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VISUALIZATION OF INCIDENT OBLIQUE SHOCK WAVE ON SHARP LEADING-EDGE AND SURFACES WITH RAMPS

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Abstract: This work presents a computational simulation of inviscid air flow, at hypersonic speed, when it encounters a sharp surface with ramps. The objective is to visualize and determine the angles of the incident shock waves and compare them with the results obtained from the theoretical mathematical relationships used to study the formation of plane oblique shock waves. The modeling and simulation was carried out in the academic version of Ansys/Fluent®, considering a two-dimensional geometry.
Keywords: CFD, Shock waves, Hypersonic, Thermodynamic properties.

INTRODUCTION

The use of hypersonic vehicles began in 1949 with the German V-2 rocket, evolving into the X-15 aircraft in the 1960s, and eventually to scramjet vehicles (supersonic combustion ramjet) in the 2000s (Anderson, 2003). These advances demonstrate the importance of studying hypersonic flows in the development of space access vehicles and the need to undertake efforts to understand the aerodynamics of high Mach numbers, and its characteristic phenomena (Araújo, 2019; Toro, 2012; Barreto, 2021). One is the occurrence of shock waves, a phenomenon caused by sudden changes in gas properties. In this context, this work seeks to develop a computational fluid dynamics model (Freire, 2021; Carvalhal, 2015), for the visualization of shock waves establishing at a leading-edge and over an interception with two inclined ramps. Simulations in Ansys/Fluent® were carried out to determine the angles of the incident shock waves and the thermodynamic properties along the considered geometry, allowing the comparison of the results obtained analytically with those found numerically.

OBLIQUE SHOCK WAVE THEORY

When atmospheric air, at supersonic speed, encounters slopes inclined at an angle θ, there is a sudden change in its thermodynamic properties, forming a shock wave with an angle β. The flow has an increase in pressure (p), temperature (T) and density (ρ), but the Mach number (M) is reduced (Anderson, 2003). The relationships between these quantities of interest are described by Equations (1-4).

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

$$M_{out} = \left[\frac{1}{\sin(\beta - \theta)}\right]\sqrt{\frac{(M_{in}sin\beta)^2 + \frac{2}{(\gamma-1)}}{\frac{2\gamma}{(\gamma-1)}(M_{in}sin\beta)^2 - 1}} \quad (2)$$

$$\frac{p_{out}}{p_{in}} = 1 + \frac{2\gamma}{(\gamma+1)}[(M_{in}\sin\beta)^2 - 1] \quad (3)$$

$$\frac{\rho_{out}}{\rho_{in}} = \frac{(\gamma+1)(M_{in}\sin\beta)^2}{(\gamma-1)(M_{in}\sin\beta)^2 + 2} \quad (4)$$

$$\frac{T_{out}}{T_{in}} = \frac{p_{out}}{p_{in}}\frac{\rho_{in}}{\rho_{out}} \quad (5)$$

For the development of this work, a generic geometry with two ramps was considered, as shown in figure 1. To discretize the domain, it was necessary to adapt the geometry, allowing the visualization of the incident shock waves. For reasons of simplification and existing limitations in the academic version of ANSYS, a two-dimensional analysis was chosen.

MESH

Domain discretization was performed using Ansys/Meshing. Boundary conditions and refinement regions were defined as shown in figure 2. A total of 3 meshes with different levels of refinement were produced, having an element size of 2 mm, 1 mm and 0.5 mm.

THERMONDYNAMIC PROPERTIES CONSIDERED

In this work, air was treated as a calorically perfect gas and viscous effects were disregarded due to the high Reynolds number of the flow. Pressure, temperature and density data were considered at an altitude of 35 km and speed of 2153.43 m/s (equivalent to Mach 7). These properties were obtained using the U.S. Standard Atmosphere (1976), shown in Table 1.

RESULTS

As established by the oblique shock wave theory, there was an increase in pressure, density and temperature after the formation of the shock waves, while the Mach number decreased (Figure 3).

