Supplemental Notes to the Lecture on "Theoretical Analysis of Flow Starting in Hypersonic Air Intakes with CFD Illustrations"

by

Evgeny Timofeev* and Sannu Mölder
Department of Mechanical Engineering, McGill University
817 Sherbrooke St. W.
Montreal, P.Q.
CANADA

evgeny.timofeev@mcgill.ca / smolder@sympatico.ca

1.0 ADDITIONAL READING

In view of the exceedingly vast material to be covered the lecture is of introductory and overview nature. Much more detailed information on various techniques of intake starting may be found in the references listed below. These publications also contain rather extensive reference lists to previous works by various authors including the classical works by Kantrowitz and other researchers. If desired, the papers listed below may be requested in an electronic form via e-mails given above.

Overview Paper

Tahir, R., Timofeev, E., and Molder, S., "On recent developments related to flow starting in hypersonic air intakes," AIAA Paper 2008-2512

Thesis Work covering Various Aspects of Intake Starting

Tahir, R., "Starting and unstarting of supersonic intakes," Master Thesis, Ryerson University, 2003.

Tahir, R., "Analysis of shock dynamics in supersonic intakes," PhD Thesis, McGill University, 2008.

Intake Starting via Variable Geometry

Baig, S., and Timofeev, E. "A simple moving boundary technique and its application to supersonic inlet starting," In: Proceedings of 16th Annual Conference of the CFD Society of Canada, Saskatoon, Saskatchewan, June 9-11, 2008

Intake Starting via Mass Spillage through Wall Perforations

Studzienny, A., Molder, S., Timofeev, E., and Voinovich, P., "Starting of a Perforated Supersonic Inlet - a CFD Simulation," In: Ball, G.J., Hillier, R., Roberts, G.T. (Eds.), *"Shock Waves", Proceedings of the 22th International Symposium on Shock Waves*, London, UK, 18-23 July, 1999, University of Southhampton, 1999, Vol. 2, pp. 1631-1636.

* Presently on sabbatical leave at the University of New South Wales at Australian Defense Force Academy, Canberra, Australia.

Molder, S., Timofeev, E.V., and Tahir, R.B., "Flow Starting in High Compression Hypersonic Air Inlets by Mass Spillage," AIAA Paper 2004-4130.

Najafiyazdi, A., Tahir, R., Timofeev, E.V., and Molder S. "Analytical and Numerical Study of Flow Starting in Supersonic Inlets by Mass Spillage," AIAA Paper 2007-5072.

Intake Staring via Overboard Spillage

Veillard X., Tahir R.B., Timofeev E.V., and Molder, S. "Limiting Contractions for Starting Simple Ramp-Type Scramjet Intakes with Overboard Spillage," Journal of Propulsion and Power, Vol. 24(5), 2008, pp. 1042-1049.

Moradian, N., and Timofeev, E., "Limiting contractions for starting Prandtl-Meyer-type scramjet inlets with overboard spillage. In: Kontis, K. (Ed.) *Proceedings of the 28th International Symposium on Shock Waves*, Manchester, UK, 17-22 July, 2011, Springer, 6 pages.

Intake Starting via Unsteady Effects

Tahir, R.B., Molder, S., and Timofeev, E.V., "Unsteady Starting of High Mach Number Air Inlets – A CFD Study," AIAA Paper 2003-5191.

2.0 ADDITIONAL COMMENTS ON THE NUMERICAL SIMULATIONS SHOWN ON SLIDES

Slides 15-16

Intake Start/Unstart Hysteresis via Exit Area Variation

Between the isentrope and the Kantrowiz line on the area ratio-Mach number diagram both started and unstarted solutions are physically possible, depending on the history of the flow. Thus, an area-ratio-driven hysteresis becomes possible as demonstrated on slides 15-16.

