnation pressure, ρ is the static density, ρ_o is the stagnation density, M is the flow mach number, and γ is the specific heat ratio.

B. Oblique Shock Wave

The flow from the atmosphere, through the Concorde inlet, passes through a sharp edge that's inclined into the flow at some angle θ, called turn angle, which leads to an obliques shock that's estimated using an equation that relates the oblique shock angle and flow Mach number as:

$$\tan\theta = 2\cot\beta \left[\frac{M_1^2 \sin^2\beta - 1}{M_1^2 (\gamma + \cos 2\beta) + 2}\right] \tag{4}$$

where θ is the turn angle, β is the oblique shock angle, and M_1 is the upstream Mach number. This is a non-linear equation that's solved numerically, using SciPy [5], for β. When the ramp is deflected into the flow, a second oblique shock is expected because the flow downstream of the first oblique shock is still supersonic. The flow properties across the oblique shock are obtained by considering normal shock wave through the normal component of the oblique shock.

C. Expansion Wave

Downstream, of the oblique shock is expansion wave as shown in Fig 2. The flow across the expansion wave is isentropic and is characterized by the Prandtl-Meyer angle which is expressed as [4]:

$$\nu = \sqrt{\frac{\gamma+1}{\gamma-1}} tan^{-1} \sqrt{\frac{\gamma-1}{\gamma+1}} - tan^{-1} \sqrt{(M^2-1)} \tag{5}$$

where ν is the Prandtl-Meyer expansion angle.

D. Normal Shock Wave

Downstream of the expansion wave is a diverging duct within which a normal shock wave is expected in order to fully slow down the flow to subsonic speed. The flow across the normal shock is modeled through the normal shock equations.

$$M_2^2 = \frac{1 + [(\gamma-1)/2]\, M_1^2}{\gamma M_1^2 - (\gamma-1)/2} \tag{6}$$

$$\frac{P_2}{P_1} = 1 + \frac{2\gamma}{\gamma+1}(M_1^2 - 1) \tag{7}$$

$$\frac{T_2}{T_1} = \left[1 + \frac{2\gamma}{\gamma+1}(M_1^2 - 1)\right]\left[\frac{2 + (\gamma-1)M_1^2}{(\gamma+1)M_1^2}\right] \tag{8}$$

$$\frac{\rho_2}{\rho_1} = \frac{(\gamma+1)M_1^2}{2 + (\gamma-1)M1_2} \tag{9}$$

In the normal shock equations above T is temperature, P is pressure, and ρ is density. The subscripts 1 and 2 represents the upstream and downstream properties respectively.

E. Diverging Nozzle

The isentropic flow through the diverging nozzle was modelled by using the area ratio equation:

$$\left(\frac{A}{A^*}\right)^2 = \frac{1}{M^2}\left[\frac{2}{\gamma+1}\left(1 + \frac{\gamma-1}{2}M^2\right)\right]^{\frac{\gamma+1}{\gamma-1}} \tag{10}$$

where $\left(\frac{A}{A^*}\right)$ is the area ratio and M is the Mach number. This equation is a nonlinear equation and was also solved using SciPy [5] which employs Newton Raphson method. For this study, $\left(\frac{A}{A^*}\right)$ is assumed to be 1.3

F. Specified Parameters and Assumptions

In order to define the problem and build a python program to model it, the specified parameters and assumptions used are summarized in Table 1 below.

Table 1 Parameters and assumption summary

M	$\boldsymbol{\gamma}$	$\boldsymbol{\theta_1}$	$\boldsymbol{\theta_2}$	$\boldsymbol{\theta_3}$	$\boldsymbol{A/A^*}$	**Flight Altitude**
3	1.4	10	5-25	40	1.3	18300

In Table 1, θ_1 is the deflection angle from the Concorde intake sharp edge, θ_2 is the ramp deflection angle that's assumed to range between 5° and 25°, θ_3 is the expansion angle and A/A^* is the ratio of the nozzle area to the characteristic area (corresponding to $M^* = 1$). The angles θ_1 and θ_3 are relative to the horizontal line which corresponds to the free stream flow direction for a level/cruise flight while θ_2 is relative to θ_1 (i.e. for $\theta_2 = 5°$ relative to θ_1, $\theta_2 = 15°$ relative to the freestream flow direction).

