38 Numerical Methods to Simulate 2D and 3D Inlet Starting

by

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ABSTRACT

In the present paper we outline our recent activities on the application of previously developed locally adaptive unstructured numerical codes for essentially unsteady shocked flows to the simulation of inlet starting process and demonstrate their possibilities. Results for 2D and 3D inlets are presented.

1. Introduction

Various hypersonic airplane concepts are being considered now as a potential economical way to deliver payloads to low Earth orbits. Within this concept, air-breathing propulsive engines represent a possible way of reducing space launch costs. Air enters the engines through a converging air intake which must operate stably, predictably, and efficiently through a wide range of flight Mach number and altitude. That is why the design of efficient inlets for hypersonic vehicles is presently a subject of interest (see, for instance, [1]).

Once the design procedure has been completed, the resulting inlet should be tested to evaluate its performance and the limits of its starting. Hypersonic inlet testing using experimental facilities may be rather costly, especially taking into account the manufacturing of numerous models and multiple runs at different conditions for each of them. Besides, variable geometry is sometimes needed for inlet starting and subsequent operation. Since the test time in shock and gun tunnels may be limited, it is difficult to ensure very fast and precise motions of inlet components. Thus, a computer code simulating inlet starting processes would be of considerable help. Certainly, it would not fully substitute experimental testing. However, the required number of experiments may be drastically reduced based on the computational analysis.

In the present paper we apply 2D and 3D locally adaptive unsteady numerical codes [3] to the simulation of inlet starting process and study their possibilities.

2. Main Features of the Phenomenon

The inlet starting is a very complex gasdynamical phenomenon. First of all, inlets themselves may have fairly complex geometry which is essential for good operational characteristics. Secondly, the starting process is essentially unsteady, with shock waves traveling in and/or out of the inlet and interacting with each other and solid walls. In the latter case, shock wave/boundary layer interactions may play an essential role.

Generally, the problem requires full Navier-Stokes calculations considering unsteadiness and, possibly, turbulence. To begin with, we consider here the Euler (inviscid, non-heat-conducting) gas model.

3. Numerical Technique

Based on the above considerations, we adopt the following numerical strategy. The discretization of a computational domain is done using fully unstructured triangular or tetrahedral grids which are most flexible for complex geometries. As a base, the grid generators [2] are used. In case of three-dimensional inlets an additional code has been written creating surface mesh and providing output in

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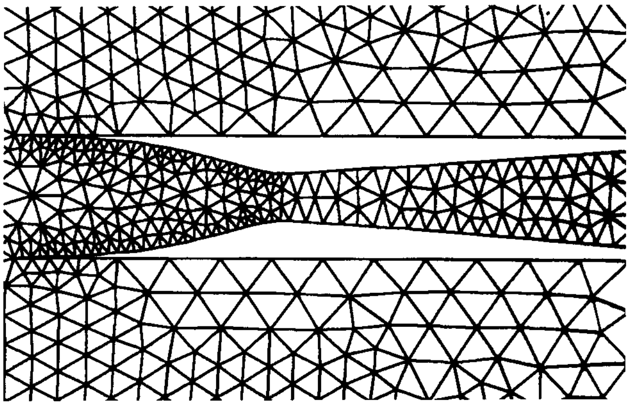

Fig. 1: The geometry of the two-dimensional inlet employed in this study and the background unstructured grid to be adaptively refined in the course of flow development.

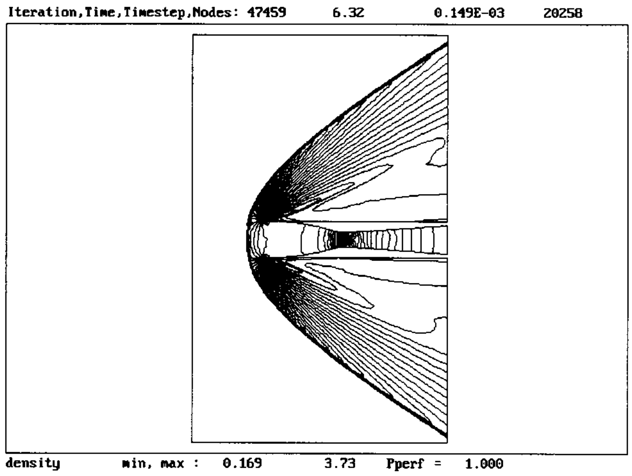

Fig. 2: The initial unstart state of the supersonic inlet at Mach 2.5 with the bow shock standing in front of the inlet's entrance (density contours).

the input format of the grid generator [2]. Typical computational domain includes inlet's interior and an area just ahead of the inlet's entrance to accommodate the bow shock in case the inlet unstarts.

