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**Original Research Article**

# Guidelines on Conceptual and Preliminary Design of Hypersonic Waveriders with Different Number of Inlet Ramps

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## ABSTRACT

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*Many of the savants in the field of aeronautical engineering presume that air-breathing hypersonic flight is the last boundary of aerial vehicle design to be pushed back. A "Waverider," using the Scramjet engine cycle as its propulsive system, is an auspicious design configuration for the prospective hypersonic transport vehicles of the future. Two-dimensional CFD Analysis and case-to-case study of three pre-defined waverider configurations with 2-ramp, 3-ramp, and 4-ramp inlet geometries are carried out in the hypersonic flight regime of Mach numbers 5, 6, and 7. This is done in an attempt to study the single-oriented and correlative-oriented impacts of increasing/decreasing the number of inlet ramps and increasing/decreasing the flight Mach number upon the behavior of final aerodynamic coefficients and ratios. The paramount outcome of the present work is the generation of some tables that can be utilized as primary guidelines for aeronautical design engineers who are designing waverider configurations on a preliminary basis.*

## Introduction

Browsing through the history of aviation, we can see that going "faster and higher" has always been the intrinsic doctrine pursued by aeronautical engineers. The flight regime which comprises speeds of the order of approximately five times the speed of sound and higher as well as exceedingly high elevations of the Earth's atmosphere is classified as hypersonic aerodynamics, in which certain physical phenomena, not so salient at supersonic speeds, become dominant. Air-breathing hypersonic flight is assumed by plenty of pundits in the aeronautical engineering discipline as the last boundary of aerial vehicle design to be crossed [1].

To assess the aerodynamic efficiency of an aerial vehicle flying in the Earth's atmosphere, a parameter known as the maximum lift-to-drag ratio, $(L/D)_{Max}$, is used. Unluckily, for hypersonic flight vehicles, the increase in freestream Mach number leads to an apparent decrease in $(L/D)_{Max}$, which is due to the rapidly increasing shockwave strength encountered as the Mach number increases and, subsequently, the rapidly increasing wave drag, also known as the compressibility drag. Hence, compared to the more conventional flight vehicles flying at lower speed and elevation regimes, the $L/D$ of hypersonic vehicles is of low order. This, in fact, is bothersome when it is desired to design vehicles capable of performing sustained hypersonic flight in the atmosphere [1], [2]. There is a class of configurations for hypersonic flight vehicles capable of producing higher values of $L/D$ compared to other conventional configurations—"waveriders." A waverider is a hypersonic flight vehicle that has attached shockwave throughout its leading edge, riding on top of its own generated shockwave, hence the term "waverider." The aerodynamic convenience in such a configuration is that the high-pressure flow behind the shockwave beneath the vehicle does not leak around the leading edge, finding its way to the upper surface. This is the so-called phenomenon of

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"compression lift," in which the high-pressure flow field over the lower surface is preserved, and, consequently, the amount of lift force produced is of higher order. The first person who introduced the waverider concept was Nonweiler [3] in 1959, generating waverider configurations with caret-shaped (∧) cross sections through the flow field produced by a wedge. An inceptive extension introduced to the work of Nonweiler was by Jones [4] in 1963. He used the flow field produced by a cone in order to generate more convoluted shapes for a waverider [1], [2], [5].

By and large, a waverider is an aircraft, a wing, and a propulsion system simultaneously. It is a promising design configuration for the hypersonic transport vehicles of the future. The propulsion system capable of propelling a waverider is the air-breathing Supersonic Combustion Ramjet engine cycle, also known as the SCRAMjet. A Scramjet engine is not dependent upon turbo-machinery in order for the rushing air into the engine's inlet to be compressed, but rather a system of shockwaves generated by the inlet geometry of the waverider. The number of inlet ramps utilized in a waverider configuration not only influences the overall efficiency of the entire Scramjet engine but also influences the overall aerodynamic efficiency of the waverider configuration itself from a design vantage point. This is owing to the fact that the structure of oblique shockwaves generated on the waverider's configuration is directly dependent on the arrangement of inlet geometry, such as the number of inlet ramps to be used and the angles between each pair of adjacent ramps [1], [2], [5], [6].

Two-dimensional computational fluid dynamics (CFD) analysis and case-to-case study of three pre-defined waverider configurations [6] with 2-ramp, 3-ramp, and 4-ramp inlet geometries, in the hypersonic flight regime of Mach numbers 5, 6, and 7, are conducted in an endeavor to investigate the single-oriented (constant waverider geometry in a variable Mach number flight regime or variable waverider geometry in a constant Mach number flight regime) and also the correlative-oriented (variable waverider geometry in a variable Mach number flight regime) effects of increasing/decreasing the number of inlet ramps as well as increasing/decreasing the flight Mach number on the behavior of final aerodynamic coefficients and ratios. The predominant outcome of the present work is the generation of some tables that can be utilized as primary guidelines for aeronautical design engineers designing waverider configurations on a primary basis. Using these tables, they can get a better vantage of each and every single design decision they make regarding the number of inlet ramps to be used and the appropriate flight Mach number range to be chosen during the conceptual and preliminary phases of the design procedure.

## Modeling and Simulation Methodology

Three waverider configurations with two, three, and four inlet ramps were excerpted from [6], as shown in Figures 1 to 3. The three configurations were drawn in the Ansys Design Modeler and accompanied by proper fluid domains. Next, the domains were meshed, using the Ansys Meshing, in a fully structured quadrilateral manner with a maximum value of 0.165 for the skewness metric, a minimum value of 0.926 for the orthogonal quality metric, and an entire wall Y-plus distribution below 1 for the turbulence metric, leading to roughly 3 million elements of mesh for each domain. Fig. 4 shows the mesh for the 2-ramp configuration as a sample. Afterward, the models accompanied by their mesh were transferred to the Ansys Fluent Software. The CFD analysis was carried out using conservation equations of continuity, momentum, and energy with the assumption of ideal gas, utilizing a density-based solver (with the implicit solution approach) and K-Omega SST (Shear Stress Transport) turbulence model. The operating conditions in which the study has been done [6] are demonstrated in Table 1 below. Cases were put into a run mode until the convergence criteria were satisfied, and the simulations' results were validated, domain-, and grid-independent.