III. Results

The discussion of the result is split into the impact of the various flow regions/nature on the flow properties and the impact of the ramp deflection of the flow properties, specifically, static and stagnation pressure.

A. Impact of The Shock Waves, Expansion Wave, and Diverging Nozzle on The Flow Properties

The cases were ran for different deflection angles but the first case is for 5° ramp deflection (i.e. $\theta_2 = 5°$) with the results as summarized in Table2.

Table 2 Summary of flow properties across Concorde intake at 5○ ramp deflection

Parameter	Atmospheric Condition	Oblique Shock 1	Oblique Shock 2	Expansion Wave	Normal Shock	Diverging Nozzle
M	3.00	2.51	2.30	3.54	0.45	0.52
T (K)	216.7	269.0	295.3	172.9	583.1	575.3
P (kPa)	7158.05	14706.02	20303.87	3119.41	45127.46	43055.26
$\rho (kg/m^3)$	0.1151	0.1904	0.2396	0.0629	0.2696	0.2607
$T_o (K)$	606.62	606.62	606.62	606.62	606.62	606.62
$P_o (kPa)$	262934.81	253228.15	252364.60	252364.60	51840.98	51840.98
$\rho_o (kg/m^3)$	1.5100	1.4542	1.4493	1.4493	0.2977	0.2977

Following a-priori knowledge, there is reduction in Mach number across shock waves but increase in Mach number through the expansion wave as shown in Fig 3. Oblique shock slows down the flow but not to subsonic speed while normal shock wave slows down the speed to subsonic speed. This portrays the difference in the strength of the two shock wave. The tangential component of the velocity and Mach number across and oblique shock is constant, while the normal components across an oblique is identical to a normal shock wave behavior. Consequently, normal shock wave is generally stronger than oblique shock wave. At supersonic speed, increasing speed increases the flow speed and thus the Mach number. This explains the increase in Mach number across the expansion wave shown in Fig 3. The final Mach number at the diverging nozzle section is a result of the assumed value of A/A^* as discussed earlier.

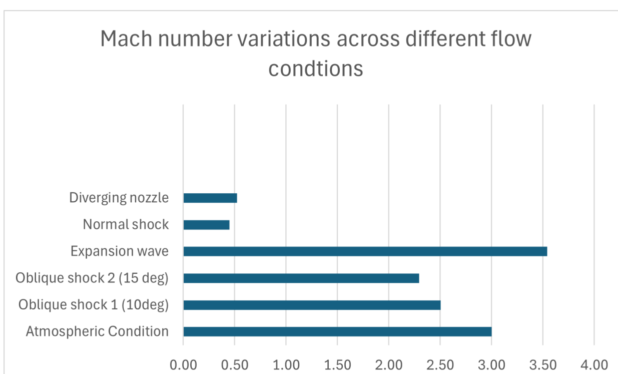

Fig. 3 Variation of Mach number across the waves

The static pressures are observed to increase across oblique and normal shock waves, as shown in Fig 4, which is one of the essence of this variable intake Concorde engine geometry. The drop in static pressure across the expansion fan is due to the enlargement of the pressure area. The total pressures, shown in Fig 4, drops across oblique and normal shock. Due to the difference in the oblique shock angle, the loss of total pressure shown in Fig 4, across the first oblique shock is more significant than the second oblique shock. The loss of total pressure across the normal shock is much more significant due to the increase in entropy across a normal shock. This loss of pressure energy is converted to heat and other form of energy. Conversely, flows across an expansion wave and diverging nozzle are isentropic, thus total pressure across these regions remain constant.

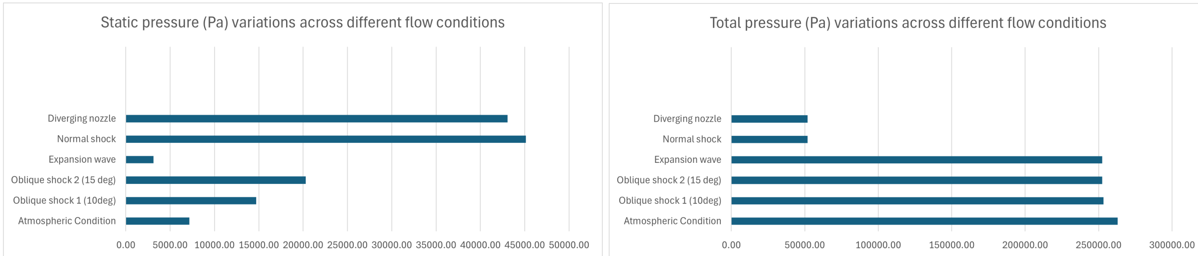

Fig. 4 Static (left) and total (right) pressures variation across the shock waves

