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Foreword

Special Issue of the Journal of Applied Mechanics on Modeling and Simulation of Turbulent Flows Dedicated to the Late Professor Charles G. Speziale

A Symposium on Modeling and Simulation of Turbulent Flows was held in memory of Professor Charles G. Speziale at the 4th ASME/JSME Joint Fluids Engineering Conference on July 6–10, 2003, in Honolulu, Hawaii. This special issue consists of a collection of papers presented at that conference. We are grateful to the Editor of the Journal of Applied Mechanics, Professor Robert McMeeking, for dedicating a special issue of the Journal to selected papers from that meeting. Charles served as an associate editor of JAM, and it is only appropriate that this collection of selected papers in his honor appear among the pages of this prestigious Journal.

This Foreword is accompanied by an addendum which puts together a compendium of thoughts and recollections of friends and colleagues of Charles under the rubric "Reflections on Charles Speziale." We are deeply grateful to those who have taken the time to contribute to this section.

The papers in this special issue dedicated to the late Professor Charles Speziale address several crucial issues that are relevant to ongoing research on modeling and simulation of turbulent flows, issues that formed the core theme of Charles' research during the latter part of his professional life. A few of Charles' publications relevant to the articles which appear in this special issue are listed below. The papers in this issue may be classified into four broad categories: large eddy simulation (LES) of turbulent flows by dynamical schemes; development of turbulence models that are capable of capturing complex features of the flow field such as curvature and rotation by the use of single-point closure that arises in conjunction with the Reynolds-averaged Navier-Stokes equations (RANS); continuous models that bridge the spectrum between the RANS and LES; and theoretical and heuristic analysis of turbulent flows that range from stability analysis to scaling to the use of numerical dissipation.

The LES models are covered by the first four articles. Professor Speziale had been involved in the development of effective subgrid scale models for LES that can capture anisotropy arising from curvature, rotation, and thermal field. The following articles are of direct relevance to his work.

The article by Brilliant et al. concerns the near-wall behavior of the subgrid-scale diffusivity in the presence of thermal effects in LES. The constant subgrid-scale Prandtl number model is not applicable. The direct modeling of subgrid-scale diffusivity is considered instead. Large-eddy simulations are carried out in a turbulent channel flow configuration with three different thermal boundary conditions and two different filters. The results are shown to compare favorably with direct numerical simulations.

The work of Kajishima and Nomachi involves the development of a one equation subgrid model using a dynamic procedure for energy production; subgrid-scale kinetic energy is computed by solving the transport equation as part of the large eddy simulation (LES) for describing the energy transfer from the resolved scales to the subgrid (SGS) portion. This procedure is applied to the production term in the transport equation for subgrid-scale kinetic energy with a statistically-derived model to improve predictions. Computations for fully-developed turbulent flow in a plane channel and plane channels subject to solid body rotation are shown to agree well with DNS results and capture the decay of SGS turbulence in the vicinity of the suction side wall.

While LES is typically restricted to simple geometries, the work of Mahesh et al. describes a dynamic approach for LES of complex geometries. A gas turbine combustor is efficiently analyzed with the use of hexagonal mesh and a three-dimensional, unsteady, computational approach where the unsteady Navier-Stokes equations are spatially filtered, the large scales are directly computed, and the effect of the filtered scales on the resolved scales is modeled. A flamelet progress approach is used to represent combustion and the procedure is shown to be effective for the analysis of practical gas turbine combustors.

The work of Tsubokura deals with subgrid-scale modeling of thermally-stratified turbulent channel flow by dynamic LES. A lower order simulation is first used in conjunction with available DNS data to develop an anisotropic subgrid-scale model suitable for thermally-stratified flows. An efficient finite-difference scheme is then used for the resulting LES. The approach is shown to effectively predict the turbulent stresses and the heat flux.

The second set of two papers involves Reynolds-averaged Navier-Stokes equations (RANS) for analyzing complex turbulent flows that involve thermal effects, curvature, and swirl. The RANS approach is still the mainstay of the industrial sector for the analysis of turbulence in complex geometries, and Professor Speziale had made seminal contributions to provide the necessary rigor to the RANS models by careful inclusion of anisotropic effects and by ensuring that the resulting models capture the correct asymptotic behavior without violating the material frame indifference requirement.

The paper on predicting the effect of streamline curvature on the turbulent Prandtl number by Younis and Berger involves the use of explicit and nonlinear models for the effective prediction of turbulent scalar fluxes, especially in the presence of stabilizing curvature effects. Streamline curvature in the plane of the mean flow is known to exert a proportionately greater effect on the turbulent mixing processes, and when heat transfer is present, the experimental findings appear to suggest that the rate of heat transfer by turbulent motions is more sensitive to the effects of curvature than momentum transport. Thus, the conventional models that utilize constant turbulent Prandtl number are often ineffective. The authors build on the earlier work of Professor Speziale as well as their past collaborations to develop an effective anisotropic RANS model that is suitable for the analysis of turbulent channel flows with spanwise curvature.

