Unsteady transition from a Mach to a regular shockwave intersection

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Abstract: The purpose of this research work is to perform accurate numerical computations of supersonic flow with second order discretization of governing terms in a converging nozzle and specifically to study Mach disks. The latter process has been widely studied over the last years. In the present study numerical simulations are performed for transient supersonic flow, tracing the transition from a Mach reflection to a regular one. This has been done by enforcing the walls of a converging nozzle to come closer together, changing the deflection angle with time. Viscosity was taken into account and the full Navier-Stokes have been solved. The results obtained clearly show the gradual extinction of the Mach disk and the eventual wave intersection to a single point.

1 Introduction

The properties that distinguish a shock wave from other waves are that its thickness is negligible compared with other characteristic lengths, and that the state of the medium is changed irreversibly by the passage of the wave. Shocks are therefore a highly nonlinear phenomenon, and parameter changes may be expected to lead to numerous bifurcations. The multitude of possibilities is compounded when more than one shock occurs, such as in the interaction of a shock with a solid surface or symmetry plane (i.e., in shock reflection). Interesting considerations on this topic may be found in recent references [1-3]. The subject of shock reflection is complicated and it is necessary to solve the full viscous Navier-Stokes equations to get insight to the process.

A symmetrical parabolic converging nozzle of inlet diameter 4 m and outlet 3 m was used to generate shock waves (Fig.1). According to shock reflection theory, when the shock angle φ is smaller than the Von-Neumman critical angle φ_v the shock wave reflects into a regular reflection. In our case both shock waves induced from the top and bottom walls intersect to a regular intersection (single point) [4-7]. For shock angles greater than the detachment angle φ_d a Mach intersection will be induced, which means that the intersecting waves form a Mach disk [8,9]. In the range between φ_v and φ_d both types of reflection could be induced.

Despite the existence of those critical angles, the transition conditions are not very clear. There are differences between experimental and numerical results, especially in the Mach disk region and considerable disagreement between numerical and theoretical values concerning the above mentioned critical angles.

The waves' intersection closely to an axis of symmetry is examined here. At the inlet region, due to the deflection of walls, oblique shock waves are formed.

These waves intersect at two points, known as Mach or triple points, leading to a normal shock wave, the Mach disk. Afterwards these waves reflect on the walls downstream. According to theory, depending on flow conditions, there form two slip lines or discontinuity lines and a vortex sheet.
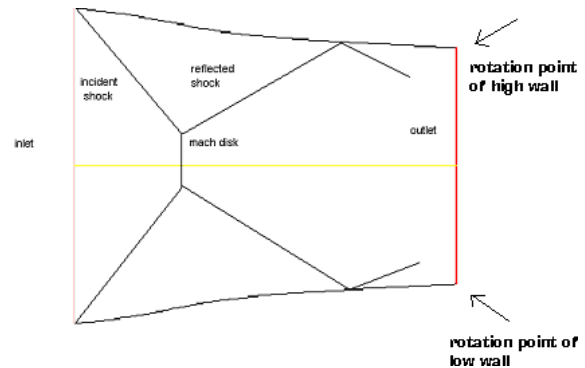

Fig. 1. Shock wave intersections, causing mach disk.

In transient problems hysteresis is observed, due to the continuous changes of the deflection angle [10,11]. The result is transitions from Mach to regular reflections and vice versa. In more detail when the deflection angle is less than θ_v (Von-Neumann criterion) then we have regular reflection. When it reaches the value θ_d (the detachment angle) we get Mach reflection. Then θ decreases (deflection angle is the maximum angle), while the shock reflection remains Mach, and when it reaches again θ_v we have conversion to regular [12-14]. This cyclic behaviour denotes that the phenomenon presents hysteresis. Only the transition process is dealt with in this work.