**Table 1:** Freestream Conditions [6]

| Mach Number | Total Pressure (Pascal) | Total Temperature (Kelvin) | Total Density (Kilograms per cubic meter) |
|---|---|---|---|
| 5 | 2860.2 | 220.7 | 0.045141 |
| 6 | 1986.8 | 224.8 | 0.030775 |
| 7 | 1459.8 | 229.3 | 0.022165 |

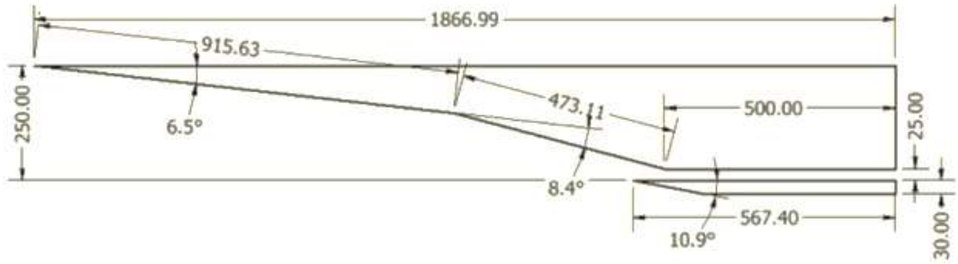


**Fig. 1:** 2-Ramp Waverider Configuration, excerpted from **[6]**

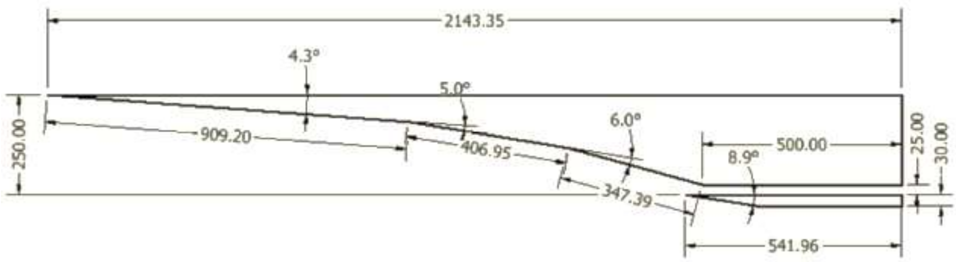


**Fig. 2:** 3-Ramp Waverider Configuration, excerpted from [6]

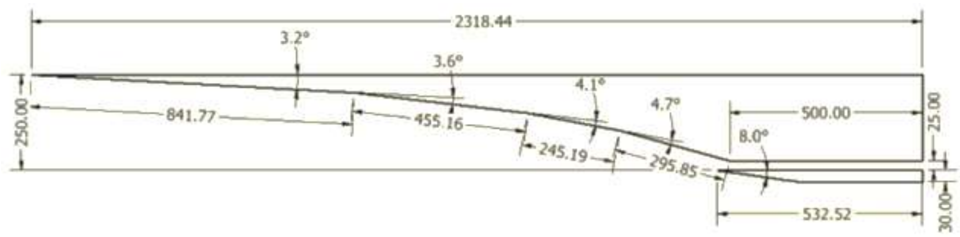


**Fig. 3:** 4-Ramp Waverider Configuration, excerpted from [6]

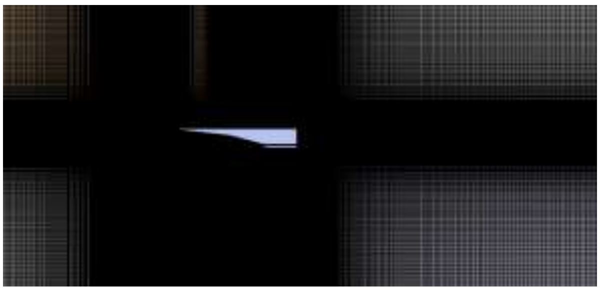

**Fig. 4:** Mesh Generated for the 2-Ramp Configuration

It is worth mentioning that the work presented here is the continuation of another piece of research [7], written by the same authors, in which the operating condition of Mach number 5 was solely investigated for the same geometries. In [7], distinct facets of the physics of the flow field around the geometries, compared to the current work, were studied.

## Validation of Results

In order to validate the results obtained from the simulations, the data on static pressure over the compression ramps of the 2- and 3-ramp configurations in the flight regime of Mach number 5 were collected, both from the present simulation and from [6]. The acquired data from the two sources were superimposed onto one another, as shown in Figures 5 and 6.

As can be seen, figures 5 and 6 demonstrate an evident resemblance between the two sets of data, and it can be observed that the pressure levels match perfectly. The only difference between the two sets of data is some delay witnessed in the prediction of shockwave occurrence made by [6]. The reason for such a delay is that the modeling and simulation conducted in [6] have a lower level of accuracy than those of the present simulation. In [6], the simulation domain is meshed in an unstructured manner, using triangular elements, which, in total, aggregate approximately 100 thousand elements. This is whilst the modeling and simulation carried out in the present work benefit from a fully structured quadrilateral domain meshed with roughly 3 million elements, showing an entire wall Y-plus distribution below 1. What is more, not only do the static pressure levels acquired in this study match perfectly with those acquired in [6] by the usage of CFD, but they also match flawlessly with the pressure levels obtained from the oblique shock theory, also calculated in [6]. The only point to bear in mind is that the oblique shock theory can merely predict the effects engendered by pressure distribution, and it is not capable of predicting the impacts caused by shear stress distribution. That is why some slight fluctuations in the static pressure data gained through CFD analysis compared to those obtained from the oblique shock theory, demonstrating a constant level of pressure over each compression ramp after the occurrence of each single shockwave, can be observed. The CFD analysis not only considers the effects originated by pressure distribution but also accounts for the ones triggered by viscosity.