In the course of computation the unstructured grid is dynamically refined following the solution at the transient locations of discontinuities ensuring good resolution and contributing to high computational efficiency. The good efficiency is also based on the original data structure of the code [3,4] supporting the grid connectivity and its dynamic variations. A second-order Godunov-type scheme with a TVD limiter (see [5]) is used providing high resolution of shock waves in the wide range of their intensities.

3. Demonstrative Applications

3.1 2D Inlet

The first problem under consideration is the flow in a perforated, reversed deLaval nozzle at a freestream Mach number 2.5 (Fig. 1). The inlet has a contraction ratio of 2.64 being too high to allow the inlet to start (Fig. 2). Perforations on inlet's surface may ensure sufficient mass spillage to eventually swallow the bow shock which forms in the unstarted condition (Fig. 3). The perforations were modeled by switching boundary conditions on certain wall segments from the impermeable wall condition to the specified pressure condition. Good qualitative comparison with the experiment [6] can be seen in Fig. 4.

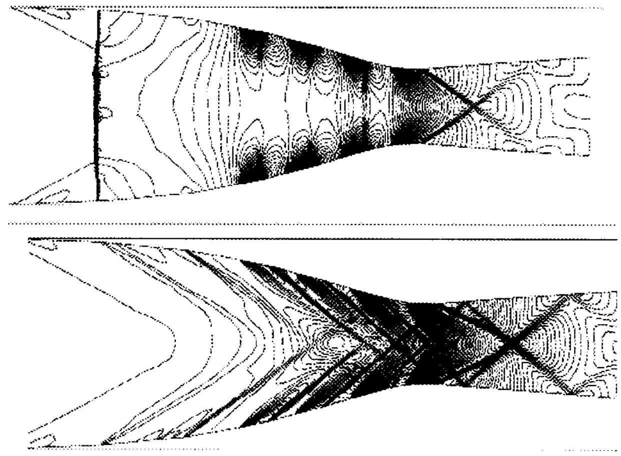

Fig. 3: An example of successful inlet starting using perforations. Top: a part of the bow shock (see Fig. 2) has entered the converging portion of the duct. Bottom: the shock has moved completely past the throat and flow through the inlet is fully supersonic. Density contours are shown.

It was shown that the inlet, based on a reversed deLaval nozzle, could be restarted to have the normal shock move out the exit, provided a minimum perforation/nozzle throat area ratio is achieved and that the distribution and location of the perforations away from the throat would result in the shock becoming stationary in the convergent portion of the inlet. It was also shown that the pressure in

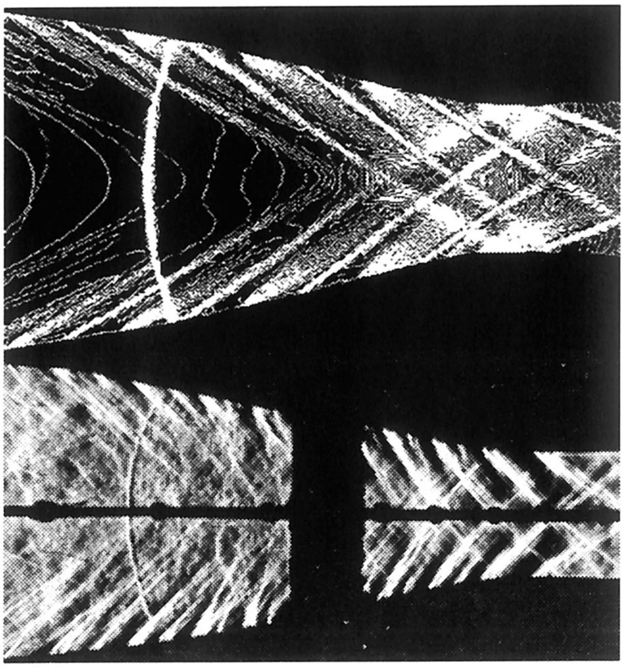

Fig. 4: Bottom: schlieren photograph of flow in the experimental inlet from [6] at Mach 2.5; double exposure shows starting shock and subsequent started flow. Top: 2-D CFD simulation of flow for the same configuration and similar conditions, showing constant density contours.

the perforations could also be varied to cause the shock to become stationary between the lip and the throat of the inlet. More details on this study are given in [7].