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2 Solving the flow equations

2.1 The mathematical problem

The flow is described by the Navier-Stokes equations as applied for supersonic flight. The discretized equations must be set up considering the movement of the grid since the flow passes through moving boundaries (walls). For that reason the velocity vector υ is equal to the difference of the absolute flow velocity and grid velocity of the moving mesh. The equations are hyperbolic in nature and in an abbreviated form are as follows [4,15-17]:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \upsilon) = 0 \qquad (1)$$

$$\frac{\partial}{\partial t}(\rho \upsilon) + \nabla(\rho \upsilon \upsilon) = -\nabla p + \nabla(\bar{\tau}) \qquad (2)$$

where $\bar{\tau} = \mu[(\nabla \upsilon + \nabla \upsilon^T) - \frac{2}{3} \nabla \upsilon I]$ (I is the unit tensor)

$$\frac{\partial}{\partial t}(\rho E) + \nabla \cdot (\upsilon(\rho E + p)) = \nabla \cdot (k_{eff} \nabla T - (\bar{\tau} \upsilon)) \qquad (3)$$

where $E = h - \frac{p}{\rho} + \frac{\upsilon^2}{2}$

The symbols $\mu, \rho, p, \underline{\upsilon}$, τ , k_{eff} , h, T,E, respectively, denote molecular viscosity, density, static pressure,velocity vector, stress tensor, total thermalconductivity, enthalpy, static temperature and energy.

2.2 Numerical Solution and Turbulence Modelling

The above differential equations are solved by the finite volume technique on a Pentium IV machine with a single core and 8 GB maximum available memory. The SIMPLE-Consistent algorithm was chosen for accounting for the pressure-velocity coupling [18,19]. Second order upwind scheme was used for the convective terms and central for the diffusion terms. The temporal discretization was of first order.

The formulation for this scheme was fully implicit and the system of the algebraic equations for every time step was solved iteratively by a classic Gauss-Seidel point iterative method.

For reasons of convergence acceleration, a pseudo-time step relaxation was used in every time step with a suitable relaxation factor [19-21]. Furthermore, a classic V-cycle multigrid algorithm was used for the same reason.

Turbulence modelling was used when accounting for the viscous solutions of equations. For that purpose the Spalart-Allmaras model [22,23] was chosen, which solves only one equation, the equation for eddy viscosity. The model was designed initially for low Reynolds numbers but it is used widely for aerospace applications (transonic-supersonicspeeds) [24], despite the fact that its dependent variable is a fictitious one.

The transport equation for the eddy viscosity v is derived by arguments of dimensional analysis and Galilean invariance, and is given by

$$\frac{\partial}{\partial t}(\rho v) + \frac{\partial}{\partial x_i}(\rho v u_i) = G_v + \frac{1}{\sigma_v}[\frac{\partial}{\partial x_j}\{(\mu + \rho v)\frac{\partial v}{\partial x_j}\} + C_{b2}\rho(\frac{\partial v}{\partial x_j})^2] - Y_v \qquad (4)$$

$$G_{v=} C_{b1}\rho S v , S = S_1 + v f_{u2} / k^2 d^2 , f_{u2} = 1 - \frac{\chi}{\chi f_{u1}} ,$$

$$Y_v = C_{w1}\rho f_w (\frac{v}{d})^2$$

where G_v is the production of turbulence viscosity and Y_v is the destruction of turbulence viscosity that v occurs in the near-wall region. The symbols d ,S, χ f_{u2} , f_{u1} respectively, denote wall distance, deformation tensor, ratio of molecular to kinematic viscosity and functions of molecular and kinematic viscosity. The other symbols are constants.

For the numerical solution of supersonic flow inside the nozzle, two commercial codes were used, FLUENT and GAMBIT (mesh generator), both provided by Fluent Inc. An unstructured mesh of 67000 cells was employed. Inlet conditions were: atmospheric pressure and Mach number of 1.8 and outlet conditions, pressure of 255000 pascal. No slip conditions apply at both nozzle walls and classic wall functions were used [19,25,26].

Density is computed via the perfect gas law (admission of isentropic flow). Finally, concerning the molecular viscosity μ, because during a supersonic flow there exist substantial temperature gradients, a function was defined, which describes the changes of viscosity with respect to temperature. The law of Sutherland [24] was chosen:

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$$\mu(T) = \mu_o($$

where T_o=273.16K and μ_o=1.78 kgm^{-1}s^{-1} are the reference values.