All things considered, it can be concluded that all the data output by the simulations carried out in this study are valid and reliable.

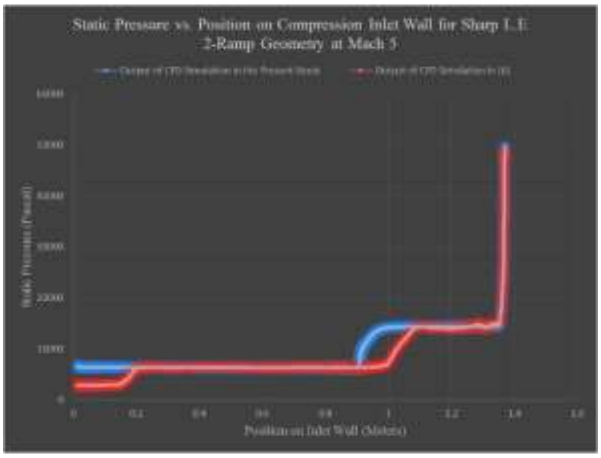


**Fig. 5:** Comparison between Static Pressure Data over the Compression Ramps of the 2-Ramp Configuration at Mach 5, obtained from both the present simulations and [6]

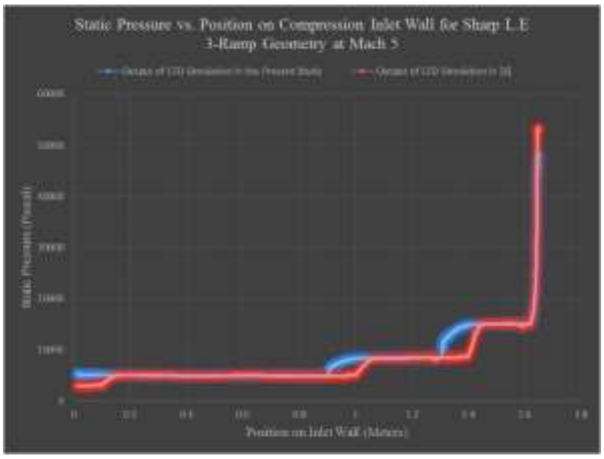


**Fig. 6:** Comparison between Static Pressure Data over the Compression Ramps of the 3-Ramp Configuration at Mach 5, obtained from both the present simulations and [6]

## Results and Discussion

The desired output data of the simulations were extracted from the Ansys CFD-Post.

### Studying the Generic Behavior Observed in the Total Aerodynamic Forces, Moments, Coefficients, and Ratios

Tables 2 to 4 demonstrate the total amount of lift and drag forces (in Newtons) and also the total amount of pitching moments (in Newtons. meter), acting on each of the three geometries at Mach numbers 5, 6, and 7, respectively.

**Table 2:** Total Amount of Aerodynamic Forces and Pitching Moments on the Three Geometries under Study at Mach 5

| | |
|---|---|
| 2 Ramp Geometry | |
| Lift (N) | 6017.1554 |
| Drag (N) | 3234.0518 |
| Moment (N.m) | -2241.3754 |
| 3 Ramp Geometry | |
| Lift (N) | 6249.3981 |
| Drag (N) | 3004.3987 |
| Moment (N.m) | -3686.4856 |
| 4 Ramp Geometry | |
| Lift (N) | 6383.7441 |
| Drag (N) | 2955.0613 |
| Moment (N.m) | -4652.8225 |

**Table 3:** Total Amount of Aerodynamic Forces and Pitching Moments on the Three Geometries under Study at Mach 6

| | |
|---|---|
| 2 Ramp Geometry | |
| Lift (N) | 4954.4059 |
| Drag (N) | 3009.1757 |
| Moment (N.m) | -1640.1707 |
| 3 Ramp Geometry | |
| Lift (N) | 5220.9027 |
| Drag (N) | 2769.0831 |
| Moment (N.m) | -2993.0185 |
| 4 Ramp Geometry | |
| Lift (N) | 5312.6956 |
| Drag (N) | 2726.0097 |
| Moment (N.m) | -3751.4622 |

**Table 4:** Total Amount of Aerodynamic Forces and Pitching Moments on the Three Geometries under Study at Mach 7

| | |
|---|---|
| 2 Ramp Geometry | |
| Lift (N) | 3921.22 |
| Drag (N) | 2914.2404 |
| Moment (N.m) | -949.75923 |
| 3 Ramp Geometry | |
| Lift (N) | 4094.7214 |
| Drag (N) | 2652.428 |
| Moment (N.m) | -1934.8527 |
| 4 Ramp Geometry | |
| Lift (N) | 4216.897 |
| Drag (N) | 2603.4091 |
| Moment (N.m) | -2639.4174 |

Subsequently, in tables 5 to 7 below, the total amount of non-dimensional aerodynamic coefficients and ratios (the aerodynamic efficiency parameter, i.e., lift over drag coefficient ratio), acting on each of the three geometries at Mach numbers 5, 6, and 7, respectively, are yielded.

