Optimization of an external compression fixed geometry ramp scramjet intake for performance across a wider range of Mach numbers

Brandon Kong

Abstract

Scramjets are a type of air breathing propulsion that operate at speeds above Mach 5, and provide opportunities for cheaper and more efficient transport to space. Traditional LH2/LOX rocket engines have a specific impulse (I_{sp}, a measure of efficiency) of around 450s [6], whereas scramjets can have an I_{sp} of around 3500s. However, scramjets face a multitude of issues, one of which being that fixed geometry scramjets are a point design optimized for a single speed, resulting in performance losses when not at the optimum speed. This paper is intended to optimize the performance across a wider range of Mach numbers in fixed geometry ramp intakes. The optimum number of ramps and the angles of them will be optimized to increase pressure recovery and prevent shock impingement. Typically, a greater number of shocks with oblique shocks at a less extreme angle results in better such performance. Research on such improvement has been done, but have focused on different inlet designs. This research instead focuses on fixed geometry external compression ramp intakes based on Oswatitsch and Kantrowitz criteria, and optimizes the inlet for speeds from Mach 6 to 8.

Variables

γ = specific heat ratio, = 1.2 for this paper
C_r = contraction ratio
P_r = pressure recovery coefficient
E_r = compression ratio
x = intake length
y = intake height
Θ_0 = initial ramp angle
$\Delta\Theta$ = ramp increment angle
Δf = change factor
I_{sp} = specific impulse
M = Mach number

Introduction

Scramjet inlets are designed to compress supersonic flow for the engine. Unlike other traditional airbreathing designs, such as gas turbine jet engines or ramjets, the combustion chamber of a scramjet works with supersonic flow. Therefore, scramjet inlets compress air, but unlike other inlets, do not slow the flow down below Mach 1 (speed of sound). Ref. [12] describes the lower bound for the amount of compression necessary for this inlet. Based on Ref. [12], the minimum E_c is 50, meaning that the stagnation pressure needs to be increased by 50 in the inlet for operation to be possible.

The development of more feasible scramjet technology would allow for space travel to be cheaper. Ref. [5] describes these benefits. It also describes the primary differences between scramjets and other jet propulsion technology. Scramjets are also advantageous since they are significantly more efficient than rocket engines and are able to operate at much higher Mach numbers than normal jet engines/ramjets. Ref. [8] compares the performance between scramjets and other propulsion methods. Specifically, it shows that scramjets can operate at much higher speeds than gas turbine jet engines and ramjets, while being able to have a higher I_{sp} than rocket engines. The theoretical I_{sp} given for scramjets in this paper is up to 3500s, which is significantly higher than rockets at around 400s.

External compression ramp intakes, like the one in this current study, operate by generating oblique shocks by turning supersonic flow, as shown in Figure 1.

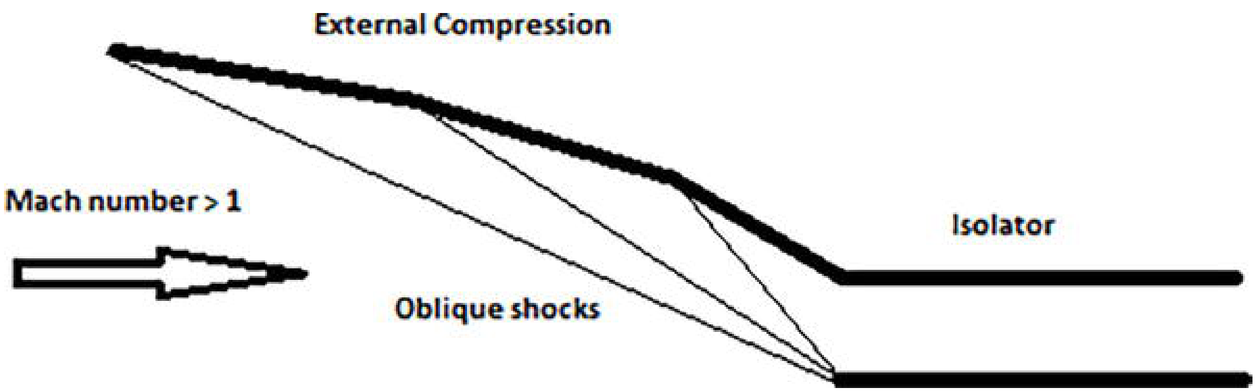

Fig. 1, Ref. [4]: Diagram of how external compression scramjet inlets work

These shock waves are what perform compression on the flow. The goal of intakes are to capture and compress as much air as efficiently and as adiabatically possible, increasing efficiency.