On the images of slides 15-16 the intake is formed by the lower boundary of the computational domain (which may be considered as a plane of symmetry or a plane wall) and a cowl. The cowl consists of two parts: a fixed geometry part represented by a white body and a variable-geometry part represented by the dark-blue green-outlined body. The lower-right corner of the variable-geometry part is capable of moving up and down (very slowly so that at each time the flow may be considered as quasi-steady), thus changing the area ratio of the intake and its internal contour.

On all images the distribution of Mach number in the flowfield is shown at various time moments of the quasi-steady hysteresis process. The flow (M=3) is from left to right.

Image 1 corresponds to an area ratio which is higher than the Kantrowitz area ratio for M=3. At such area ratio the intake flow starts by itself when freestream Mach number is increased slowly from zero to M=3. The flow through the intake is all supersonic. The compression wave from the leading part of the cowl coaleces into an oblique shock which reflects regularly from the plane of symmetry.

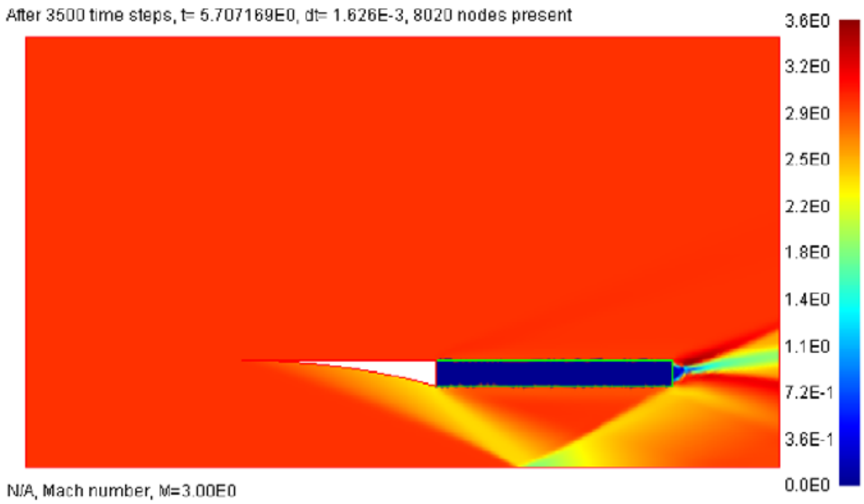


Image 1.

Then the exit area (and hence the area ratio) is gradually reduced and at the moment corresponding to Image 2 the flow has just choked at the exit and a weak (M~1) nearly normal shock appears in the throat region. It should be noted that choking occurs at the area ratio which is greater than the isentropic area ratio for M=3. This is because the intake flow contains a few oblique shocks resulting in total pressure loss (see slide 10).

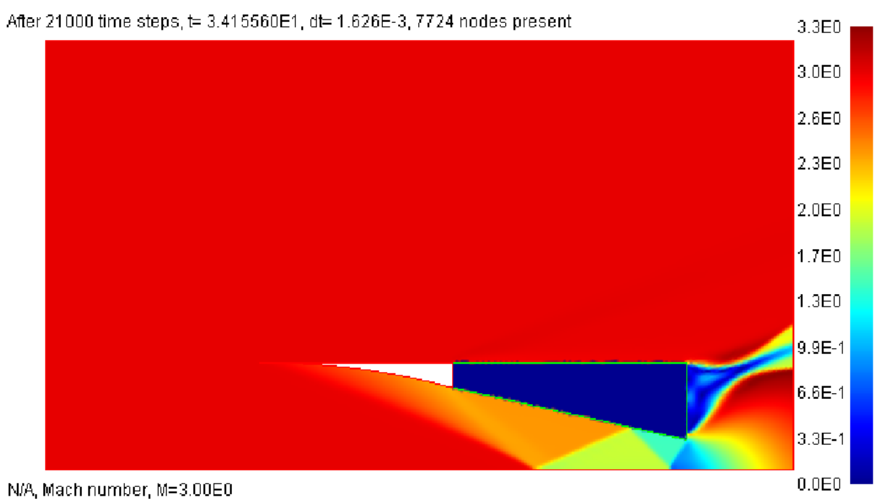


Image 2.

