

Advances in Mathematical Fluid Mechanics

Fernando Carapau  
Ashwin Vaidya  
Editors

# Recent Advances in Mechanics and Fluid-Structure Interaction with Applications

The Bong Jae Chung Memorial  
Volume

 Birkhäuser

Fernando Carapau, Ashwin Vaidya, Editors

# Recent Advances in Mechanics and Fluid-Structure Interaction with Applications

The Bong Jae Chung Memorial Volume

This volume examines current research in mechanics and its applications to various disciplines, with a particular focus on fluid-structure interaction (FSI). The topics have been chosen in commemoration of Dr. Bong Jae Chung and with respect to his wide range of research interests. This volume stands apart because of this diversity of interests, featuring an interdisciplinary and in-depth analysis of FSI that is difficult to find conveniently collected elsewhere in the literature. Contributors include mathematicians, physicists, mechanical and biomechanical engineers, and psychologists. This volume is structured into four thematic areas in order to increase its accessibility: theory, computations, experiments, and applications. *Recent Advances in Mechanics and Fluid-Structure Interaction with Applications* will appeal to established researchers as well as postdocs and graduate students interested in this active area of research.

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# Advances in Mathematical Fluid Mechanics

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The *Advances in Mathematical Fluid Mechanics* series is a forum for the publication of high-quality, peer-reviewed research monographs and edited collections on the mathematical theory of fluid mechanics, with special regards to the Navier-Stokes equations and other significant viscous and inviscid fluid models. Titles in this series consider theoretical, numerical, and computational methods, as well as applications to science and engineering. Works in related areas of mathematics that have a direct bearing on fluid mechanics are also welcome. All manuscripts are peer-reviewed to meet the highest standards of scientific literature.

Edited by

Giovanni P. Galdi, University of Pittsburgh, Pittsburgh, USA


Fernando Carapau • Ashwin Vaidya  
Editors

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*In loving memory of our dear friend  
and colleague Bong Jae Chung.  
April 1, 1967–February 12, 2021*

# Preface

This book brings together current scholarship in the area of mechanics and its applications to various branches of mathematics, science, and engineering, specifically around themes of computation and modeling in fluid mechanics, in honor of our dear friend and colleague, Dr. Bong Jae Chung, a computational scientist who passed away on February 12, 2021. Bong Jae or Chung, as he was often referred to by his friends, was born in Daegu, South Korea, where he completed his undergraduate degree in physics at Kyung Hee University. He came to the United States in 1994 as a graduate student. After a brief stint in Georgia, he moved to Pittsburgh for his master's degree and eventually graduated from the University of Pittsburgh in 2004 with a PhD in mechanical engineering under the guidance of Professor Anne Robertson. He worked for several years as a postdoc and research professor at various universities including Johns Hopkins University (with Prof. Aleksander Popel), the University of North Carolina Chapel Hill (with Profs. Richard McLaughlin, Roberto Camassa, and Alberto Scotti), and George Mason University (with Prof. Juan Cebal) before securing a tenure track position in the Department of Mathematical Sciences and Department of Applied Mathematics & Statistics at Montclair State University, New Jersey, where he was employed for a little more than three years before his untimely passing.

Bong Jae was a prolific researcher with diverse interests ranging from problems of classical fluid mechanics, flows pertaining cerebral aneurysms, protein aggregation modeling, vortex-induced vibrations, and pattern formation in fluids to non-equilibrium thermodynamics. More recently, he had started working on modeling problems related to drug delivery, a topic on which his student Nicholas Jeffoupolous wrote a master's thesis<sup>1</sup>. Bong Jae also had a keen interest in experimental work having spent several months as a postdoc with Prof. George Klinzing in the Department of Chemical Engineering at the University of Pittsburgh, where he participated in the experiments related to pneumatic conveying, and also at the fluid dynamics laboratory at UNC Chapel-Hill, where he was part of the

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<sup>1</sup> You can find his article with Bong Jae on this topic in Chap. 14

team studying vortex-induced vibrations. Bong Jae was an essential member of the Complex Fluids Laboratory at Montclair State University and was looking forward to getting involved in a variety of experiments and using our particle image velocimetry system to better understand wake vortex dynamics, which he was also modeling numerically.