It is possible to observe in figure 3 that the incident oblique shock waves converge-to a common point, and from there generate a diffuse region of properties, which was not analyzed in this work.

The properties presented in Table 3, it shows the changes in thermodynamic properties after the formation of oblique shock waves in each ramp.

For the geometry used, the theory of the oblique shock wave establishes, according to Equation 1, that the first shock wave has an angle of 14.84° and the second of 18.78°. The shock waves found numerically present inclinations very close to the angles found analytically, with errors in the tenths place.

The convergence test was performed using the GCI method developed by Celik, et al., (2008). The analysis used the average of the air properties in the outlet region. The GCI test indicated the convergence of the mesh with the highest refinement in terms of velocity and density. For pressure and temperature, which showed greater variations between meshes, a GCI index slightly above the limit was observed. To work around this problem, future analyzes with more refined meshes become necessary.

CONCLUSION

In this work, the construction of a bi-dimensional geometry with inclined ramps was carried out for the construction of a CFD model, allowing the visualization of the incident oblique shock waves, formed in a hypersonic flow.

The thermodynamic properties obtained numerically were compatible when compared to those obtained with the oblique shock wave theory, being possible to graphically determine the angles of the incident shock waves, demonstrating that the results are reliable. The model proved to be adequate, however, it is necessary to continue and carry out new works.

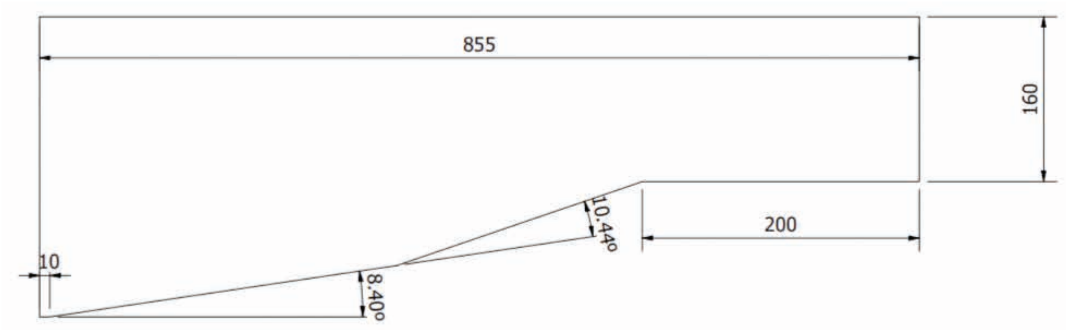

Figure 1 - Initial geometry used. (dimensions is mm).