There have been operational scramjets. The NASA X-43 A Hyper X tested a scramjet (Ref. [9]), and was able to achieve speeds of up to Mach 9.6, demonstrating the viability of scramjets.

There are, however, issues that scramjets currently have. As with all supersonic intakes, the inlet must be able to start (form stable shocks), such that airflow can properly be compressed and turned. Should an intake unstart, flow can spill out of the intake and cause malfunction of the scramjet. Shocks may also impinge on parts of the scramjet body, causing mechanical and thermal stress. Ref. [11] describes shock-wave/boundary layer interactions that occur in supersonic inlets that cause shock impingement. Ref. [1] describes how shock impingement results in damaging effects. Shock impingement, which is when a shock interacts with a boundary layer, causes issues such as excess heating and vibrations, which can easily damage scramjets. Due to this, the inlet will be optimized to avoid risk of impingement and reduce possibility of damage. This will be done by reducing movement of oblique shocks and including a buffer in the inlet design to prevent this. This paper will investigate how to optimize the performance of scramjet inlets at multiple points (different Mach numbers); should a scramjet inlet be optimized only for one point, performance can be significantly worsened at off-design conditions, possibly resulting in shock impingement, inlet unstart, or significantly reduced P_r.

Scramjets must obey certain criteria to both function and increase efficiency. Ref. [6] provides data on Kantrowitz starting criteria to obey during optimization of scramjet inlet. The Kantrowitz starting criteria is semi empirically derived and determines the maximum C_r an inlet can achieve to be able to self start. This paper uses γ = 1.4; for the purposes of this paper, γ = 1.2 to account for chemical effects at high Mach numbers. The equation for the Kantrowitz starting criteria are displayed in Figure 2.

$$\mathrm{CR}_{\mathrm{Kantr.}} = \frac{A}{A^*} = \left[\frac{(\gamma+1)M^2}{(\gamma-1)M^2+2}\right]^{0.5}\left[\frac{(\gamma+1)M^2}{2\gamma M^2-(\gamma-1)}\right]^{1/(\gamma-1)}$$

Fig. 2, Ref. [6]. Shows the equation for the Kantrowitz starting criteria.

This equation was graphed in Ref. [6], and is displayed in Figure 3 (γ = 1.4 in Figure 3).

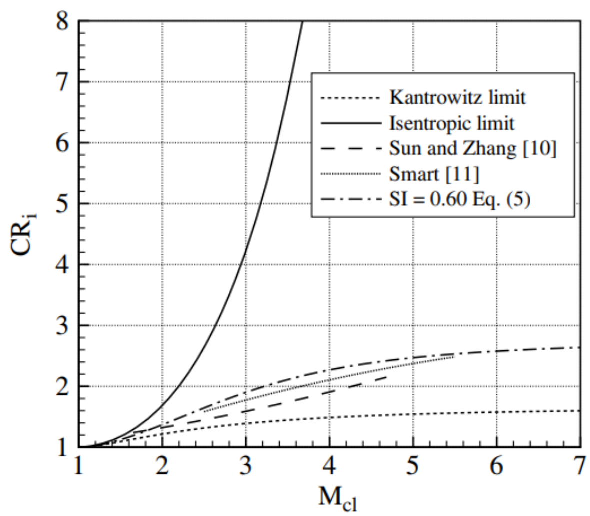

Fig. 3, Ref. [6]. Shows Kantrowitz limit along with other limits. M_{cl} is Mach number, CR_i is contraction ratio. The other lines represent other limits on contraction ratio; the Kantrowitz limit is used in this paper.

There is also the Oswatitch criteria (Ref. [4]), which states that shocks should be of equal strength to optimize efficiency. To do so, each turn in the inlet will differ by the same angle.

Other research has been done on the optimization of scramjet inlets. However, they have focused on different inlet designs; Ref. [2], for example, describes other multipoint design optimization for scramjets. Ref. [2] optimized a Busemann based intake, which differs from a ramp intake and has a more complex geometry. This paper instead focuses on external compression ramp intakes, which are simpler in design and would therefore reduce cost. Fixed geometry design has also been chosen for the same reason. Performance is measured through both movement of shocks under differing speed conditions, as well as P_r. Ref. [7], a sample model for a possible design for a scramjet inlet. This research is used as a target goal to try and exceed in performance. This paper also provides the performance metric P_r that will be used for the determination of the performance of the scramjet inlet being optimized.

