

# Finite Volume/Immersed Boundary Solvers for Compressible Flows: Development and Applications

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in partial fulfillment of the requirements  
for the Degree of

**DOCTOR OF PHILOSOPHY**

*in*

Mechanical Engineering

*by*

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“The journey is the reward”

— The Pirates (Steve Jobs)

Dedicated to  
*Ma, Baba and Dada*

# CERTIFICATE

This is to certify that the work presented in the thesis entitled “**Finite Volume/Immersed Boundary Solvers for Compressible Flows: Development and Applications**” submitted by Shuvayan Brahmachary to Indian Institute of Technology Guwahati for the award of the degree of Doctor of Philosophy in Mechanical Engineering is a bona fide record of research work carried out by the student himself under our supervision and have not been submitted elsewhere for any degree or diploma.

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# ABSTRACT

This thesis is devoted to the development of a robust and accurate Immersed Boundary/Finite Volume (IB-FV) framework for compressible flows and their applications to design and optimisation. The framework is devised by combining an unstructured data based finite volume flow solver with a sharp interface immersed boundary method. The finite volume flow solver employs limited linear reconstruction in conjunction with vanLeer and AUSM schemes for convective fluxes while central differencing is employed for viscous fluxes. A new approach to compute gradients, which are critical to the computation of inviscid and viscous fluxes, based on a variant of Gauss divergence theorem is proposed. The strategy referred to as Modified Green Gauss (MGG) reconstruction is a one-step approach but leads to marginally lesser dissipation and allows for the use of marginally higher Courant number than existing reconstruction techniques. A novel non-iterative variant of MGG reconstruction for non-orthogonal meshes is also described and its robustness in high-speed flows has been studied. A sharp-interface Immersed Boundary (IB) technique based on local reconstruction of the solution has been proposed for inviscid and viscous flows. The boundary conditions are imposed directly at the geometry interface and is employed to obtain the solution in the near vicinity of the solid(s). This reconstruction approach which also employs the finite volume solutions obtained away from the solid, is effectively an interpolation technique that does not strictly conserve the mass, momentum and energy. Two different strategies, based on inverse distance weighting (IDW) for inviscid flows and one-dimensional reconstruction (HCIB) for viscous flows are described and explained in this work. We show that the finite mass conservation errors diminish linearly with grid refinement and that the reconstruction approach does not degrade the nominal second-order accuracy of the flow solver. The IB-FV solver computes wall pressure and skin-friction distributions quite accurately, although the latter requires sufficient fine meshes in the vicinity of the body. However, finite levels of mesh refinement does not produce accurate heat flux estimates in laminar hypersonic flows past blunt geometries. We probe the possible causes of this under-prediction using an in-depth diagnostic analysis. The investigations indicate that errors due to temperature reconstruction which are linked to a loss in energy conservation are primarily responsible for the inaccurate estimation of wall heat-flux and stagnation point heat transfer. We prove using numerical experiments that the use of adaptive meshes and non-linear/non-polynomial interpolations do not improve the heat flux estimates

and that the errors are larger as Reynolds and Mach numbers become higher. The utility of the FV and IB-FV frameworks proposed in this work are highlighted by their application to three selected problems of design and optimisation. These frameworks are employed in conjunction with variable fidelity approaches for the design of minimum drag geometries, scramjet intakes and supersonic nozzle. The large spectrum of canonical problems in this thesis over a wide range of Mach and Reynolds number indicate the efficacy of the IB-FV solver while also highlighting some of its drawbacks. The IB-FV framework, despite its limitations, is also found to be a promising tool to evolve multi-fidelity optimisation frameworks that can accelerate the design and optimisation in hypersonic flows.