Due to the movement of the wall boundaries (as they approach each other) the mesh must be updated with time. Specifically the walls move with the rotation speed of 3 degrees per second. The original point of rotation is the edge point of outlet for every wall respectively (Fig.1). As a result it is obvious that the grid is continuously deforming and it has to be updated at every time step. The main techniques applied for updating the deforming mesh is the spring- based smoothing method and local remeshing**.** The last method has been described in detail in Anthony Anderson's research work [27].

2.3. Grid refinement and time independency.

Three different unstructured meshes were generated in order to indicate which mesh produces results independent of further grid refinement. Fig.2 shows the pressure distribution along the axis of symmetry for the three meshes. That of 67000 cells has almost the same distribution of the most refined mesh. The same istrue for the other variables as well. So it was selected for time saving reasons (cpu time).

The second step is the time independency investigation. For this purpose we considered three different time steps (0.05, 0.1 and 0.2 sec). Again pressure distributions are presented at the symmetry plane for three different real time positions. Fig. 3 shows that the choice of time step 0.1 sec is acceptable.
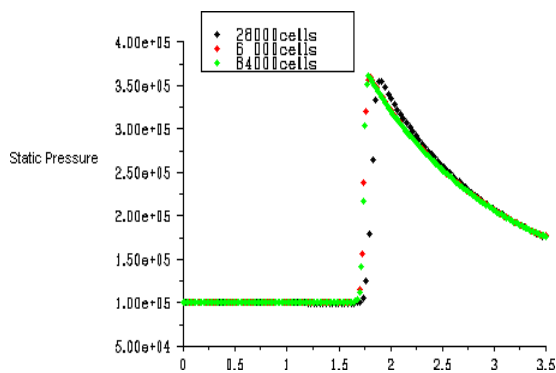

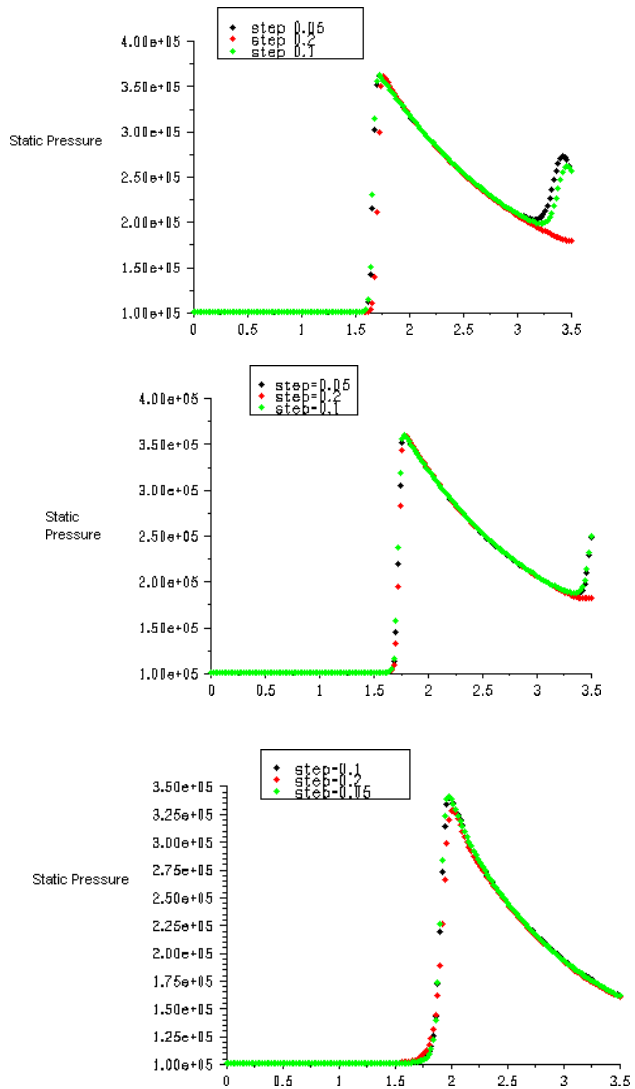Fig.2. Pressure distribution along axis of symmetry for three different meshes.