Methods

MATLAB was used to generate the theoretical optimal ramp geometry given a specified Mach number, Θ_0, $\Delta\Theta$, number of shocks, γ, and intake height. Ref. [10] describes the equations used in the MATLAB calculations for determination of optimal geometry given a single Mach number. The ramp increment angle, and the number of shocks were adjusted to determine the optimal number of oblique shocks. The data collected was the position of the interception of the shocks along with the length and height of the intake. Tests were run at Mach 6 and 8 (the range of Mach numbers to be optimized over) and γ was set to 1.2.

Spreadsheets were used to collect data and normalize it. Normalization was done by summing the length and height of the intakes for each run for a specific initial angle and ramp increment angle at Mach 6 and 8. Then, the sum of the x and y coordinates for the oblique shock intercept at Mach 6 and 8 was divided by the previous sum at the respective Mach number. The difference between these 2 numbers for a specific initial angle and ramp increment is the Δf. The aim is to reduce this value, as larger values increase risk for shock impingement. The C_r for each specific intake configuration was also measured by finding the ratio between the height of the inlet after compression and in free stream.

Once the data was collected, the C_r and the Δf were plotted using Desmos and are shown in figure (number). For each of these, a curve of best fit was found. Along with these curves, the upper limit for contraction, the Kantrowitz starting limit, was plotted as a green dotted line. The approximate minimum increment angle for each number of shocks to achieve a E_c of 50 (Ref. [4]) was also plotted as an orange curve, and a curve of best fit was found for these values. This creates an important region for ramp increment angles for different numbers of shocks with Θ_0=6° between the orange curve and dotted line that, for the purposes of this paper, the inlets must be in for them to be able to self start and operate with high enough Ec for efficient combustion (Fig. 4).

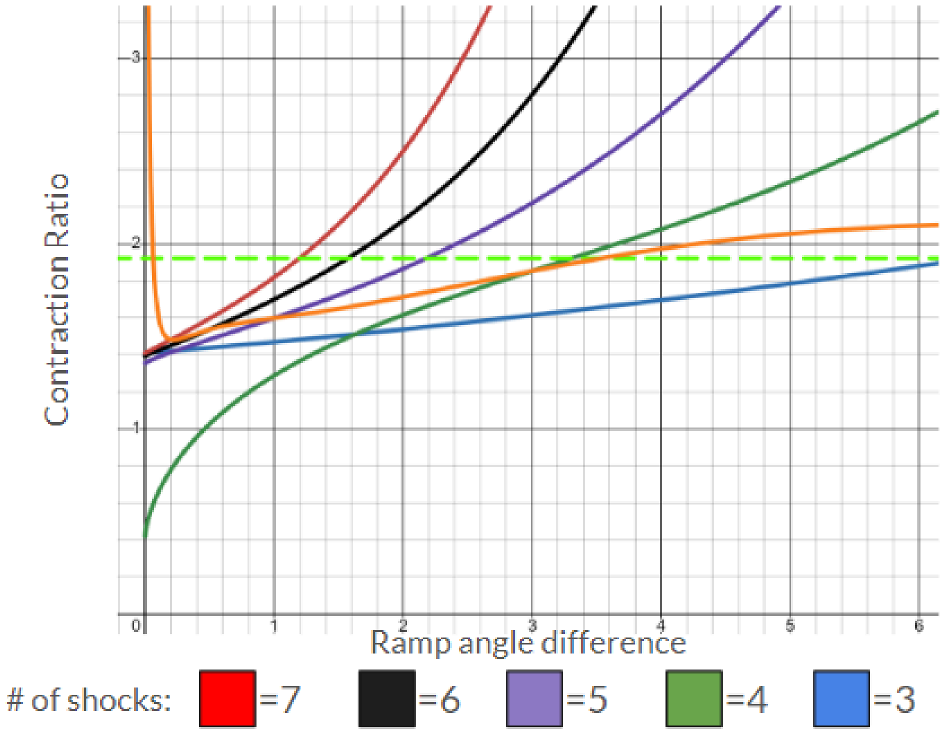

Fig. 4. Graph of contraction ratio vs. ramp angle difference for differing numbers of shocks. The orange curve represents minimum compression, the green dotted line represents maximum contraction.