This volume contains work by scholars from several countries who are experts in the different areas of theoretical and computational fluid mechanics and other areas of science in which Bong Jae shared keen interest. Many of the contributions here are by his mentors, friends, and collaborators and also scholars he wanted to work with in the future. To the extent possible, we have taken care to prepare the articles so that they are accessible and relevant not only to other researchers but also to graduate students, postdocs, and those wanting to pursue new lines of research in these areas of mechanics. For this reason, the papers have been prepared in a semi-tutorial style, where possible. While scholarship in the area of Fluid Structure Interaction (FSI) has been gaining ground, especially with developments in computational techniques and technology, most books in this area are restricted to very specific topics. The particular novelty and interesting aspect of this book lies in its interdisciplinarity, with contributions from mathematicians, physicists, mechanical and biomechanical engineers, and even psychologists, all bringing new perspectives to the study of mechanics.

This book is truly an eclectic mix of articles on various themes. We have therefore decided to organize the book into four thematic parts: (1) Theory, (2) Computations, (3) Experiments, and (4) Applications. In some cases where the papers fall in multiple categories, we have tried to assign them to a part we feel it best represents.

Part I on theoretical fluid mechanics consists of four papers which range from mathematical (existence of solutions) issues for fluids (Chap. 1: Berselli and Růžička) and fluid solid systems (Chap. 3: Galdi) to modeling the physics of fluids (Chap. 2: Carapau, Correia and Areias; Chap. 4: Camassa, Ding, McLaughlin, Overman, Parker, and Vaidya).<sup>2</sup> Part II on CFD and numerical methods features six papers. The first of these (Chap. 5: Bodnár, Keslerová, and Lancmanová) on the numerical methods for flow in branching channels was a repeating theme in much of Bong Jae's computational biomechanics work. Other papers in this part are focused on Galerkin methods in problems of plasticity (Chap. 6: Areias, Carapau, Lopes, and Rabczuk) and novel uses of modern computational techniques in mechanics such as use of machine learning techniques to understand emergence of patterns in kinetic models related to protein aggregation (Chap. 7: Pateras, Vaidya, and Ghosh), reduced order modeling (Chap. 8: Snyder, Mou, Liu, San, De Vita, and Iliescu), numerical issues in the modeling of viscoelastic fluid flows (Chap. 9: Pires and Bodnár), and cellular automata modeling of complex fluids (Chap. 10: Ramos, Carapau, and Correia). Part III on experiments includes two papers. The first of these

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<sup>2</sup> It is worth mentioning that Bong Jae was very interested in the problem discussed in (Chap. 4) which was initiated by the authors during his postdoctoral days at UNC-CH in 2008–2009; he even helped with debugging the initial codes written for this work.



is on the thermomechanics of self-organization in dissipative systems (Chap. 11: De Bari and Dixon) on which Bong Jae had previously published and wished to contribute more to in the coming years. The second paper in this part is devoted to the use of vortex-induced vibrations towards hydrokinetic energy generation (Chap. 12: Wulandana and Haque), which was one of his primary research interests. In fact, a significant part of his computational effort after his arrival in New Jersey was devoted to development of numerical methods to study fluid-solid interactions, specifically vortex-induced oscillations. Part IV on applications of fluid mechanics covers areas of deep interest to Bong Jae including drug delivery (Chap. 13: Azhdari, Emami, and Ferreira; Chap. 14: Jefopolous and Chung ), carbon sequestration (Chap. 15: Phouc and Massoudi), and Ocular flow (Chap. 16: Chung, Martinez, and Vaidya). Two of these chapters feature articles by Chung and his past students Brandon and Nicholas (Chaps. 14 and 16).