Fig.3. Pressure distribution along axis of symmetry for three different time steps: t=0.2 sec, 0.6 sec and 1.2 sec from top to bottom respectively

3 Results and discussion

Computational results were obtained on a Pentium IV Machine with a cpu time of about 6 hours for full convergence of the primitive variables: x and y velocity, eddy viscosity and static pressure. Convergence is deemed to occur when the scaled residuals fall below 10e-5. The total number of time steps was 16, from 0.1 sec to 1.6 sec.

Beginning the analysis of results, and observing at time t=0.2 sec the Mach contours, we see the Mach disk formed around the middle of the axis (Fig.4). At the next time steps, we can easily observe both walls approaching each other. As a result, the deflectionangle is decreasing, causing the reduction of disk's length. After 1.5 seconds the Mach disk does no longer exist and the waves intersect at a regular intersection.
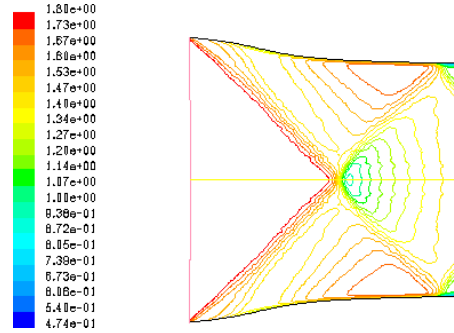
Fig. 4 illustrates the presence of an additional process. The disk is moving towards the outlet with time, and the decrease of the deflection angle causes a corresponding decrease to the shock angle of the waves. As a result they become weaker and of course they expand more in the flow domain.
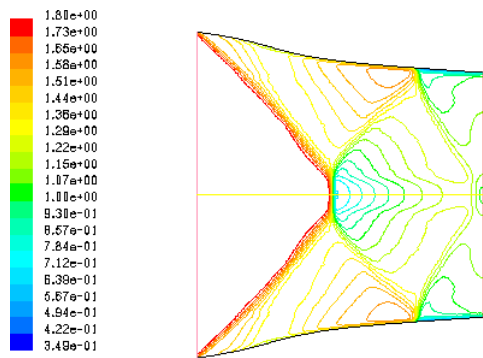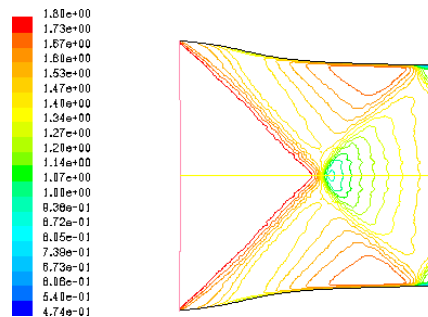

t=1.3 sec
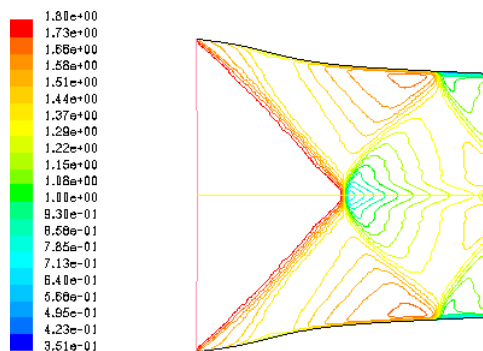
t=0.2 sec

t=1.6 sec

Fig.4. Mach contours plotted versus time (t=0.2sec to 1.6 sec).

t=0.9 sec

3.1 Transition from Mach to Regular intersection..

In shock wave reflection studies a main objective is to compute the height and position of the Mach disk versus time [27]. In this study, theindependent variable is not the wedge angle, as used in most studies, but time, because of the transient nature of the process. To perform height computation we need information at every time provided by the results obtained until then. Because the Mach disk is a normal shock wave, we trace the region where considerable discontinuities occur (subsonic to supersonic flow). Thiscriterion gives us direct guidelines for evaluating the height value. At first the Mach number distribution at the axis plane is estimated. Fig. 5 displays a significant decrease of Mach number, indicating the position where the Mach disk begins to expand. The first point of this spontaneous change defines the starting point of disk's thickness. The flow there