3.2 3D Inlet

As a test problem for 3D computations we consider here a simplified three-dimensional inlet shown in Fig. 5 and 6. Some preliminary results are presented below.

Sudden insertion of the inlet into supersonic flow has been used as initial condition. It has been found that at the freestream Mach number $M = 4$ the inlet starts. Fig. 7 illustrates the final steady flow in the inlet. Inside the inlet there are two oblique shocks originating on the opposite walls of the inlet and interacting at the vertical plane of symmetry. In case the inlet exit is closed, a bow shock forms in front of the entrance, as seen in Fig. 8.

At $M = 2$ the initial stages of the flow development under the above-mentioned initial condition lead to a shock pattern similar to that for $M = 4$. However, a high-pressure region builds up later near the inlet's exit; a normal shock forms and propagates towards the entrance, eventually unstarting the inlet.

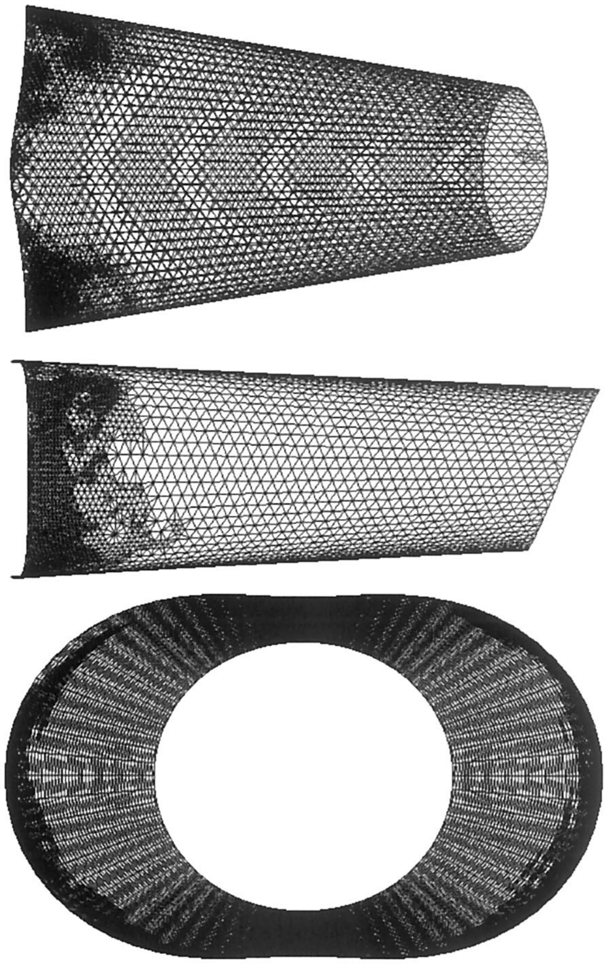

Fig. 5: A simplified three-dimensional nozzle under consideration; top, side and axis views are shown (from top to bottom); the images are not to scale.

Thus, it has been revealed that the code on hand predicts well the motion of shocks in the 3D unsteady starting process and allows to judge the final outcome of starting procedures.

4. Conclusion

The adopted approach to the simulation of inlet starting seems to be very promising. More realistic 3D inlet geometries and Navier-Stokes computations are under our consideration now.

References

[1] Smart, M.K., "Design of Three-Dimensional Hypersonic Inlets with Rectangular to Elliptical

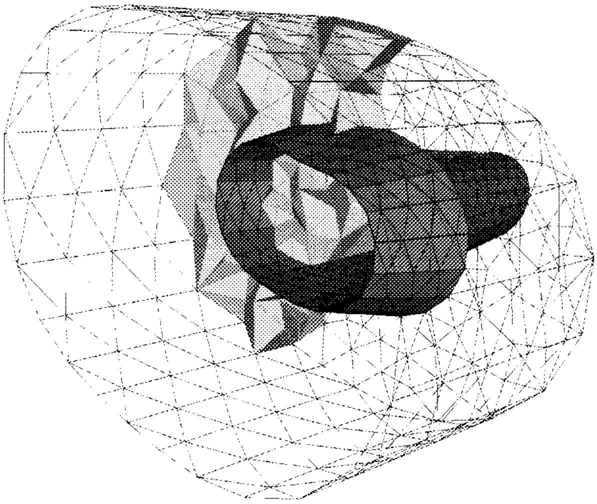

Fig. 6: General view of the computational domain. A cowl and an outer part are attached to the inlet shown in Fig. 5. The latter is to accommodate a bow shock in case the inlet unstarts. Surface mesh on some boundaries of the computational domain and some part of the internal tetrahedra are shown; the inlet's and cowl's surfaces and tetrahedra are shaded.