It is certainly worth mentioning that a special issue of this kind is rare. Such honor is reserved for the "generals" of science not "foot soldiers". A commonly held view among scientists, whose essential sentiment is even expressed by the likes of David Bohm, is captured in the following statement:<sup>3</sup>

*In the whole of human history, perhaps only a few people have achieved it [creativity]. Most of the rest of human action has been relatively mediocre, though it is interlaced with flashes of penetrating insight that help raise it above the level of mere humdrum.*

We respectfully reject this viewpoint and the overarching hierarchical value system that it imposes on scientific contributions. It is being slowly recognized that creativity happens at all levels, and while we all admire and rely on the paradigm shifting, "wall-breaking" efforts to eliminate barriers to knowledge, there are those who do the same, one brick at a time. Their efforts are no less valuable, and collectively taken, such efforts are essential for the next great scientific transformation. When sincere and consistent, such work also deserves acknowledgment. I am therefore deeply appreciative of all colleagues who have volunteered to contribute to and supported this volume, in honor of a soldier of science; they remind us that knowledge seeking is a collective effort and every contribution has merit, much of it yet unforeseen.

We convey special thanks to Professor Giovanni Paolo Galdi for his help and encouragement in getting the book published in this series and to Professor Anne Robertson, Bong Jae's PhD advisor and collaborator, for her encouragement and commitment to this project. Bong Jae expressed deep admiration for all his teachers and mentors and was deeply influenced by them, especially Dr. Robertson. On his behalf, we would therefore like to thank all his mentors, including Dr. Aleksander Popel (Biomedical Engineering, Johns Hopkins), Dr. Richard McLaughlin (Mathematics, UNC-Chapel Hill), Dr. Alberto Scotti (Marine Sciences, UNC-Chapel Hill), Dr. Roberto Camassa (Mathematics, UNC-Chapel Hill), and Dr. Juan Cebal (Biomedical Engineering, George Mason) for their mentorship and for the

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<sup>3</sup> Bohm, D. (2004) *On Creativity*, editor Lee Nichol. London: Routledge.

intellectual stimulation they provided. We also thank Bong Jae's students Nicholas and Brandon, both of whom lost a mentor midway through their thesis project and yet persisted in completing the work and are featured in this book. We acknowledge the help and support of Mr. Chris Eder and Ms. Saveetha Balasubramaniam at Birkhauser-Springer for helping us see this volume through and for making this such a smooth process for us.

Montclair, NJ, USA  
Évora, Portugal  
June 2022

Ashwin Vaidya  
Fernando Carapau

## Personal Memories and Tributes

I feel fortunate to have served as Dr. Bong Jae Chung's doctoral advisor, and therefore had the opportunity to get to know him personally, watch him grow intellectually, share the joy of immersing in shared research on fluid and solid mechanics, experience his genuine kindness and see the happiness he drew from his wife and dear friends. Bong Jae was my second doctoral student. I first met him in the early stages of his graduate studies at the University of Pittsburgh as a member of his Masters' thesis committee. His research focused on the numerical study of freely moving bubbles in a stirred column. I was impressed by Bong Jae's determination to deeply understand this difficult topic and, with his advisor, Dr. Hwang's agreement, recruited him to my research group for his doctoral studies. One of the things that stood out to me even at that time, was his great love of learning and discovery. He was clever, determined, and ready to take on new and difficult topics.

Dr. Chung's doctoral research covered challenging topics involving theoretical and computational studies of cerebral aneurysms. His initial computational work evaluated flow in arterial bifurcations, where cerebral aneurysms are typically found. He built on these results to design, for the first time, an in vitro flow chamber to expose endothelial cells to the same wall shear stress field found at the apices of cerebral bifurcations. While most of his research and coursework was fluid mechanics, during the last year of his doctoral work, we began discussing possible ways of improving existing arterial wall models. Despite the fact that his background in solid mechanics was limited, he independently learned the material in the advanced graduate text, *Theoretical Elasticity*, by Green and Zerna. He then moved on to use this knowledge to apply the theory of small on large elastic deformations to the arterial system, for the first time. As a postdoctoral researcher at George Mason University, Dr. Chung had an extremely productive collaboration with Dr. Juan Cebral, one of the top computational biofluid dynamicists. This work led to important publications in the field of cerebral aneurysms, including Bong Jae's first author review article in the *Annals of Biomedical Engineering*, *CFD for evaluation and treatment planning of aneurysms: review of proposed clinical uses and their challenges*. It was a pleasure to continue to work with Bong Jae through joint research with Juan and Bong Jae on cerebral aneurysms.