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# CONTENTS

<b>1</b>	<b>Introduction</b>	<b>1</b>
1.1	Gradient reconstruction strategy . . . . .	4
1.2	Cartesian grid based methods . . . . .	6
1.3	Multi-fidelity framework for optimisation/design problems . . . . .	11
1.4	Objectives of the thesis . . . . .	13
1.5	Outline of the thesis . . . . .	14
<b>2</b>	<b>Governing Equations and Mathematical Preliminaries</b>	<b>15</b>
2.1	Navier-Stokes equations . . . . .	15
2.2	Finite volume formulation . . . . .	17
2.3	Inviscid and viscous flux computations . . . . .	19
2.3.1	Inviscid flux discretisation . . . . .	19
2.3.2	Viscous flux discretisation . . . . .	21
2.4	Temporal discretisation . . . . .	22
2.5	Implementation of boundary conditions . . . . .	22
2.5.1	Supersonic inlet & outlet . . . . .	23
2.5.2	No-slip walls . . . . .	23
2.5.3	Inviscid wall or symmetry boundary . . . . .	23
<b>3</b>	<b>Modified Green-Gauss Reconstruction</b>	<b>25</b>
3.1	Overview of Green–Gauss reconstruction . . . . .	26
3.2	Modified Green Gauss reconstruction . . . . .	29
3.3	Numerical studies . . . . .	34
3.3.1	Supersonic vortex flow . . . . .	35
3.3.2	Grashof vortex . . . . .	38
3.3.3	Hypersonic flow past compression ramp . . . . .	40

3.4	Summary	43
<b>4</b>	<b>Sharp Interface Immersed Boundary for Inviscid Flows</b>	<b>44</b>
4.1	Sharp interface immersed boundary method	45
4.1.1	Classification	46
4.1.2	Reconstruction	46
4.2	Discrete Conservation	51
4.2.1	Transonic flow past bump	51
4.2.2	Supersonic flow past wedge	54
4.3	Order of accuracy study	56
4.4	Numerical investigations	58
4.4.1	Supersonic flow past a cone	59
4.4.2	Hypersonic Flow past Sphere	61
4.4.3	Hypersonic flow past a double ellipse	62
4.4.4	Hypersonic flow in a scramjet intake	64
4.4.5	Supersonic flow with moving bodies: Cylinder lift-off	67
4.4.6	Shape optimisation: Minimum drag geometries in hypersonic flow	69
4.5	Summary	71
<b>5</b>	<b>Sharp Interface Immersed Boundary for Viscous Flows</b>	<b>72</b>
5.1	Hybrid Cartesian Immersed Boundary Method	73
5.1.1	Reconstruction for velocities	75
5.1.2	Reconstruction for pressure	76
5.1.3	Reconstruction for temperature	76
5.1.4	Reconstruction for density	77
5.1.5	Calculation of wall pressure, shear stress and heat flux	78
5.2	Numerical investigations	80
5.2.1	Inviscid hypersonic flow past a hemisphere	80
5.2.2	Subsonic flow past NACA0012 airfoil	81
5.2.3	Transonic flow past biplane NACA0012 airfoil	84
5.2.4	Low supersonic flow past a 4% thick bump	85
5.2.5	Supersonic flow past NACA0012 airfoil	87
5.2.6	Hypersonic flow past a flat plate	89
5.2.7	Hypersonic flow past a compression ramp	90
5.2.8	Hypersonic flow past a cylinder	92
5.2.9	Hypersonic flow past a sphere-cone model	95
5.3	Summary	97

<b>6</b>	<b>Revisiting the Sharp Interface Immersed Boundary for Viscous Flows</b>	<b>98</b>
6.1	Resolution and reconstruction errors . . . . .	99
6.2	Studies with local grid refinement . . . . .	103
6.3	Selective solution reconstruction . . . . .	106
6.4	Alternate reconstruction approaches . . . . .	108
6.5	Dependence on freestream and wall conditions . . . . .	111
6.6	Discussions and remedial approaches . . . . .	116
6.7	Summary . . . . .	119
<b>7</b>	<b>Applications Towards Design and Optimisation</b>	<b>120</b>
7.1	Aerodynamic shape optimisation of nose cone . . . . .	121
7.2	Design of scramjet inlets . . . . .	131
7.3	Design of optimal nozzle for supersonic flows . . . . .	136
7.4	Summary . . . . .	140
<b>8</b>	<b>Conclusions and Future Scope</b>	<b>142</b>
8.1	Conclusions . . . . .	142
8.2	Scope of future work . . . . .	145
	<b>Appendix A</b>	<b>147</b>
	<b>Publications</b>	<b>149</b>
	<b>References</b>	<b>152</b>

