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

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Abstract
Air-breathing hypersonic flight is presumed by many of the savants in the field of aeronautical engineering as the last boundary of aerial vehicle design to be pushed back. An auspicious design configuration for the prospective hypersonic transport vehicles of the future is a "Waverider," using the Scramjet engine cycle as its propulsive system. 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 also 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 which can be utilized as primary guidelines for aeronautical design engineers who are designing waverider configurations on a preliminary basis.
Keywords: *Hypersonics- Waverider Design- Inlet Ramps- Aerodynamic Coefficients- CFD*

1. 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 5 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].

In order 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, which is capable of producing higher values of L/D compared to other conventional configurations − "waveriders." A waverider is a hypersonic flight vehicle which has attached shockwave throughout its leading edge, riding on top of its own generated shockwave, hence the term "waverider." The aerodynamic convenience found 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 "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 very first person who introduced the concept of waverider 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 all at the same time. 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

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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 preponderant outcome of the present work is the generation of some tables which 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 on 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.

## 2. 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, 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. Afterwards, 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 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 run until the convergence criteria were satisfied, and the simulations' results were validated, domain, and grid independent.
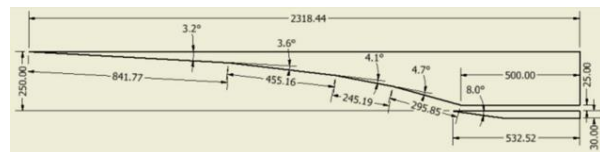
Table 1: Freestream Conditions [6]

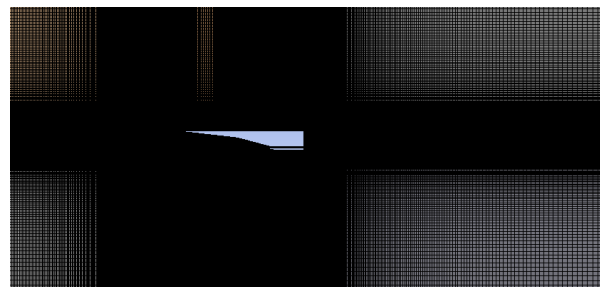| Mach Number	Total Pressure (Pascal)	Total Temperature (Kelvin)	Total Density (Kilograms per cubic meter)
5	2860.2	220.7	0.045141
6	1986.8	224.8	0.030775
7	1459.8	229.3	0.022165
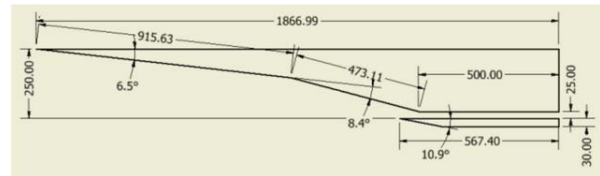
Fig. 1: 2-Ramp Waverider Configuration, excerpted from [6]
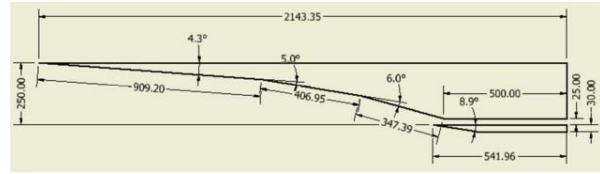
Fig. 2: 3-Ramp Waverider Configuration, excerpted from [6]

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

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

It is worthy to mention 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.

3. Results and Discussion
The desired output data of the simulations were extracted from the Ansys CFD-Post.

3.1. 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 5 to 8, 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.
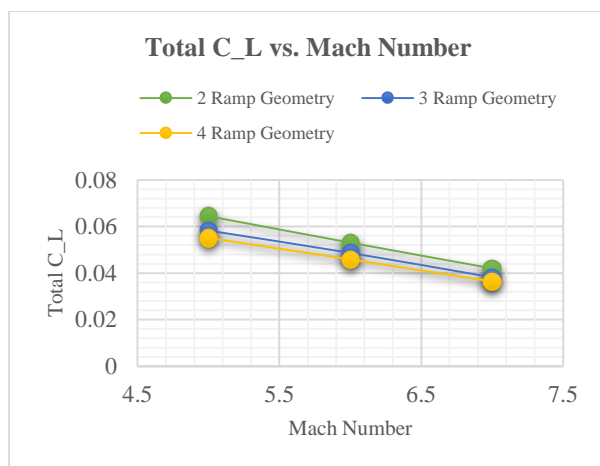
Fig. 5: Total Lift Coefficient Changing Trend versus Mach Number

As can be seen, changing the Mach number from 5 through 7 and keeping the geometry type constant simultaneously, 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. 5, occurring in the waverider configuration flying in a Mach number range.