Shape Transition," AIAA Paper 98-0960, 1998.
[2] Galyukov, A. and Voinovich, P., "Two and Three-Dimensional Unstructured Triangular/Tetrahedral Grid Generators," Advanced Technology Center, St. Petersburg, Russia, 1993-1997 (unpublished).
[3] Voinovich, P., "Two and Three-Dimensional Unstructured Adaptive Euler Codes", Advanced Technology Center, St. Petersburg, Russia and Shock Wave Research Center, Sendai, Japan, 1993-1996 (unpublished).
[4] Voinovich, P., et al., "3D Unstructured Adaptive Supercomputing for Transient Problems of Volcanic Blast Waves", AIAA Paper 98-0540, 1998.
[5] Timofeev, E., Takayama, K., and Voinovich, P., "Numerical and Experimental Observation of Three-Dimensional Unsteady Shock Wave Structures", AIAA Paper 97-0070, 1997.
[6] Clark, J.P.C., "An Experimental Investigation of a Two-Dimensional Perforated Inlet at a Nominal Free Stream Mach Number of 2.5," University of Toronto, UTIAS TN 24, 1958.
[7] Studzienny, A.J., et al., "Starting of a Perforated Supersonic Inlet: a CFD Simulation," Proceedings of the 22nd Int. Symp. on Shock Waves, Vol. 2, pp. 1631–1636, London, UK, July 18-23, 1999.

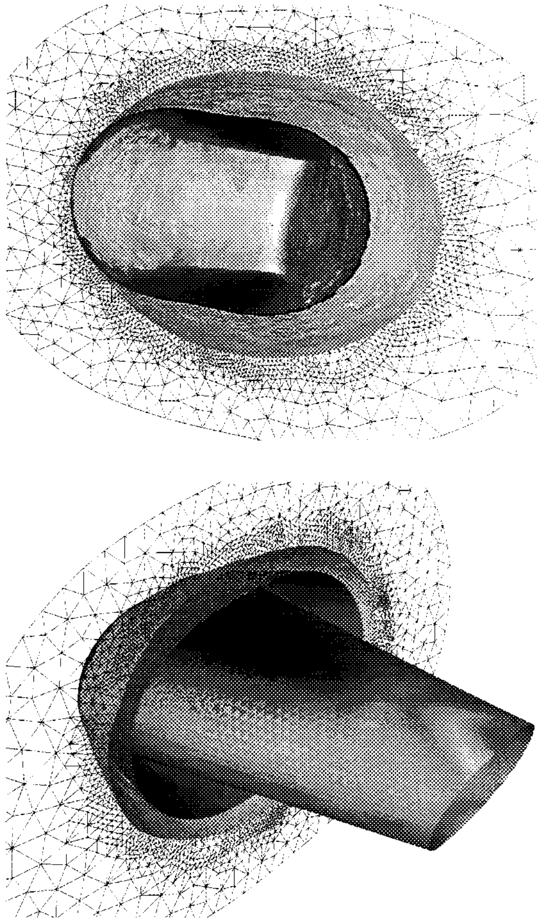

Fig. 7: The inlet starts at the freestream Mach number $M = 4$. The flow pattern to be eventually established is shown here from two different viewpoints. A pressure isosurface approximately represents the oblique shock wave attached to the cowl and a shock wave system inside the inlet. The inlet surface is colored according to pressure values.

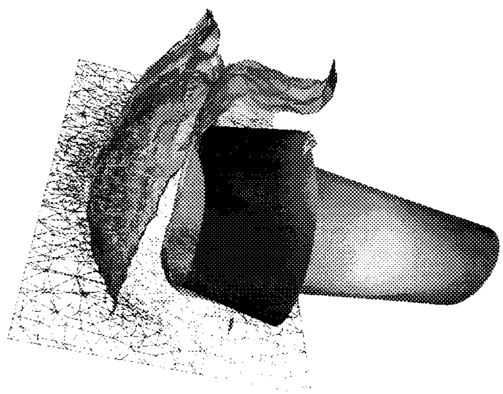

Fig. 8: In case the inlet exit is closed a bow shock shown here as a pressure isosurface is established in front of the inlet (parts of the isosurface being attached to the inlet surface correspond to the same value of pressure downstream of the bow shock). An adaptive grid pattern in a cross-section is also shown.