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## LIST OF FIGURES

1.1	(a) Overlapping grid approach (b) Cartesian cut-cell approach . . . . .	6
1.2	(a) Diffused-interface IB approach (b) sharp-interface IB approach . . . . .	8
1.3	(a) Interpolation scheme for ghost-cell (b) neighbouring points (NP) . . . . .	9
2.1	Cell nomenclature . . . . .	18
2.2	Linear reconstruction for the cell centered scheme . . . . .	20
3.1	(a) Cell geometry (b) nomenclature for non-orthogonal grid . . . . .	26
3.2	Schematic for the supersonic vortex flow computational domain . . . . .	36
3.3	Computational grid adopted (a) uniform (b) stretched (c) triangulated . . . . .	37
3.4	(a) Numerical dissipation for inviscid isentropic vortex (b) behaviour of numerical dissipation with limiter constant $K$ . . . . .	39
3.5	Computational grid adopted for flow past ramp . . . . .	41
3.6	Steady-state convergence for flow past compression ramp at (a) CFL = 0.1 (b) CFL = 0.175 . . . . .	41
3.7	(a) $C_f$ distribution for flow past compression ramp (b) $P_w/q$ distribution for flow past compression ramp . . . . .	42
4.1	Classifications of cells in the immersed boundary finite volume (IB-FV) solver . . . . .	46
4.2	Schematic of reconstruction scheme where subscript $j$ refers to the immersed cell . . . . .	47
4.3	Computational stencil for inverse-distance weighting (IDW) reconstruction . . . . .	48
4.4	Computational domain for transonic flow past bump along with boundary condition . . . . .	52

4.5	Mach contours depicting normal standing shock for different grid (a) 150 × 50 (b) 225 × 75 (c) 300 × 100 (d) 450 × 150 (Min: 0, $\Delta$ : 0.117, Max: 1.52) (Top:- IB-FV solver; Bottom:- FV solver on body fitted mesh)	53
4.6	Coefficient of pressure distribution along the surface of the body from (a) IB-FV solver on non-conformal grid (b) FV solver on conformal grid	53
4.7	(a) Coefficient of pressure distribution along the surface of the body on conformal and non-conformal mesh (b) Numerical entropy generation along immersed cells	54
4.8	Variation of mass defect $\Delta m$ with grid refinement	56
4.9	Computational domain for supersonic vortex flow	57
4.10	Order of accuracy for IB-FV (non-conformal grid) and FV (conformal grid) using (a) $L_2$ norm (b) $L_\infty$ norm	58
4.11	Shock wave angle $\beta$ with grid refinement	59
4.12	(a) Comparison of coefficient of pressure distribution with theoretical correlation and body-fitted FV result (b) Coefficient of pressure distribution using IB-FV solver on two different grid resolution (zoomed view)	60
4.13	Comparison of numerical Schlieren (below) and experimental Schlieren (top) [116] for supersonic flow over cone	60
4.14	Comparison of (a) coefficient of pressure distribution obtained using IB-FV solver with experimental data (b) shock shape obtained using IB-FV solver with theoretical correlation	61
4.15	Comparison of numerical Schlieren (below) and experimental Schlieren (top) [117] for hypersonic flow over sphere	62
4.16	(a) Uniform (b) non-uniform Cartesian grid employed in IB-FV solver for flow over double-ellipse	62
4.17	(a) Coefficient of pressure distribution (b) Mach contours for double ellipse (Min: 0, $\Delta$ : 0.5, Max: 8.15)	63
4.18	Entropy distribution on uniform and non-uniform grid	63
4.19	Scramjet geometry	64
4.20	Curvilinear grid used with struts immersed in it (every fourth grid line shown)	65
4.21	Mach contours for scramjet simulations (Min: 0, $\Delta$ : 0.22, Max: 5.4)	66
4.22	(a) Center-line Mach number variation (b) Pressure coefficient distribution along the surface of scramjet struts	66
4.23	Location of body and shock at time $t = 0$ s	67
4.24	Two numerical solutions	67
4.25	Two numerical solutions	67