**Table 5:** Total Amount of Non-dimensional Aerodynamic Coefficients and Ratios on the Three Geometries under Study at Mach 5

| | |
|---|---|
| 2 Ramp Geometry | |
| C_L | 0.064450986 |
| C_D | 0.034640592 |
| C_M | -0.012859731 |
| C_L / C_D | 1.860562468 |
| 3 Ramp Geometry | |
| C_L | 0.058306184 |
| C_D | 0.028030703 |
| C_M | -0.016047449 |
| C_L / C_D | 2.080082813 |
| 4 Ramp Geometry | |
| C_L | 0.05506843 |
| C_D | 0.025491402 |
| C_M | -0.017314563 |
| C_L / C_D | 2.160274679 |

**Table 6:** Total Amount of Non-dimensional Aerodynamic Coefficients and Ratios on the Three Geometries under Study at Mach 6

| | |
|---|---|
| 2 Ramp Geometry | |
| C_L | 0.05306967 |
| C_D | 0.032233121 |
| C_M | -0.009410719 |
| C_L / C_D | 1.646432909 |
| 3 Ramp Geometry | |
| C_L | 0.048712284 |
| C_D | 0.025836215 |
| C_M | -0.013029248 |
| C_L / C_D | 1.885426515 |
| 4 Ramp Geometry | |
| C_L | 0.045830926 |
| C_D | 0.023516414 |
| C_M | -0.013960858 |
| C_L / C_D | 1.948890938 |

**Table 7:** Total Amount of Non-dimensional Aerodynamic Coefficients and Ratios on the Three Geometries under Study at Mach 7

| | |
|---|---|
| 2 Ramp Geometry | |
| C_L | 0.042005401 |
| C_D | 0.031218304 |
| C_M | -0.005449748 |
| C_L / C_D | 1.345537588 |
| 3 Ramp Geometry | |
| C_L | 0.038207302 |
| C_D | 0.024749454 |
| C_M | -0.008423391 |
| C_L / C_D | 1.54376345 |
| 4 Ramp Geometry | |
| C_L | 0.036380261 |
| C_D | 0.022460283 |
| C_M | -0.009823104 |
| C_L / C_D | 1.619759645 |

In the following, in tables 8 to 11, the amounts of the total lift coefficient, total drag coefficient, total pitching moment coefficient, and total lift over drag coefficient ratio on the three geometries at Mach numbers 5, 6, and 7 are categorized, respectively, based on the type of the non-dimensional coefficient or ratio and in order to give a better view of the output data to the reader.

**Table 8:** Categorization of the Amount of Total Lift Coefficient on the Three Geometries under Study at Mach Numbers 5, 6, and 7, respectively

| 2 Ramp Geometry | |
|---|---|
| Mach | Total C_L |
| 5 | 0.064450986 |
| 6 | 0.05306967 |
| 7 | 0.042005401 |
| 3 Ramp Geometry | |
| 5 | 0.058306184 |
| 6 | 0.048712284 |
| 7 | 0.038207302 |
| 4 Ramp Geometry | |
| 5 | 0.05506843 |
| 6 | 0.045830926 |
| 7 | 0.036380261 |

**Table 9:** Categorization of the Amount of Total Drag Coefficient on the Three Geometries under Study at Mach Numbers 5, 6, and 7, respectively

| 2 Ramp Geometry | |
|---|---|
| Mach | Total C_D |
| 5 | 0.034640592 |
| 6 | 0.032233121 |
| 7 | 0.031218304 |
| 3 Ramp Geometry | |
| 5 | 0.028030703 |
| 6 | 0.025836215 |
| 7 | 0.024749454 |
| 4 Ramp Geometry | |
| 5 | 0.025491402 |
| 6 | 0.023516414 |
| 7 | 0.022460283 |

**Table 10:** Categorization of the Amount of Total Pitching Moment Coefficient on the Three Geometries under Study at Mach Numbers 5, 6, and 7, respectively

| 2 Ramp Geometry | |
|---|---|
| Mach | Total C_M |
| 5 | -0.012859731 |
| 6 | -0.009410719 |
| 7 | -0.005449748 |
| 3 Ramp Geometry | |
| 5 | -0.016047449 |
| 6 | -0.013029248 |
| 7 | -0.008423391 |
| 4 Ramp Geometry | |
| 5 | -0.017314563 |
| 6 | -0.013960858 |
| 7 | -0.009823104 |

**Table 11:** Categorization of the Amount of Total Lift over Drag Coefficient Ratio on the Three Geometries under Study at Mach Numbers 5, 6, and 7, respectively

| 2 Ramp Geometry | |
|---|---|
| Mach | Total (C_L / C_D) |
| 5 | 1.860562468 |
| 6 | 1.646432909 |
| 7 | 1.345537588 |
| 3 Ramp Geometry | |
| 5 | 2.080082813 |
| 6 | 1.885426515 |
| 7 | 1.54376345 |
| 4 Ramp Geometry | |
| 5 | 2.160274679 |
| 6 | 1.948890938 |
| 7 | 1.619759645 |

Predicated upon tables 8 to 11, figures 7 to 10, in the following, depict the changing trends in total aerodynamic coefficients and ratios with respect to Mach number change, with the geometry type change superimposed on.

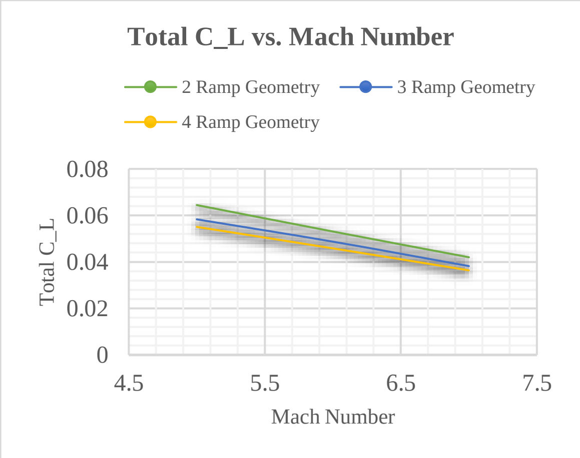


**Fig. 7:** Total Lift Coefficient Changing Trend versus Mach number

As can be seen, by changing the Mach number from 5 through 7 and simultaneously keeping the geometry type constant, we can see that the total amount of C_L for each of the three geometries has decreased. The amount of percentage change occurring by changing the Mach number, going from 5 to 6, 6 to 7, and the total loss occurring in lift coefficient, going from Mach 5 through 7, are demonstrated in Table 12 below.