Bong Jae maintained his focus on learning and developing new knowledge through all the different chapters of his life, while persistently working toward his goal of being a professor. His wife, Kelly Yoo, fondly described their shared love of camping and that on these trips, “he always had his back pack full with heavy books, research notes and computer.” Like the rest of us, she appreciated Bong Jae’s thirst for learning and sharing knowledge with others. Bong Jae will live on in all of our memories with love and deep respect.

Pittsburgh, PA, USA

Anne M. Robertson

Chung and I were dear friends and close collaborators for nearly 24 years so this is a deep personal loss. We studied together and graduated a few days apart. We were most fortuitous to even share part of our postdoctoral experience at the University of North Carolina—Chapel Hill together and thought it miraculous that we would end up as faculty members in the same university. I have fond memories of our working deep into the night, engaging in exciting scientific and philosophical discussions and making elaborate future plans for exciting projects.

Chung was dedicated to his work and very passionate about it. He was extremely prolific, the rate and diversity of his contributions, especially in the last decade of his life are impressive (see the following pages for a full list of his publications). However, to him, his research and even teaching were not about achievements or reputation—it stemmed from a sincere joy of learning and sharing his knowledge with others. In his friendships also, he was about filling moments together with laughter and love; it did not matter what he was doing with his friends it was about making the interaction memorable. In all his encounters, he was about listening, not talking; about compassion, forgiveness and seeking the best in others. I greatly admired and appreciated his wisdom of kindness and simplicity. There are a great many reasons to mourn the loss of a friend and colleague, but we see this volume as a celebration of a humble, thoughtful, and passionate scientific life.

Montclair, NJ, USA

Ashwin Vaidya

In September 2000 I started my PhD work at the Department of Mechanical Engineering and Materials Science, Pittsburgh, PA, USA under the supervision of Professors Anne M. Robertson and Adélia Sequeira (DMAT/IST, Portugal). As part of the work in this group, under the guidance of Professor Anne M. Robertson, I met my colleague Chung (as many of us referred to him), with whom I developed a solid friendship over the years, not only in scientific terms, but also in our personal lives. We were brothers. Chung was a warm, simple person and friend to everyone. His scientific observations and precious collaboration within the working group were appreciated by all. The scientific community and science itself have prematurely lost a good thinker. Chung, wherever you are, a big hug from your brother Fernando!

Évora, Portugal

Fernando Carapau

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(a)



(b)



(c)



(d)



(e)

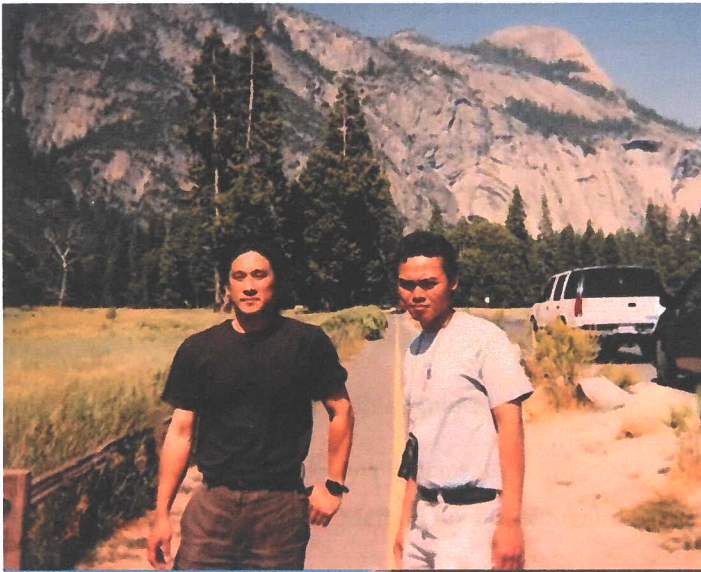


(f)

Bong Jae with friends and colleagues and mentors in Pittsburgh between 2000–2004 (a, b, c) and Capo Miseno, Italy in 2001 (d, e, f)



(a)



(b)

Bong Jae with (a) colleagues in Fairfax, VA around 2008 and (b) fellow graduate student in California in 2000

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