The conversion of the pressure energy, from the total pressure losses from Fig 4, into heat is shown in Fig 5 with an increase in temperature increase across the oblique and normal shock waves. This also corresponds to the rise and falls of the static pressures. Similarly, flow across the expansion fan records significant drop in temperature. The flow throughout the Concorde engine is adiabatic which shows why the stagnation temperature is a flat line. Fig 5 also shows how the flow across the shocks compresses the air, making it denser, and how the expansion fan expands the flows and reduce the density. Since the system is adiabatic, the stagnation density also remains constant across the isentropic flow regions.

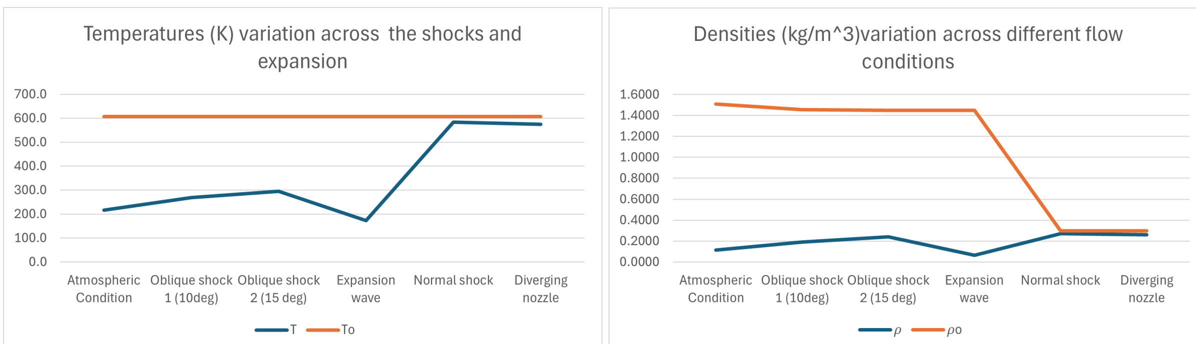

Fig. 5 Variation of the total, T_o, and static temperature, T, (left) and the total, ρ_o and static density, ρ, (right) across the shock waves

B. The Impact of Ramp Deflections on Flow Pressures

Following the discussion of the impacts of different flow regions in the Concorde engine intake on the flow properties, the deflection of ramp at different angles has significance impacts on the flow pressures. The deflection of the ramp creates the second oblique shock wave downstream of the first, but doesn't affect any flow properties upstream of the second oblique. This is shown by the thick, concentrated line across the atmospheric condition and oblique shock 1 regions in Fig 6.

As the ramp deflection angle increases, the strength of the oblique shock wave increases which is shown by increase in the static pressure in Fig 6 across oblique shock 2. Due to the reduction of static pressures across an expansion wave, all pressures reduce across the expansion fan but the magnitude of the pressures remain higher at higher deflection angle, signifying the impact of the ramp deflection and stronger oblique shock wave upstream of the expansion wave. The flow between the normal shock wave and the diverging nozzle tend to show a diverging nature, with pressure decrease at small deflection angle then increase across the diverging nozzle at larger deflection angle, typically because the A/A^* value was fixed and the Mach number at the end of the diverging nozzle remains constant. Nonetheless, the maximum final pressure is achieved by the highest ramp deflection.