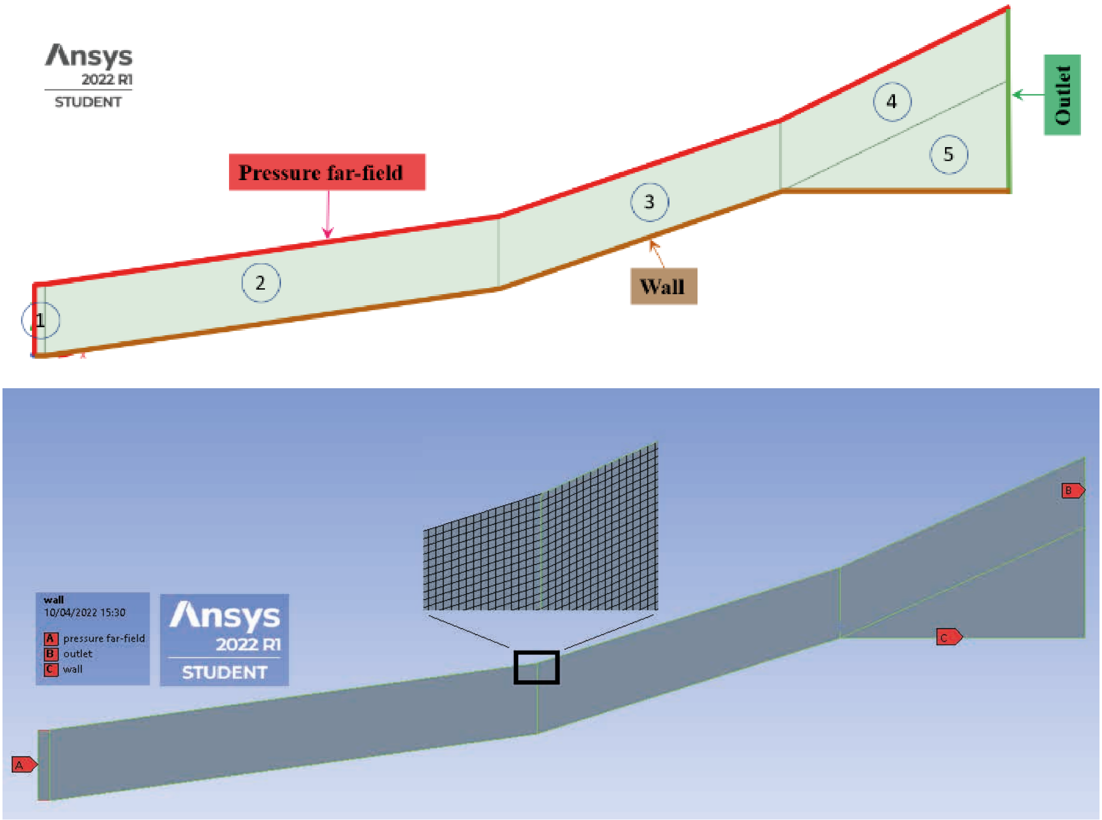

Figure 2 - Boundary conditions and refinement regions for the generated mesh.

Thermodynamic Properties (*U.S. Standard Atmosphere*)				Flight conditions	
Altitude [km]	Pressure [Pa]	Temperature [K]	Density [kg/m³]	Speed [m/s]	Mach Number
35	574.59	236.51	0.0085	2153.43	7

Table 1 - Operation conditions

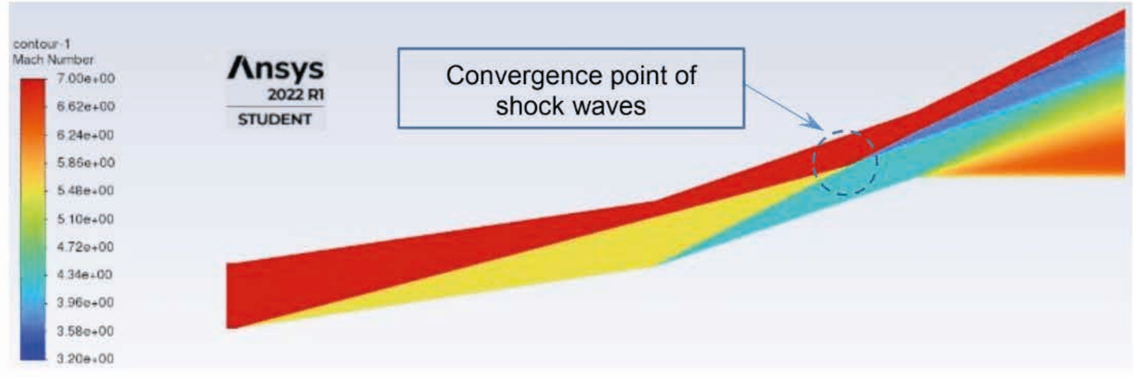

Figure 3 – Contour chart of Mach number

uu	Units	Free Stream	Ramp 1	Ramp 2
M_{in}	-	7	7	5.52
M_{out}	-	-	5.52	4.29
θ_{in}	°	-	8.40	10.44
β_{in}	°	-	14.88	18.96
p_{out}	[Pa]	575	2059	7218
T_{out}	[K]	236.5	360.2	545.1
ρ_{out}	[kg/m³]	0.0085	0.0199	0.0461
u_{out}	[m/s]	2153	2098	2008

Table 3 – Thermodynamic properties obtained numerically.

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