As soon as the shock is formed near the throat it propagates upstream, even though the area ratio is kept constant (Image 3). This is an illustration of the fact that a normal shock is unstable in converging area ducts. The flow downstream of the shock is subsonic and choked near the exit.

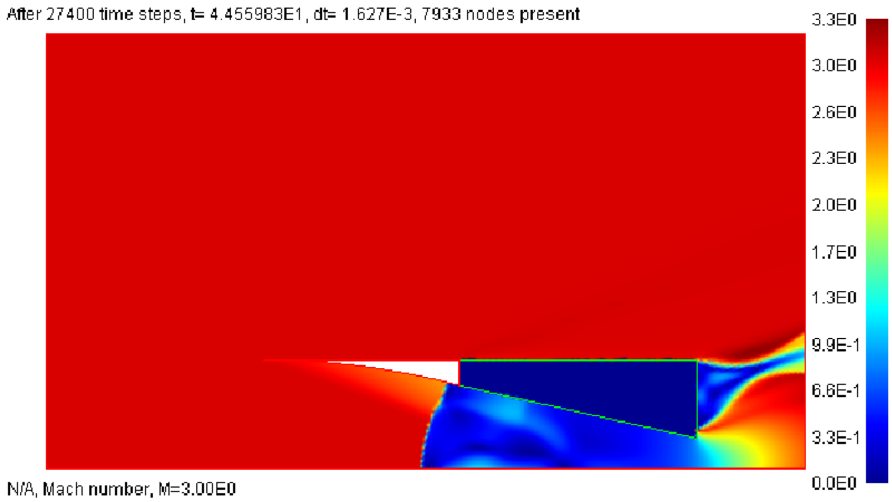


Image 3.

Eventually the shock comes out of the intake and becomes a bow shock in front of the intake. It provides for necessary spillage of excessive mass. The intake flow is subsonic and choked near the exit. The upper boundary of the computational domain is a wall (for the sake of simplicity) and the bow shock reflects from it as a Mach reflection.

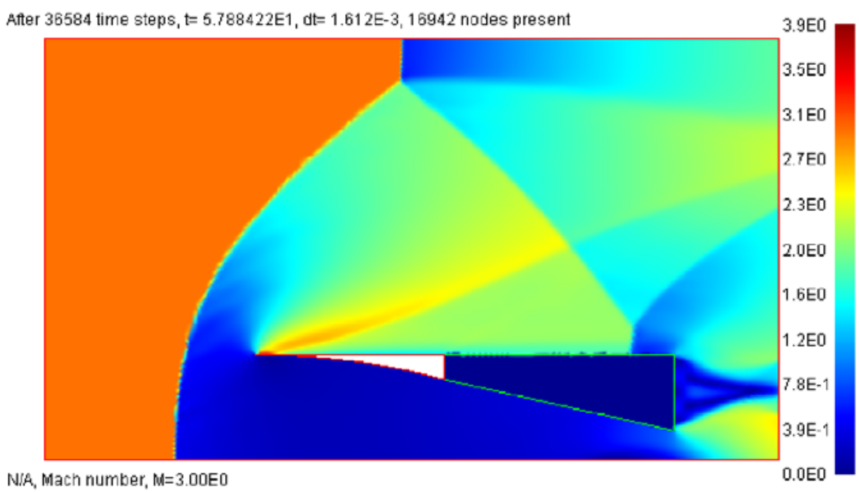


Image 4.

At the next stage of the numerical experiment, the area ratio is gradually increased. This is accompanied by the gradual decrease of the stand-off distance of the bow shock, see Image 5 (larger exit reduces the amount of mass to be spilled overboard).