Similar to static pressure, the stronger oblique shock, due to higher ramp deflection, has higher magnitude of impact on the stagnation pressure but the physics remains the same. Oblique shock consumes the stagnation pressure, with most consumption (maximum stagnation pressure loss across the second oblique shock) emanating from highest ramp deflection. The declination in the magnitude of the loss of stagnation pressure across the normal shock wave shown in

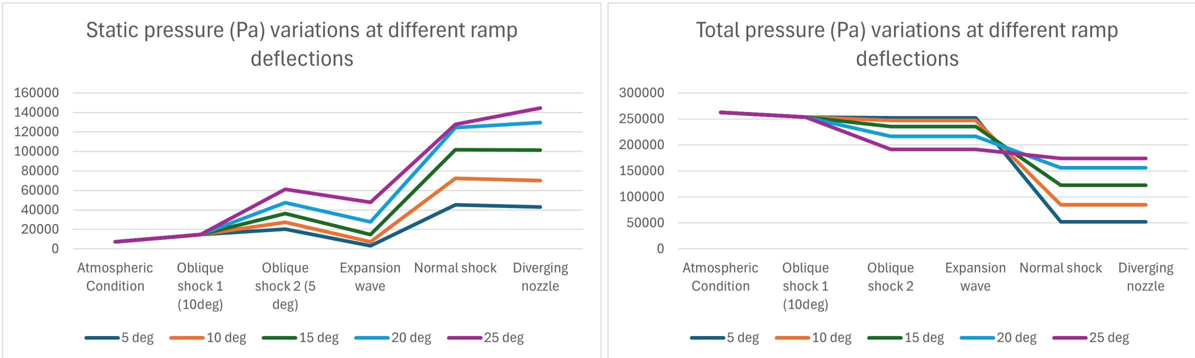

Fig. 6 Impact of ramp deflection on static pressure (left) and stagnation pressures (right) across the flow regions

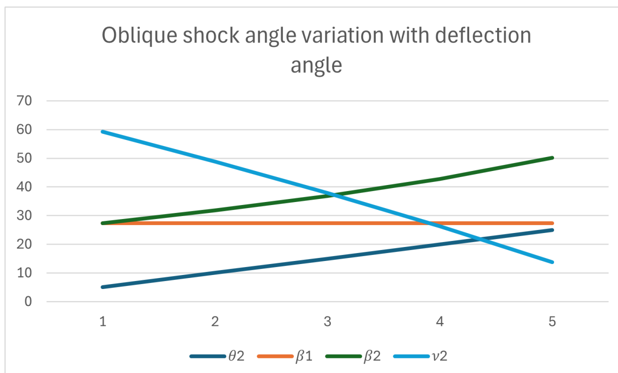

Fig. 7 Relationship between ramp deflection (θ_2), oblique shock 1 angle (β_1), oblique shock 2 angle (β_2), and expansion wave angle at the downstream (ν_2)

Fig 6 is due to the decrease in the effective expansion angle, as shown in Fig 7 that in turn results in lower Mach number upstream of the normal shock wave. By geometry, expansion angle, θ_3, in Table 1, remains constant relative to the free stream flow direction but the effective expansion angle, relative to the upstream flow reduces as the ramp deflection increases as shown in Fig 7, thus reducing the strength of the expansion wave and the result flow speed/mach number across the expansion wave (i.e directly upstream of the normal shock wave). For flow across a normal shock wave, the lower the Mach number, lower the strength of the normal shock wave, tho lower the stagnation pressure variation across the normal shock wave, and the more the downstream stagnation pressure resembles the upstream stagnation pressure. This explains the behavior of the stagnation pressure variation across the normal shock wave. Finally, again, the flow across the expansion fan and diverging nozzle are isentropic, thus total/stagnation pressure across these regions remain constant.

IV. Conclusion

This study of the variations in flow properties across the Concorde engine inlet shows the impacts of oblique shock, expansion wave, normal shock, and diverging nozzle on flow properties. Oblique shock and normal shock waves play important roles on increasing pressure that's needed for enhanced performance of the jet engine which is located at the end of the Concorde engine intake. In order to generate more pressures for the jet engine, high ramp deployment/deflection would be employed as evident by the highest pressure of $145kPa$ achieved by 25° ramp deflection at the end of the diverging nozzle, shown in Fig 6. Expansion wave is effective in speeding up supersonic flows which could be useful for the bypass air, as illustrated in Fig 2, that aids further thrust generation and engine cooling. The occurrence of normal shock wave in the diverging nozzle is also helpful in breaking flow into subsonic speed to prevent flows from passing through the jet engine at supersonic speed because supersonic flow through the jet engine compressors could lead to shock waves which could break the compressor blades.

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