From here, optimization was performed to find the optimal initial angle and increment angle. Different initial integer angles between 1 and 4 and increment angles between 1 and 4 (depending on the initial angle) were iteratively tested for their performance. The performance for each initial ramp angle was plotted and a curve of best fit was found, with P_r being compared to E_r. Performance was determined by the P_r of each condition. This was tested for both Mach 6 and Mach 8, and each graph for each Mach number is shown in Figure 4.

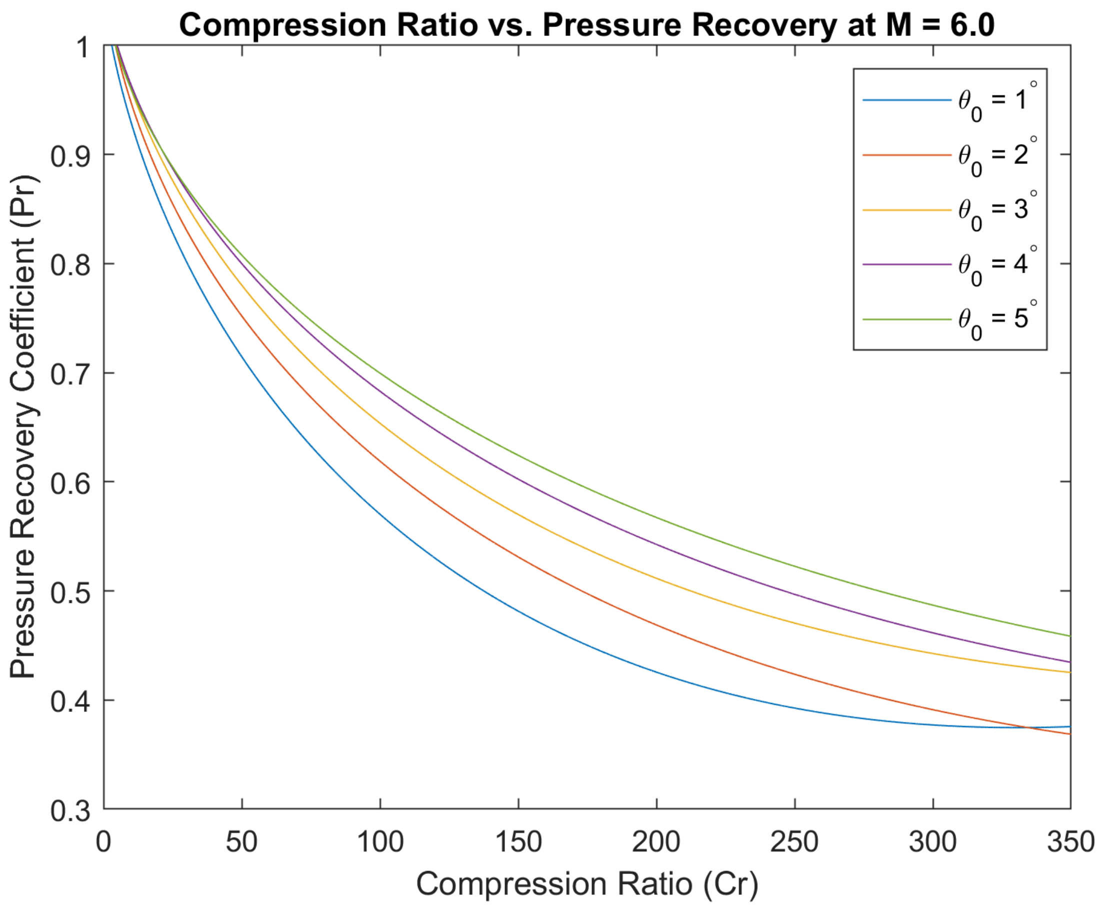

Fig. 5. Graph of P_r vs. C_r at Mach 6 for several different Θ_0.