Looking at Fig. 5, 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, 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.
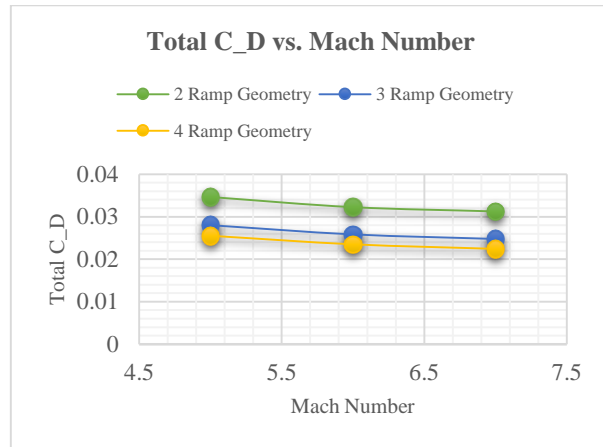
Fig. 6: Total Drag Coefficient Changing Trend versus Mach Number

As can be seen, changing the Mach number from 5 through 7 and keeping the geometry type constant simultaneously, 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, 6 to 7, and the total reduction occurring in 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 has occurred in the 4-ramp geometry, and the minimum reduction has 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. 6, 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, 3-ramp to 4-ramp, and the total reduction occurring in 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.
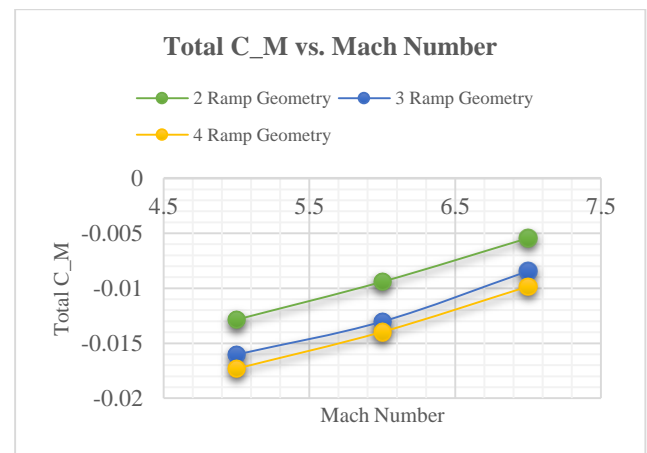
Fig. 7: Total Pitching Moment Coefficient Changing Trend versus Mach Number

As can be seen, changing the Mach number from 5 through 7 and keeping the geometry type constant

simultaneously, 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, 6 to 7, and the total reduction occurring in 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 has occurred in the 2-ramp geometry, and the minimum reduction 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 pitching moment coefficient reduction, 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_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.
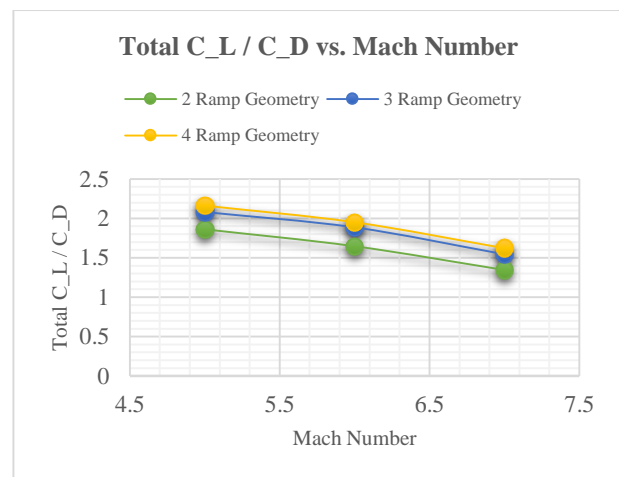
Fig. 8: Total Aerodynamic Efficiency Parameter Changing Trend versus Mach Number

As can be seen, changing the Mach number from 5 through 7 and keeping the geometry type constant simultaneously, 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 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. 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_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.

3.2. 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.

4. 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 the exploitation of such tables, aeronautical design engineers gain the upper hand in each and every single design decision they make whilst designing waverider configurations on a conceptual and/or preliminary basis.

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