4.26	Two numerical solutions . . . . .	69
4.27	Optimal configuration of the axisymmetric forebody . . . . .	70
5.1	Reconstruction for obtaining $\phi$ at immersed cells . . . . .	75
5.2	(a) Comparison of shock shape with Billig correlation [118] (b) comparison of numerical (bottom) and experimental (top) Schlieren . . . . .	80
5.3	Comparison of normalised pressure coefficient with experimental data [117] . . . . .	81
5.4	(a) Computational domain (not to scale) (b) Non-uniform initial grid . . . . .	82
5.5	Three levels of refinement across the NACA0012 airfoil at (a) leading-edge portion (b) trailing-edge region . . . . .	82
5.6	Surface distribution of (a) pressure coefficient $C_p$ (b) skin-friction $C_f$ (c) $C_f$ along region of separation . . . . .	83
5.7	(a) Computational domain (not to scale) (b) Non-uniform initial grid . . . . .	84
5.8	Streamlines for flow past NACA0012 staggered airfoil (a) Jawahar and Kamath [129] (b) Qiu et al. [130] (c) IB-FV . . . . .	84
5.9	Comparison of surface distribution of (a) pressure coefficient $C_p$ and (b) skin-friction coefficient $C_f$ . . . . .	85
5.10	(a) 4% thick bump in a channel configuration (b) non-uniform computational grid (c) enlarged portion of the bump with adapted grid . . . . .	86
5.11	(a) Mach contour (Min: 0, $\Delta$ : 0.04, Max: 1.42) . . . . .	87
5.12	Comparison of skin-friction coefficient $C_f$ along the bump and wall with [131] . . . . .	87
5.13	(a) Computational domain (not to scale) (b) non-uniform adapted grid . . . . .	87
5.14	Mach contour (Min: 0.2, $\Delta$ : 0.11, Max: 2.18) . . . . .	88
5.15	Comparison of surface distribution of (a) pressure coefficient $C_p$ and (b) skin-friction coefficient $C_f$ . . . . .	88
5.16	Distribution along the surface of the wall for (a) wall pressure (b) Stanton number with experimental data of Lillard and Dries [133] . . . . .	89
5.17	(a) Ramp geometry (b) locally adapted grid (c) pressure contour for flow past compression ramp (Min: 0, $\Delta$ : 51.66, Max: 620) . . . . .	91
5.18	Comparison of (a) pressure coefficient $C_p$ (b) skin-friction coefficient $C_f$ (c) Stanton number $St$ with experimental data [109] . . . . .	92
5.19	(a) Cylinder geometry (b) pressure contour for flow past cylinder (Min: 0, $\Delta$ : 5087, Max: 71220) . . . . .	93
5.20	Pressure distribution along the cylinder and its comparison with experimental data [134] . . . . .	93

5.21	(a) Sphere-cone model (b) pressure contour for flow past the sphere-cone model (Min: 0, $\Delta$ : 5700, Max: 74930)	95
6.1	(a) Stair-step boundary (b) body conformal grid	100
6.2	Comparison of (a) pressure (b) skin-friction coefficient $C_f$	101
6.3	Distribution of near wall temperature	102
6.4	(a) Comparison of skin-friction coefficient $C_f$ on adapted grid (b) enlarged view of adapted grid	103
6.5	Distribution of (a) near wall temperature (b) normalised wall heat flux $q/q_o$	104
6.6	Comparison of skin-friction coefficient $C_f$ along the cylinder on the adapted grid	104
6.7	Comparison of (a) skin-friction coefficient $C_f$ (b) wall heat-flux	106
6.8	Comparison of near wall temperature along the cylinder	107
6.9	Comparison of (a) pressure coefficient $C_p$ (b) skin-friction coefficient $C_f$ , along the cylinder	109
6.10	Comparison of skin-friction $C_f$ along the cylinder for freestream Mach number (a) 2.0 (b) 3.5 (c) 5.0	111
6.11	Comparison of near wall temperature distribution for freestream Mach number (a) 2.0 (b) 3.5 (c) 5.0	112
6.12	Comparison of skin-friction $C_f$ along the cylinder for freestream Reynolds number (a) 500 (b) 5000	113
6.13	Comparison of near wall temperature distribution for freestream Reynolds number (a) 500 (b) 5000	113
6.14	Comparison of (a) pressure (b) skin-friction coefficient $C_f$ , along the cylinder	114
6.15	Distribution of skin temperature	114
7.1	Flowchart describing the proposed multi-fidelity optimisation framework	124
7.2	Optimal bodies at different $l/d$	124
7.3	Semi-vertex angle $\theta_{LE}$ of optimal bodies for different $l/d$	126
7.4	Convergence acceleration for maximum $C_d$ body at $l/d=2$	127
7.5	Convergence acceleration for minimum $\beta$ body at $l/d=6$	127
7.6	Min. $C_d$ body at $l/d = 2$	127
7.7	Max. $\beta$ body at $l/d = 6$	127
7.8	Cross-objective performance for different $l/d$	128
7.9	Heat flux distribution along the length of the maximum $\beta$ body at $l/d=6$	129
7.10	Heat flux distribution for optimal bodies at $l/d=6$	129