**Table 12:** Total Lift Coefficient Percentage Change Occurring by Mach Number Change in each of the Geometries

| Total C_L Percentage Change (%) | Mach 5 to 6 Percentage Change (%) | Mach 6 to 7 Percentage Change (%) | Mach 5 to 7 (Total) Percentage Change (%) |
|---|---|---|---|
| 2 Ramp | -17.65886 | -20.84857 | -34.8258 |
| 3 Ramp | -16.45434 | -21.56536 | -34.4712 |
| 4 Ramp | -16.77459 | -20.62071 | -33.9362 |

It can be deduced that, by keeping the geometry constant, the amount of loss occurring in the total lift coefficient is more intense when we go from Mach 6 to 7, compared to the case when we go from Mach 5 to 6.

It can also be seen that, by going from Mach 5 to 7, the maximum loss in the total lift coefficient has occurred in the 2-ramp geometry, and the minimum loss has occurred in the 4-ramp geometry. It can be inferred that by and large, increasing the number of inlet ramps can diminish the amount of lift coefficient loss, i.e., diminish the slope of the diagram in Fig. 7, occurring in the waverider configuration flying in a Mach number range.

Looking at Fig. 7, it can also be seen that, by changing the geometry type from 2-ramp through 4-ramp geometry and keeping the Mach number constant simultaneously, the total amount of C_L has decreased. The amount of percentage change occurring by changing the geometry type, going from 2-ramp to 3-ramp and 3-ramp to 4-ramp, and the total reduction occurring in lift coefficient, going from 2-ramp through 4-ramp geometry, are demonstrated in Table 13 below.

**Table 13:** Total Lift Coefficient Percentage Change Occurring by Geometry Type Change in each of the Mach Numbers

| Total C_L Percentage Change (%) | Mach 5 | Mach 6 | Mach 7 |
|---|---|---|---|
| 2 Ramp through 3 Ramp Geometry Change (%) | -9.53406 | -8.21068 | -9.04192 |
| 3 Ramp through 4 Ramp Geometry Change (%) | -5.55302 | -5.91505 | -4.78191 |
| 2 Ramp through 4 Ramp Geometry (Total) Change (%) | -14.5576 | -13.64007 | -13.39146 |

It can be deduced that, by keeping the Mach number constant, the amount of loss occurring in the total lift coefficient is more intense when we go from 2-ramp to 3-ramp geometry, compared to the case when we go from 3-ramp to 4-ramp geometry.

It can also be seen that, by going from 2-ramp through 4-ramp geometry, the maximum loss in the total lift coefficient has occurred in Mach 5, and the minimum loss has occurred in Mach 7, i.e., by going from Mach 5 to Mach 7, the vertical distance between constant Mach number points amongst three geometries has decreased. It should be noted here that the correlative influence of changing both the Mach number and number of inlet ramps on the total lift coefficient is convoluted and depends upon the case under study.

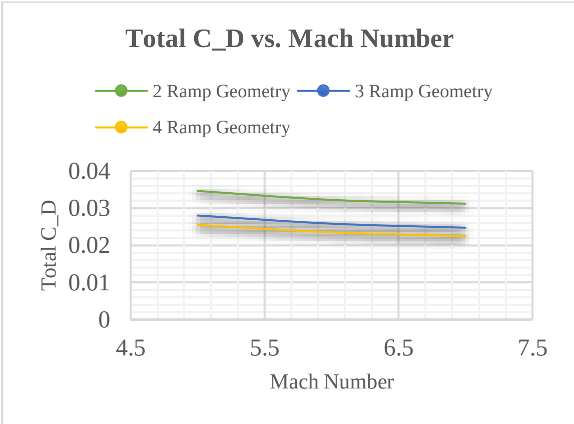


**Fig. 8:** Total Drag Coefficient Changing Trend versus Mach number

As can be seen, by changing the Mach number from 5 through 7 and simultaneously keeping the geometry type constant, we can see that the total amount of C_D for each of the three geometries has decreased. The amount of percentage change occurring by changing the Mach number, going from 5 to 6 and 6 to 7, and the total reduction occurring in the drag coefficient, going from Mach 5 through 7, are demonstrated in Table 14 below.

**Table 14:** Total Drag Coefficient Percentage Change Occurring by Mach Number Change in each of the Geometries

| Total C_D Percentage Change (%) | Mach 5 to 6 Percentage Change (%) | Mach 6 to 7 Percentage Change (%) | Mach 5 to 7 (Total) Percentage Change (%) |
|---|---|---|---|
| 2 Ramp | -6.94985 | -3.14836 | -9.87941 |
| 3 Ramp | -7.82887 | -4.20634 | -11.70591 |
| 4 Ramp | -7.74766 | -4.49103 | -11.89074 |

It can be deduced that, by keeping the geometry constant, the amount of reduction occurring in the total drag coefficient is more intense when we go from Mach 5 to 6, compared to the case when we go from Mach 6 to 7.

It can also be seen that, by going from Mach 5 to 7, the maximum reduction in the total drag coefficient occurred in the 4-ramp geometry, and the minimum reduction occurred in the 2-ramp geometry. It can be inferred that by and large, increasing the number of inlet ramps can increase the amount of drag coefficient reduction, occurring in the waverider configuration flying in a Mach number range.