remains supersonic. Behind that point, flow becomes subsonic. In this region we take a normal section (direction parallel to the y axis), and we compute the Mach number distribution in this section. We observe that as we move towards the wall (positive y), the Mach number increases (Fig. 6). There is a point where the flow becomes sonic (*M=1*). After that point the flow returns to be supersonic. The sonic point indicates where the height of the Mach disk ends. This sonic point is the Mach or triple point as mentioned above. Following this process at all time positions, we estimate height as a function of time. Fig. 7 shows that height decreases with time and becomes zero (regular reflection) at time=1.5 sec.
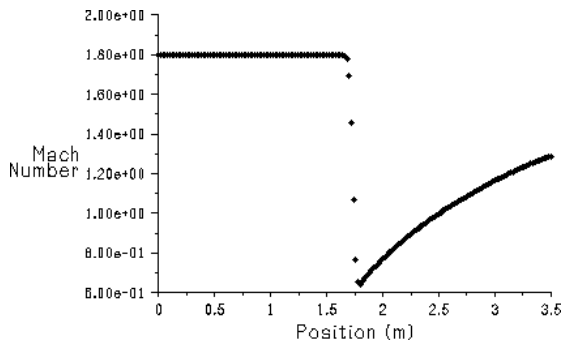

Fig.5 Mach number distribution along the axis of symmetry plane
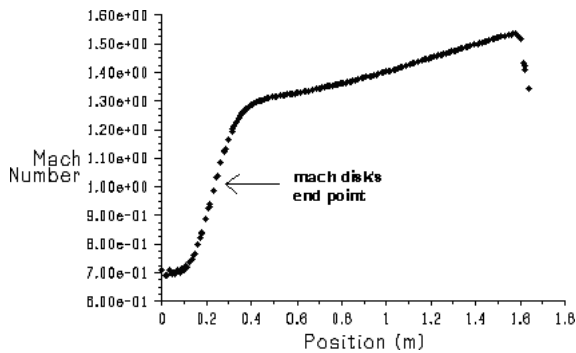 at a particular time step.

Fig.6. Mach number distribution at the symmetry plane
  at x=1.77m.

Based on the above procedure, we compute the change of Mach disk's position. From Fig. 6 we find the beginning of disk's thickness. Repeating for the remaining time steps, we plot the disk position versus

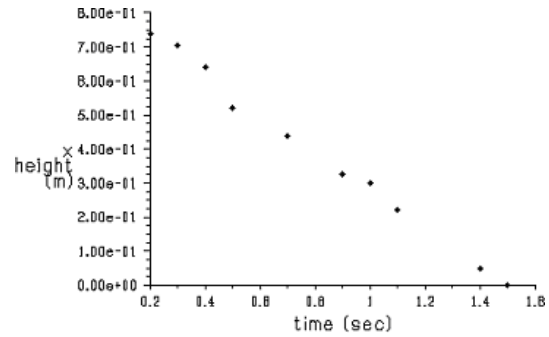time (Fig.8). It is obvious that the disk moves towards the outlet.
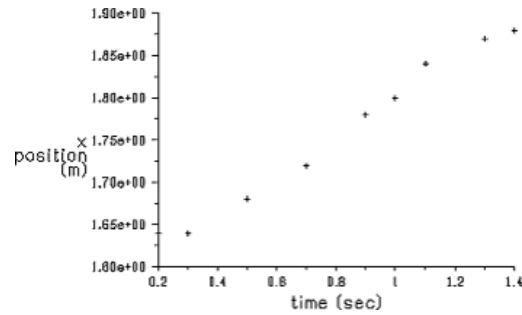

Fig. 7. Disk height varying with time.

Fig. 8. Disk position along axis of symmetry plotted against time.

4 Conclusions

Numerical simulations have been carried out, by means of special numerical and mesh-update techniques. The system equations have been solved by a segregated (not coupled) manner, using known point iterative methods. Flow viscosity was taken into consideration and the full Navier- Stokes equations were solved. The results appear plausible and the shock position and sharpness were predicted in a physically satisfactory manner without the need for special shock capturing techniques.

Finally, a further interest for numerical research would be to apply periodic movement to the walls, i.e. making them converging and diverging. Then the Mach disk would periodically form and then vanish, depicting the hysteresis process [7,13,14,28,29].

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