7.11 Scramjet inlet schematic representation where $\beta$ and $\theta$ represent the shock and flow-deflection angle respectively . . . . .	132
7.12 Low-fidelity flowchart . . . . .	132
7.13 Total pressure recovery obtained from LF framework . . . . .	134
7.14 Flow non-uniformity in the isolator . . . . .	134
7.15 Mach contour for the scramjet intake configuration (a) $n=3, m=1$ (bottom) (b) $n=3, m=2$ (top) (Min: 0, $\Delta$ : 0.888, Max: 8.0) . . . . .	135
7.16 Variable area nozzle . . . . .	137
7.17 Schematic of the nozzle configuration . . . . .	138
7.18 Convergence history . . . . .	138
7.19 Optimal nozzle configuration obtained from LFF . . . . .	139
7.20 Mach contour obtained from IB-FV flow solver for the optimal nozzle configuration (Min: 0.05, $\Delta$ :0.0493, Max: 3.45) . . . . .	139
7.21 Comparison of Mach number obtained from both flow solvers . . . . .	140

---

## LIST OF TABLES

3.1	The algorithm for MGG reconstruction . . . . .	33
3.2	Numerical dissipation produced in terms of $\Delta S$ . . . . .	38
3.3	Comparison of computational time to achieve steady-state solution using SGG and MGG reconstructions for hypersonic flow past compression ramp. The blanks indicate that the solution process did not converge . . . . .	41
4.1	Mass defect $\Delta m$ on different grids . . . . .	55
4.2	Position of centre of mass of cylinder (in m ) at time $t = 0.30085s$ . . . . .	69
5.1	Comparative study showing point of separation and force coefficients . . . . .	82
5.2	Comparison of stagnation point heat flux $q_o$ . . . . .	94
5.3	Comparison of total force on the body . . . . .	96
5.4	Comparison of stagnation point heat flux $q_o$ . . . . .	96
6.1	Comparison of stagnation point heat flux $q_o$ . . . . .	102
6.2	Comparison of stagnation point heat flux $q_o$ in adapted grid . . . . .	103
6.3	Comparison of stagnation point heat flux $q_o$ on the adapted grid . . . . .	110
7.1	Flow conditions . . . . .	125
7.2	Total computational time in hours for MFF and HFF frameworks. The number of optimisation cycles is indicated in parentheses . . . . .	127
7.3	Stagnation point heat flux and heat load at $l/d = 2$ and $6$ . . . . .	130
7.4	Comparison of LF and HF frameworks at $M_\infty=8$ for the $n=3$ and $m=2$ configuration . . . . .	135
7.5	Low-fidelity flow solver . . . . .	137
A	The flux formulas for the vanLeer and AUSM scheme are given in the Table below . . . . .	147



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## CHAPTER 1

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### INTRODUCTION

*“Heavier-than-air flying machines are impossible”*

- Lord Kelvin, 1895, *On sustainable flight*

*“Houston, Tranquility Base here. The Eagle has landed”*

- Neil Armstrong, 1969, *On moon landing*

High speed flows has been a subject matter of great interest to various groups of researchers as well as commoners. The unwavering desire to mimic bird’s flight has propelled businessman turned inventors the Wright brothers, into discovering the “flying-machine” in 1903, which since then has seen tremendous alterations by scientist, in arriving at today’s interplanetary flight vehicles [1]. The remarkable leap of such structural design in the last century has foreseen many hurdles which were primarily caused by the highly complex flow features, one of which include the infamous crash of Ralph Virden P-38 aircraft in 1941. This incident was attributed to the “*compressibility effects*” which was later addressed by NACA Langley Memorial Laboratory and Ames Aeronautical Laboratory. What followed this unfortunate incident was the re-embarkment of humankind into a new flow regime of supersonic flow where the so-called “*Mach barrier*” was crossed by Chuck Yeager in 1947 in his Bell X-1. This was soon followed by the first hypersonic flight by Robert White at Mach number of 5.3 in his X-15.

This remarkable feat was made possible by countless hours of research carried out by scientist to generate highly precise experimental data and empirical correlations.