Looking at Fig. 8, it can also be seen that, by changing the geometry type from 2-ramp through 4-ramp geometry and keeping the Mach number constant simultaneously, the total amount of C_D has decreased. The amount of percentage change occurring by changing the geometry type, going from 2-ramp to 3-ramp and 3-ramp to 4-ramp, and the total reduction occurring in the drag coefficient, going from 2-ramp through 4-ramp geometry, are demonstrated in Table 15 below.

**Table 15:** Total Drag Coefficient Percentage Change Occurring by Geometry Type Change in each of the Mach Numbers

| Total C_D Percentage Change (%) | Mach 5 | Mach 6 | Mach 7 |
|---|---|---|---|
| 2 Ramp through 3 Ramp Geometry Change (%) | -19.08133 | -19.8457 | -20.72133 |
| 3 Ramp through 4 Ramp Geometry Change (%) | -9.05899 | -8.97887 | -9.24937 |
| 2 Ramp through 4 Ramp Geometry (Total) Change (%) | -26.41176 | -27.0427 | -28.05411 |

It can be deduced that, by keeping the Mach number constant, the amount of reduction occurring in the total drag coefficient is more intense when we go from 2-ramp to 3-ramp geometry, compared to the case when we go from 3-ramp to 4-ramp geometry.

It can also be seen that, by going from 2-ramp through 4-ramp geometry, the maximum reduction in the total drag coefficient has occurred in Mach 7, and the minimum reduction has occurred in Mach 5, i.e., by going from Mach 5 to Mach 7, the vertical distance between constant Mach number points amongst three geometries has slightly increased. It should be noted here that the correlative influence of changing both the Mach number and number of inlet ramps on the total drag coefficient is convoluted and depends upon the case under study.

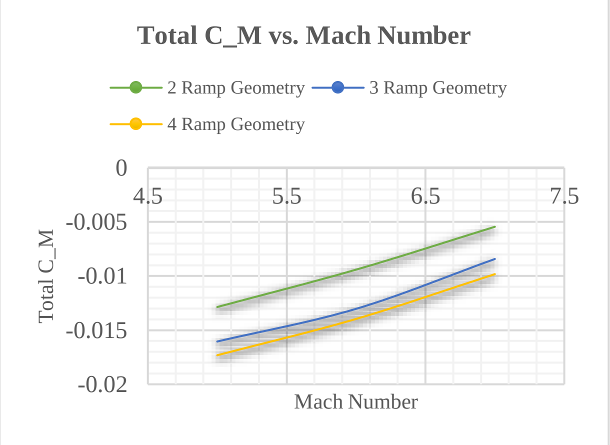


**Fig. 9:** Total Pitching Moment Coefficient Changing Trend versus Mach number

As can be seen, by changing the Mach number from 5 through 7 and simultaneously keeping the geometry type constant, we can see that the total amount of C_M for each of the three geometries has decreased (the absolute value of C_M has decreased). The amount of percentage change occurring by changing the Mach number, going from 5 to 6 and 6 to 7, and the total reduction occurring in the pitching moment coefficient, going from Mach 5 through 7, are demonstrated in Table 16 below.

**Table 16:** Total Pitching Moment Coefficient Percentage Change Occurring by Mach Number Change in each of the Geometries

| Total C_M Percentage Change (%) | Mach 5 to 6 Percentage Change (%) | Mach 6 to 7 Percentage Change (%) | Mach 5 to 7 (Total) Percentage Change (%) |
|---|---|---|---|
| 2 Ramp | -26.82025 | -42.08999 | -57.62160 |
| 3 Ramp | -18.80798 | -35.35013 | -47.50947 |
| 4 Ramp | -19.36927 | -29.63825 | -43.26681 |

It can be deduced that, by keeping the geometry constant, the amount of reduction occurring in the total pitching moment coefficient is more intense when we go from Mach 6 to 7, compared to the case when we go from Mach 5 to 6.

It can also be seen that, by going from Mach 5 to 7, the maximum reduction in the total pitching moment coefficient occurred in the 2-ramp geometry, and the minimum reduction occurred in the 4-ramp geometry. It can be inferred that by and large, increasing the number of inlet ramps can diminish the amount of pitching moment coefficient reduction occurring in the waverider configuration flying in a Mach number range.

Looking at Fig. 9, it can also be seen that, by changing the geometry type from 2-ramp through 4-ramp geometry and keeping the Mach number constant simultaneously, the total amount of C_M has increased (the absolute value of C_M has increased). The amount of percentage change occurring by changing the geometry type, going from 2-ramp to 3-ramp, 3-ramp to 4-ramp, and the total increase occurring in pitching moment coefficient, going from 2-ramp through 4-ramp geometry, are demonstrated in Table 17 below.

**Table 17:** Total Pitching Moment Coefficient Percentage Change Occurring by Geometry Type Change in each of the Mach Numbers

| Total C_M Percentage Change (%) | Mach 5 | Mach 6 | Mach 7 |
|---|---|---|---|
| 2 Ramp through 3 Ramp Geometry Change (%) | 24.78837 | 38.45113 | 54.56479 |
| 3 Ramp through 4 Ramp Geometry Change (%) | 7.89604 | 7.15014 | 16.61697 |
| 2 Ramp through 4 Ramp Geometry (Total) Change (%) | 34.64172 | 48.35059 | 80.24877 |

It can be deduced that, by keeping the Mach number constant, the amount of increase occurring in the total pitching moment coefficient is more intense when we go from 2-ramp to 3-ramp geometry, compared to the case when we go from 3-ramp to 4-ramp geometry.

It can also be seen that, by going from 2-ramp through 4-ramp geometry, the maximum increase in the total pitching moment coefficient has occurred in Mach 7, and the minimum increase has occurred in Mach 5, i.e., by going from Mach 5 to Mach 7, the vertical distance between constant Mach number points amongst three geometries has slightly increased. It should be noted here that the correlative influence of changing both the Mach number and number of inlet ramps on the total pitching moment coefficient is convoluted and depends upon the case under study.