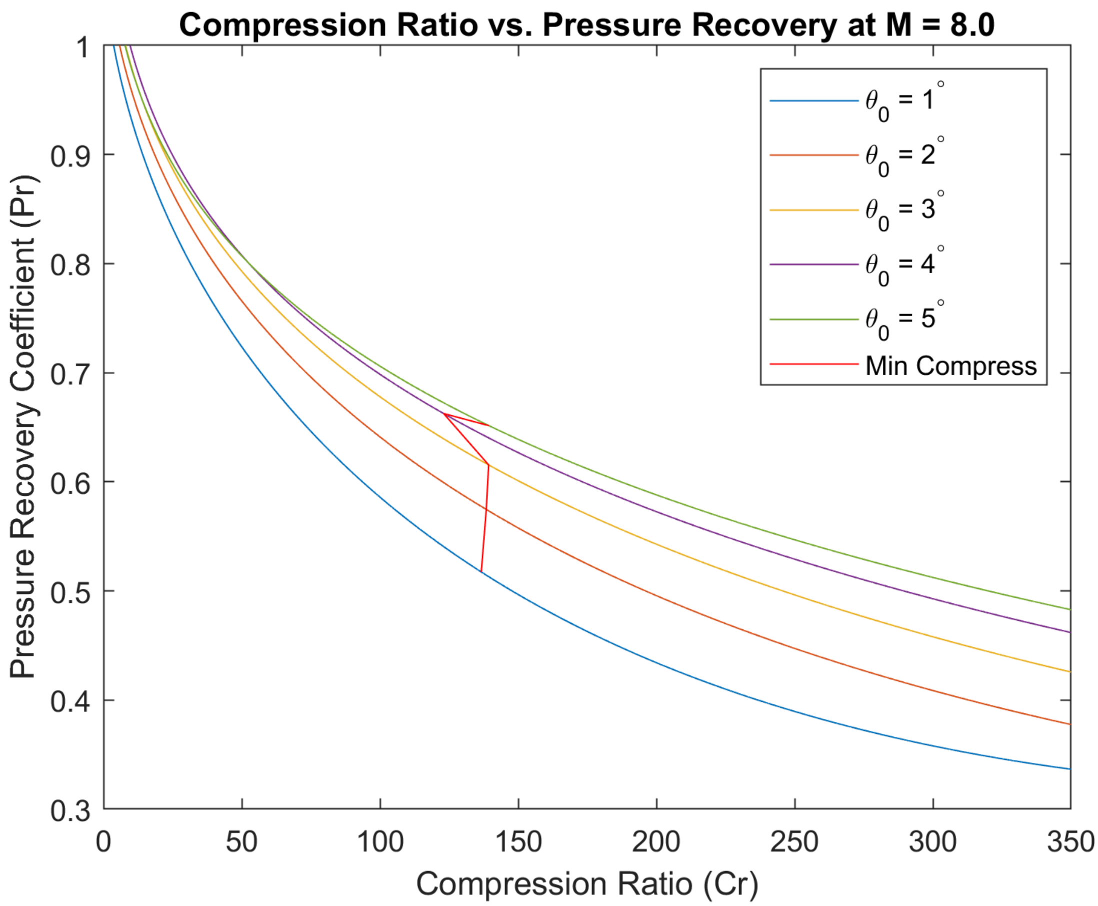

Fig. 6. Graph of P_r vs. C_r at Mach 8 for several different Θ_0. The red lines represent the minimum compression necessary to operate at Mach 6.

To find the optimal initial angle and ramp angle difference, the minimum ramp angle difference for a Ec of 50 at Mach 6 was found for each initial angle. Simply put, the higher the y-value of this graph, the more efficient the scramjet is.The compression for this angle difference condition was found for Mach 8, and plotted for Mach 8 on the E_c vs P_r, and connected between each condition to demonstrate a range of initial angles.

Results

From the tests optimizing the number of shocks, it was determined that 6 shocks was the optimum number of shocks. It falls within the region necessary for starting, and is able to achieve minimum Ec with a fewer number of shocks. Although increasing the number of shocks does result in an increase in an improved ability to achieve minimum Ec with a Cr, Δf also increases, thereby increasing risk of shock impingement in off-design conditions. Shock-wave/boundary layer interactions also occur in the inlet (Ref. [11]), which may cause boundary layer separation. Increasing the number of shocks increases the extent of this issue (more shocks = increased separation events), therefore leading to possible unstart as well as instabilities in the combustion chamber.

From here, it was then determined that the optimal Θ_0 and $\Delta\Theta$ were 4° and 0.92°, respectively. From Fig. 6, we see that it has the highest Pr.

Table 1 shows the geometry of the intake.

Number of Shocks	6
Θ_0	4°
$\Delta\Theta$	0.92°

Table 1: Geometry of optimized inlet.

Based on these conditions, it was found that at M = 6, P_r = 0.80 and at M = 8, P_r = 0.56.

