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

A thesis submitted
in partial fulfillment of the requirements
for the Degree of

DOCTOR OF PHILOSOPHY

in

Mechanical Engineering

by

Shuvayan Brahmachary

Department of Mechanical Engineering
Indian Institute of Technology Guwahati
Guwahati - 781 039

"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.

Signature: Date:

Supervisor: Dr. Ganesh Natarajan
Department of Mechanical Engineering,
Indian Institute of Technology Guwahati,
Guwahati-781039, Assam, India.

Signature: Date:

Supervisor: Prof. Niranjan Sahoo
Department of Mechanical Engineering,
Indian Institute of Technology Guwahati,
Guwahati-781039, Assam, India.

ACKNOWLEDGEMENT

Seems just like yesterday when I had enrolled for Ph.D, not knowing what laid in front of me. After 6 long years in this journey, I couldn't possibly come up with the names of all those people who have directly or indirectly helped me. Here are few important people who did.

I owe a huge debt of gratitude to my supervisors Dr. *Ganesh Natarajan* and Prof. *Niranjan Sahoo* for their guidance. They are responsible for shaping the thesis in its present form and without their support, all of this would be a distant dream. They have always been kind enough to accept my inefficiencies, provide a conducive environment for research and make me see the better side of the things. I consider myself to be extremely fortunate to have worked under them.

Sincere acknowledgements is in order for Dr. *Vinayak Kulkarni*, who has been a constant source of motivation. I am thankful to him for providing me with the opportunity to work with him as a JRF, especially before I was even a Ph.D scholar. That transition from a graduate student to a JRF was a defining point in my career. I take this opportunity to thank ISRO to provide us the financial support which were helpful towards achieving some of the contents of this thesis. I would also like to sincerely thank my DC members Prof. *Anoop K. Dass*, Dr. *Deepak Sharma* and Dr. *Suresh Kartha*, who were equally insightful and constructive in their comments towards my work. I sincerely thank Dr. *Vibin Ramakrishnan* for being my meditation instructor.

I have been blessed with very good friends on and off campus. Specifically, I would like to thank 'The League' comprising of my very good friend(s) *Jay, Cookie and Abhi.* Your presence outside of academics has been such a wonderful treat, including the memorable 'Sikkim trip'. I thank you for understanding all those days when I had to cancel on you guys at the last moment. Special mention goes to my friends: *Sumit* for being the guy that he is (omnipresent), *Siddesh* for being an ever-positive source and *Snehasish* for those interesting conversations. I can write endlessly about the days we have spent together on the campus but some things are better left unsaid; atleast not in a Ph.D thesis. I am deeply thankful to *Mukesh Kumar* for always fixing my lab PC and being extremely patient with me whenever I pulled his leg. I fondly remember some of the best food that you cooked for me and for that I must thank *Vishnu* for inviting me to his place on more than one occasion. I would like to thank

Shatru & Soni for dragging me to play badminton with them and taking pride in beating me (just don't forget you had a better badminton racket). It is only fitting for me to thank Dr. *Simon Peter* and Dr. *Jitendra Patel* for introducing me to certain concepts in IB and various other valuable inputs including LaTeX. I hope to see you both some day in a conference, while IB is still a thing, atleast for incompressible flows. I deeply thank Dr. *Bhaskar Bora* for always guiding me and being like a big brother to me. I acknowledge the fact that you possessed such an endearing personality which encouraged everyone else to stay grounded. Special thanks goes to *Mandeep* for helping me understand MGG, being my PUBG partner and so much more. While I am still figuring out to use *xfig* properly, I am grateful to you for teaching me to draw quality images in *Tecplot*. I would also like to thank *Juan* for my first guitar lesson, the Shillong road trip and introducing me to 'SW's' music. I hope to see you pursue your Doctoral studies soon. I cannot sum up my appreciation for *Jubajyoti* in few lines and I will try not to. Kidding. I am very thankful indeed for your programming lectures (so many of them!). I have learned a lot from your passion towards programming and I wish I had more days to absorb even more. I would also like to convey my thanks to *Moni* for helping me correct glaring grammatical error in the thesis. While this thesis is not a finished article yet, I really appreciate your efforts. I am grateful to *Soumya & Saibal* for being so helpful in every aspect. Your assistance in last minute arrangements will always be remembered. I fondly appreciate *Ali* for his fresh perspective upon things and those games of Basketball. I would also like to thank *Narendra Nanal* for assisting me creating mesh in Gambit and *Josef Runsten*, a.k.a *jrunsten* from CFD online community in helping me generate three dimensional block structured mesh. My days in the campus have been specially memorable due to my juniors and I am extremely grateful to them for it. I acknowledge *Rahul & Joe* for some of the most brilliant discussions we had over the years, *Naman, Nayan, Rachit, Prashant, Yash* for exhibiting fun part of hostel life and *Jai, Shobhit and Piyush* for their witty remarks.

My family are the sole reason for my accomplishments, however small it may be. I feel a deep sense of gratitude towards my *Ma, Baba and Dada* who have been extremely patient, understanding and supportive throughout this journey and beyond. I deeply appreciate the sacrifices you have made for turning my dream to reality. I would also like to convey my gratitude to *Bhavi* for the moral support throughout.

Shuvayan

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.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

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.