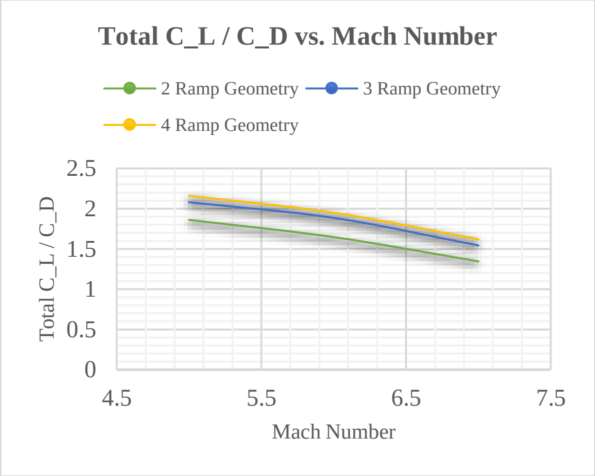


**Fig. 10:** Total Aerodynamic Efficiency Parameter Changing Trend versus Mach number

As can be seen, by changing the Mach number from 5 through 7 and simultaneously keeping the geometry type constant, we can see that the total amount of C_L / C_D for each of the three geometries has decreased. The amount of percentage change occurring by changing the Mach number, going from 5 to 6, 6 to 7, and the total loss occurring in the aerodynamic efficiency parameter, going from Mach 5 through 7, are demonstrated in Table 18 below.

**Table 18:** Total Aerodynamic Efficiency Parameter Percentage Change Occurring by Mach Number Change in each of the Geometries

| Total (C_L / C_D) Percentage Change (%) | Mach 5 to 6 Percentage Change (%) | Mach 6 to 7 Percentage Change (%) | Mach 5 to 7 (Total) Percentage Change (%) |
|---|---|---|---|
| 2 Ramp | -11.50886 | -18.27558 | -27.68113 |
| 3 Ramp | -9.35810 | -18.12126 | -25.78355 |
| 4 Ramp | -9.78503 | -16.88813 | -25.02066 |

It can be deduced that, by keeping the geometry constant, the amount of loss occurring in the total aerodynamic efficiency parameter is more intense when we go from Mach 6 to 7, compared to the case when we go from Mach 5 to 6, which is precisely what happens in the hypersonic flight regime as previously mentioned.

It can also be seen that, by going from Mach 5 to 7, the maximum loss in the total aerodynamic efficiency parameter has occurred in the 2-ramp geometry, and the minimum loss has occurred in the 4-ramp geometry. It can be inferred that by and large, increasing the number of inlet ramps can diminish the amount of aerodynamic efficiency parameter loss occurring in the waverider configuration flying in a Mach number range.

Looking at Fig. 10, it can also be seen that, by changing the geometry type from 2-ramp through 4-ramp geometry and keeping the Mach number constant simultaneously, the total amount of C_L/ C_D has increased. The amount of percentage change occurring by changing the geometry type, going from 2-ramp to 3-ramp, 3-ramp to 4-ramp, and the total increase occurring in aerodynamic efficiency parameter, going from 2-ramp through 4-ramp geometry, are demonstrated in Table 19 below.

**Table 19:** Total Aerodynamic Efficiency Parameter Percentage Change Occurring by Geometry Type Change in each of the Mach Numbers

| Total (C_L / C_D) Change (%) | Mach 5 | Mach 6 | Mach 7 |
|---|---|---|---|
| 2 Ramp through 3 Ramp Geometry Change (%) | 11.79860 | 14.51584 | 14.73209 |
| 3 Ramp through 4 Ramp Geometry Change (%) | 3.85522 | 3.36605 | 4.92278 |
| 2 Ramp through 4 Ramp Geometry (Total) Change (%) | 16.10868 | 18.37050 | 20.38011 |

It can be deduced that, by keeping the Mach number constant, the amount of increase occurring in the total aerodynamic efficiency parameter is more intense when we go from 2-ramp to 3-ramp geometry, compared to the case when we go from 3-ramp to 4-ramp geometry.

It can also be seen that, by going from 2-ramp through 4-ramp geometry, the maximum increase in the total aerodynamic efficiency parameter has occurred in Mach 7, and the minimum increase has occurred in Mach 5, i.e., by going from Mach 5 to Mach 7, the vertical distance between constant Mach number points amongst three geometries has slightly increased. It should be noted here that the correlative influence of changing both the Mach number and number of inlet ramps on the total aerodynamic efficiency parameter is convoluted and depends upon the case under study.

## Studying the Correlative Behavior Observed in the Total Aerodynamic Coefficients and Ratios

Carrying out some more arithmetic calculations on the output data demonstrated in tables 12, 14, 16, and 18, we can find invaluable data, showing the interactive influence of changing both the Mach number and the number of inlet ramps simultaneously upon the percentage change difference, being witnessed in the aerodynamic coefficients and ratios under study. Tables 20 to 23 depict such data as follows:

**Table 20:** Correlative Percentage Difference Observed in the Total Lift Coefficient

| Total C_L Percentage Change Difference (%) | Mach 5 to 6 (%) | Mach 6 to 7 (%) | Mach 5 to 7 (Total) (%) |
|---|---|---|---|
| 2 Ramp through 3 Ramp Geometry (%) | 1.20452 | -0.71679 | 0.35455 |
| 3 Ramp through 4 Ramp Geometry (%) | -0.32024 | 0.94464 | 0.53500 |
| 2 Ramp through 4 Ramp Geometry (%) | 0.88427 | 0.22785 | 0.88955 |