Conclusion

Compared to Ref. [7], the scramjet inlet in this paper performed better, as the inlet in Ref. [7] has a Pr around 0.35 compared to this paper's 0.80. This paper also achieved the goal of having improved performance across a wider range of Mach numbers, as having a low 30% loss in efficiency across a range from M = 6.0 to M = 8.0 is good.

Possible future analysis could include investigation into boundary layer bleeds. These would help to mitigate the effect of shock-wave/boundary layer interactions, and would therefore improve performance.

Other research could also look into using different, novel intakes, such as the Busemann intake discussed earlier. These intakes are more complex than external compression ramp intakes, but they can still provide performance gains.

Finally, further research could investigate the use of variable geometry intakes. Ref. [3] demonstrates such research, but also presents challenges to using these kinds of intakes. Variable geometry intakes increase weight and complexity, but they are still a possibility.

References

[1] Ahuja, Kartika, and Srisha M V Rao. “Response of a cantilevered plate to shock impingement in hypersonic flows.” *International Space Planes and Hypersonic Systems and Technologies Conferences*, 2023, pp. 1-11. *ARC*, https://arc.aiaa.org/doi/10.2514/6.2023-3072.

[2] Brahmachary, Shuvayan, and Hideaki Ogawa. “Multipoint Design Optimization of Busemann-Based Intakes for Scramjet-Powered Ascent Flight.” *JOURNAL OF PROPULSION AND POWER*, vol. 37, no. 6, 2021, pp. 850-857, https://arc.aiaa.org/doi/10.2514/1.B38383.

[3] Dalle, Derek J. “Performance Analysis of Variable-Geometry Scramjet Inlets Using a Low-Order Model.” *47th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*, 2011.

[4] “Design and Performance of Hypersonic Intake for Scramjet Engine.” *Hypersonic and Supersonic Flight: Advances in Aerodynamics, Materials, and Vehicle Design*, edited by Konstantin Nikolaevich Volkov, IntechOpen, 2022. *Intechopen*, https://www.intechopen.com/chapters/84896. Accessed 25 October 2024.

[5] Dirschel, Kevin, and et al. “Hypersonic Speed Through Scramjet Technology.” *University of Colorado Boulder*, 17 December 2015, https://www.colorado.edu/faculty/kantha/sites/default/files/attached-files/67552-116619_-_michael_riechers_-_dec_17_2015_1225_pm_-_dirscherl_riechers_sanders_final.pdf. Accessed 25 October 2024.

[6] Flock, Andreas K., and Ali Gülhan. “Modified Kantrowitz Starting Criteria for Mixed Compression Supersonic Intakes.” *AIAA Journal*, vol. 57, no. 5, 2019. *ARC*, https://arc.aiaa.org/doi/10.2514/1.J057283.

[7] Gao, Feng, and et al. “Numerical Study on Internal flow Field Dynamic Performance of Scramjet.” *MATEC Web of Conferences*, vol. 288, no. 2019 5th Asia Conference on Mechanical Engineering and Aerospace Engineering (MEAE 2019), 2019, pp. 1-5. *Matec Web of Conferences*, https://www.matec-conferences.org/articles/matecconf/abs/2019/37/matecconf_meae2019_02009/matecconf_meae2019_02009.html.

[8] Kors, David. “Design considerations for combined air breathing-rocket propulsion systems.” *ARC*, vol. AIAA, International Aerospace Planes Conference, 2nd, Orlando, FL, Oct. 29-31, 1990. 8 p., 2012. *ARC*.

[9] NASA. “X-43A Hyper-X.” *NASA*, 17 July 2017, https://www.nasa.gov/reference/x-43a/. Accessed 25 October 2024.

[10] Niemeyer, Kyle. “Oblique Shock Waves.” *Gas Dynamics notes*, 2020, https://kyleniemeyer.github.io/gas-dynamics-notes/compressible-flows/oblique-shocks.html. Accessed 25 October 2024.

[11] Sandham, Neil D.. “Shock-Wave/Boundary-Layer Interactions.” (2012).

[12] Smart, Michael K. “How Much Compression Should a Scramjet Inlet Do?” *AIAA Journal*, vol. 50, no. 3, 2012, pp. 610-619. *ARC*.

[13] Varvill, Richard, and Alan Bond. “A Comparison of Propulsion Concepts for SSTO Reusable Launchers.” *JBIS*, vol. 56, 2023, pp. 108-117. *Harvard ADS*, https://ui.adsabs.harvard.edu/abs/2003JBIS...56..108V/abstract.