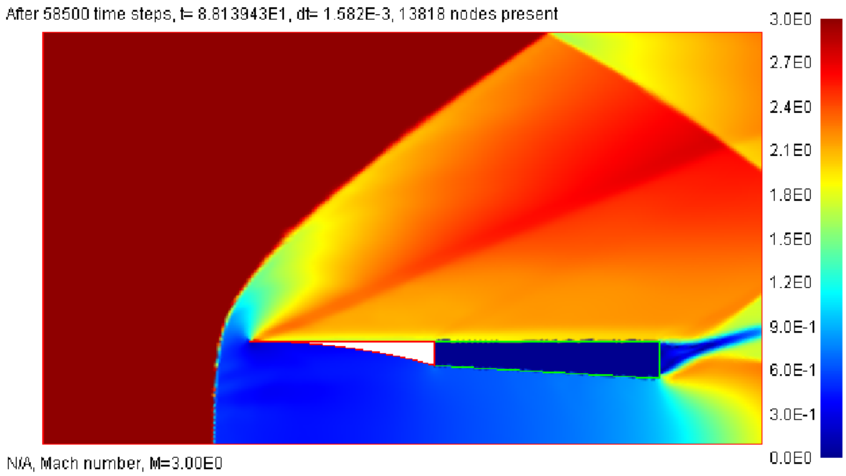


Image 5.

Finally, the shock reaches the leading edge of the cowl. The area ratio value at that moment corresponds with good accuracy to the Kantrowitz area ratio value for M=3.

As soon as the bow shock enters the intake it continues its motion downstream (Image 6), even though the exit area is kept constant, and eventually exits the intake. The flow pattern reverts to the started flow show in Image 1. This concludes the hysteresis cycle.

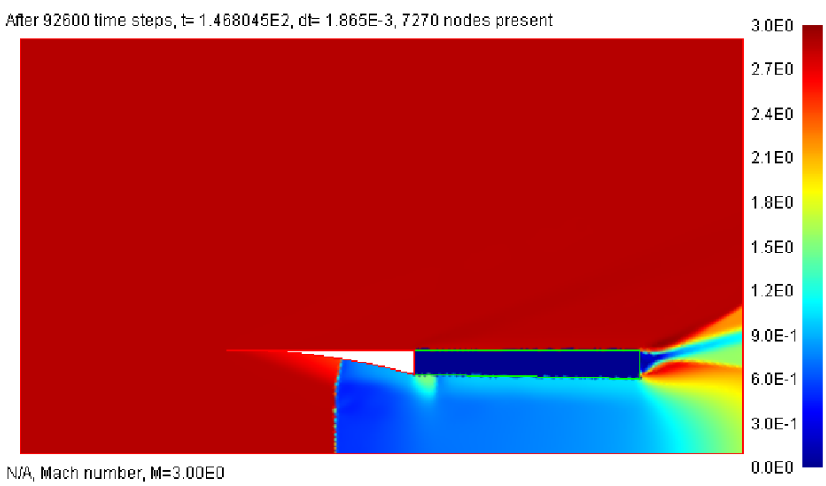
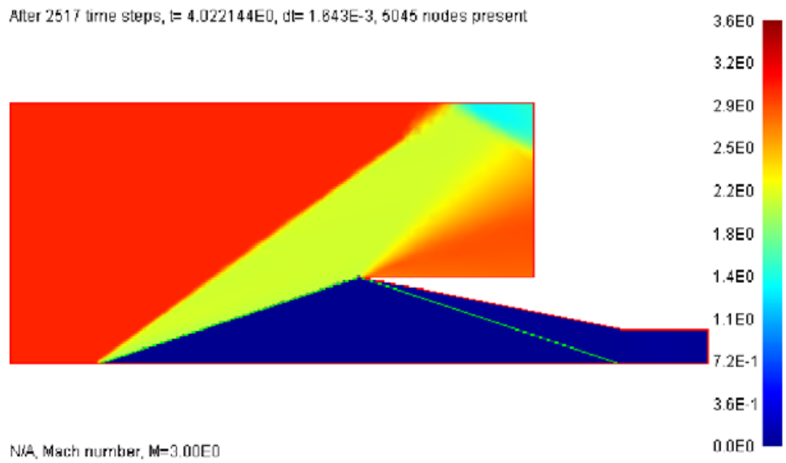


Image 6.