**Table 21:** Correlative Percentage Difference Observed in the Total Drag Coefficient

| Total C_D Percentage Change Difference (%) | Mach 5 to 6 (%) | Mach 6 to 7 (%) | Mach 5 to 7 (Total) (%) |
|---|---|---|---|
| 2 Ramp through 3 Ramp Geometry (%) | -0.87901 | -1.05798 | -1.82649 |
| 3 Ramp through 4 Ramp Geometry (%) | 0.08120 | -0.28468 | -0.18483 |
| 2 Ramp through 4 Ramp Geometry (%) | -0.79780 | -1.34266 | -2.01133 |

**Table 22:** Correlative Percentage Difference Observed in the Total Pitching Moment Coefficient

| Total C_M Percentage Change Difference (%) | Mach 5 to 6 (%) | Mach 6 to 7 (%) | Mach 5 to 7 (Total) (%) |
|---|---|---|---|
| 2 Ramp through 3 Ramp Geometry (%) | 8.01226 | 6.73986 | 10.11213 |
| 3 Ramp through 4 Ramp Geometry (%) | -0.56129 | 5.71188 | 4.24265 |
| 2 Ramp through 4 Ramp Geometry (%) | 7.45097 | 12.45174 | 14.35479 |

**Table 23:** Correlative Percentage Difference Observed in the Total Aerodynamic Efficiency Parameter

| Total (C_L / C_D) Percentage Change Difference (%) | Mach 5 to 6 (%) | Mach 6 to 7 (%) | Mach 5 to 7 (Total) (%) |
|---|---|---|---|
| 2 Ramp through 3 Ramp Geometry (%) | 2.15075 | 0.15432 | 1.89758 |
| 3 Ramp through 4 Ramp Geometry (%) | -0.42693 | 1.23312 | 0.76289 |
| 2 Ramp through 4 Ramp Geometry (%) | 1.72382 | 1.38745 | 2.66047 |

For example, in Table 20, it can be deduced that by flying at Mach 7 with the 4-ramp geometry, a roughly 0.89% reduction in the total lift coefficient loss is observed compared to the case of flying at Mach 5 with the 2-ramp geometry, which is, of course, the correlative influence of simultaneously adding two ramps to the basic 2-ramp waverider configuration and also two units of Mach number to the original flight Mach number, an observation obviously consistent with the previously mentioned deductions.

As another example, in Table 21, it can be deduced that by flying at Mach 7 with the 4-ramp geometry, a roughly 2% increase in the total drag coefficient decrease is observed compared to the case of flying at Mach 5 with the 2-ramp geometry, which is, of course, the correlative influence of simultaneously adding two ramps to the basic 2-ramp waverider configuration and also two units of Mach number to the original flight Mach number, an observation obviously consistent with the previously mentioned deductions.

As another illustration, in Table 22, it can be deduced that by flying at Mach 7 with the 4-ramp geometry, a roughly 14.35% reduction in the total pitching moment coefficient decrease is observed compared to the case of flying at Mach 5 with the 2-ramp geometry, which is, of course, the correlative influence of simultaneously adding two ramps to the basic 2-ramp waverider configuration and also two units of Mach number to the original flight Mach number, an observation obviously consistent with the previously mentioned deductions.

As another instance, in Table 23, it can be deduced that by flying at Mach 7 with the 4-ramp geometry, a roughly 2.6% reduction in the total aerodynamic efficiency parameter loss is observed compared to the case of flying at Mach 5 with the 2-ramp geometry, which is, of course, the correlative influence of simultaneously adding two ramps to the basic 2-ramp waverider configuration and also two units of Mach number to the original flight Mach number, an observation obviously consistent with the previously mentioned deductions.

It is crystal clear that tables 20 to 23 can be utilized to compare other cases as well, such as a comparison between cases of flying at Mach 6 with respect to Mach 5 or flying at Mach 7 with respect to Mach 5 or 6; and also flying with the 3-ramp geometry with respect to the 2-ramp geometry or with the 4-ramp geometry with respect to the 2-ramp or 3-ramp geometry.

As can be seen, the paramount fruit of the present study can be found in tables 20 through 23, in which the correlative influence of increasing/decreasing the number of inlet ramps as well as increasing/decreasing the flight Mach number on the behavior of the final aerodynamic coefficients and ratios in a typical waverider configuration can be found. These tables can be used as initial guidelines for aeronautical design engineers designing waverider configurations on a preliminary basis. Using these tables, they can procure a better perspective on every individual design decision they make as regards the number of inlet ramps to be exploited and the appropriate flight Mach number range to opt for during the conceptual and preliminary stages of the design process.

## Concluding Remarks

It was demonstrated that, by altering the Mach number from 5 through 7 and keeping the geometry type constant simultaneously, for each of the three geometries, the total amount of C_L decreases; the total amount of C_D decreases; the total amount of C_M decreases (the absolute value of C_M decreases); and the total amount of C_L ⁄ C_D decreases.

It was also demonstrated that, by altering the geometry type from 2-ramp through 4-ramp geometry and keeping the Mach number constant simultaneously, the total amount of C_L decreases; the total amount of C_D decreases; the total amount of C_M increases (the absolute value of C_M increases); and the total amount of C_L ⁄ C_D increases.

It was inferred that by and large, increasing the number of inlet ramps can diminish the amount of lift coefficient loss, increase the amount of drag coefficient reduction, diminish the amount of pitching moment coefficient reduction, and decrease the amount of aerodynamic efficiency parameter loss, occurring in the waverider configuration flying in a Mach number range.

Tables encompassing the interactive impact of increasing/decreasing the number of inlet ramps and, concomitantly, increasing/decreasing the flight Mach number upon the behavior of the final aerodynamic coefficients and ratios were generated (tables 20 through 23). By exploiting such tables, aeronautical design engineers gain the upper hand in every single design decision they make while designing waverider configurations on a conceptual and/or preliminary basis.

## Conflicts of Interest

The authors of this paper declared no conflict of interest regarding the authorship or publication of this article.

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