Slides 17-18

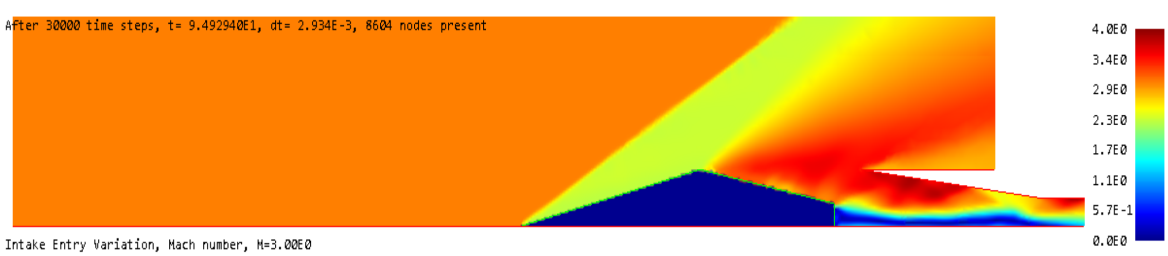
Intake Starting by Variation of Entry Area



In these simulations entry area variation is achieved by initially closing the entry by a triangular-shaped body (shown by thin green line on all images) and then by slowly lowering its tip (collapsing the triangle). In both cases the intake initially starts since the entry area is small and the area ratio is high. However, in Case 1 stronger oblique shocks are formed which produce Mach reflections on the body surface. All that leads to significant pressure losses and the quasi-steady process of frontal body collapsing fails to keep the intake above its operational limit. Hence, unstart results. In Case 2 the geometry is more slender which results in weaker internal shocks (and no Mach reflections), so that it is possible to stay above the operational limit and keep the intake started all the way till the frontal body effectively disappears (becomes very thin).

Slides 20-21

Intake Starting Using a "Tractor Rocket" Concept

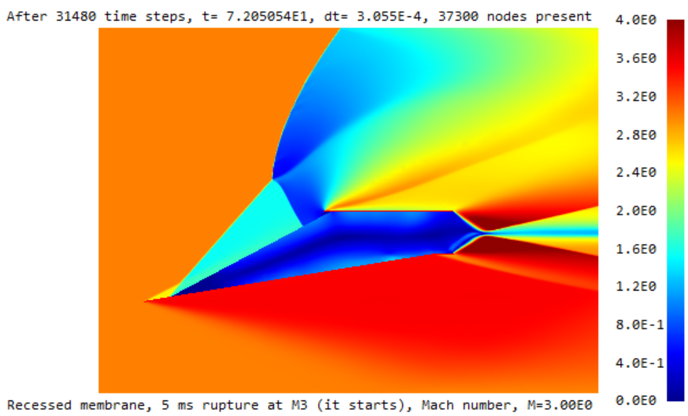


On the images of slides 20-21, the frontal moving body ("tractor-rocket") is shown in dark-blue with thin green outline. This simulation is done without rocket exhaust. The blue "ribbon" behind the body is simply a wake. It may be conjectured that the presence of exhaust may be even favourable for starting due to suction effect.

Slides 35-36

Intake Starting by Diaphragm Rupture

The diaphragm rupture is simulated in Slides 35-36 using a special boundary condition imposed at the boundary representing the diaphragm. The permeability of this boundary is changed from zero (solid wall) to unity (flow goes through as if no boundary exists at all). This change is accomplished during specified time (5 ms and 10 ms), i.e. the diaphragm essentially "dissolves without a trace" during this time interval. The simulation results demonstrate that the requirements for rupture time are rather stringent. When attempting practical implementation one should keep in mind that non-ideal effects (e.g. pieces of the diaphragm flying downstream) may lead to further reduction of rupture time required for starting.



On these images the intake is formed by thin plates forming an inclined ramp and a horizontal cowl. The M=3 flow is from left to right.