The paper on the development and application of an anisotropic two-equation model for flows with swirl and curvature by Wang and Thangam use a novel technique that involves the representation of the energy spectrum and invariance-based scaling, a methodology that is a natural follow up of the technique pioneered by Charles Speziale for the development of anisotropic RANS models. In this approach the effect of rotation is used to modify the energy spectrum, while the influence of swirl is modeled based on scaling laws. The resulting generalized two-equation turbulence model is validated for several benchmark turbulent flows with swirl and curvature.

The third set of five papers involve the development of models that bridge the LES and RANS to provide an effective tool to model turbulent flows for complex geometries that are unsteady in their mean. This was in the forefront of Professor Speziale's research during his final days, and the continuous model framework that was developed by him is widely used both as a predictive tool and to develop other models for the effective prediction of unsteady flows.

The work by Fasel et al. involves a flow simulation methodology (FSM) that is applied for the time-dependent prediction of complex compressible turbulent flows. The development of FSM was initiated in close collaboration with the late Charles Speziale, with the objective of providing the proper amount of turbulence modeling for the unresolved scales while directly computing the largest scales. The strategy is implemented by using state-of-the-art turbulence models (as developed for RANS) and scaling of the model terms with a "contribution function." The resolution requirement is determined during the actual simulation by comparing the size of the smallest relevant scales to the local grid size used in the computation. The contribution function is designed so that it approaches a DNS in the fine-grid limit and such that it provides modeling of all scales in the coarse-grid limit to approach RANS. The approach is validated by employing FSM to calculate the flow over a backward-facing step and a plane wake behind a bluff body, both at low Mach number, and supersonic axisymmetric wakes.

The next two papers involve a novel approach based on partially-averaged Navier-Stokes equations (PANS). The first work by Girimaji involves the development of a turbulence bridging method for any level of physical resolution that is fully averaged to completely resolved. The extent of partial averaging is quantified by two parameters: the unresolved-to-total ratios of kinetic energy and dissipation and is derived formally from the fully-averaged Reynolds-averaged Navier-Stokes (RANS) model equations by extracting the corresponding closure for partially-averaged statistics. The PANS equations vary smoothly from RANS equations to Navier-Stokes (direct numerical simulation) equations depending on the values of the resolution control parameters. Preliminary results are shown to be very encouraging.

This is followed by the work that involves a fixed point analysis of PANS and its comparison with unsteady RANS by Girimaji et al. It examines the behavior of the production-to-dissipation ratio based on fixed point analysis of PANS (partially-averaged Navier-Stokes) and URANS (unsteady RANS). It is shown that the production in URANS is too high, rendering it incapable of resolving much of the fluctuations. On the other hand, the production in PANS allows the model to vary smoothly from RANS to DNS depending upon the values of its resolution control parameters. Thus, PANS is ideally suited for performing variable-resolution simulations of the type sought with hybrid RANS/LES and VLES. Preliminary computations based on commercially available software clearly demonstrate this.

A time-dependent RANS-based VLES of thermal and magnetic convection at extreme conditions by Hanjalic and Kenjeres involves convection at very high Rayleigh and Hartman numbers, which are inaccessible to the conventional large eddy simulation (LES). They propose a time-dependent Reynolds-averaged Navier-Stokes (T-RANS) approach in which the large-scale deterministic motion is fully resolved by time and space solution, whereas the unresolved stochastic motion is modeled by a "subscale" model for which a one-point RANS closure is used. The T-RANS approach, with an algebraic stress subscale model, verified earlier in comparison with direct numerical simulation (DNS) and experiments in classic Rayleigh-Benard convection, is now expanded to simulate Rayleigh-Benard convection at very high Rayleigh numbers and in strong uniform magnetic fields. The results are shown to be in accord with recent experimental findings and Kraichnan asymptotic theory.

The final paper in this section deals with the development of a continuous model for simulation of turbulent flows that is suitable for representing both the subgrid-scale stresses in large eddy simulation and the Reynolds stresses in the Reynolds-averaged Navier-Stokes equations by Hussaini et al. The model development and formulation and the recursion approach that is used to bridge the length scale disparity from the cutoff wave number to those in the energy-containing range are described along with its application in conjunction with direct numerical simulations of Kolmogorov flows.

The last segment of the special issue concerns some of the theoretical and experimental aspects of turbulence. Throughout his professional life, Professor Speziale was involved with the theoretical aspects of turbulence in his attempt to gain additional insights. He was especially interested in analyzing the limiting behaviors such as the rapid distortion limit and the characteristics of turbulence decay, among others.

The first paper by Salhi and Cambon on theoretical turbulence involves new results based on rapid distortion theory (RDT) that have broad applicability ranging from rotating shear flows to the baroclinic instability. It deals with homogeneous turbulence subject to rotational mean flows, a topic the authors have collaborated on in the past with Charles Speziale. New analytical solutions and related RDT results are presented in this work for shear flows that include buoyancy, with system rotation or mean density stratification. The authors show that by combining shear, rotation, and stratification, RDT is pertinent to the baroclinic instability, which results from the tilting of mean isopycnal surfaces under combined effects of shear and system rotation in a stably stratified medium rotating about the vertical axis. The authors also address the issues related to incorporating RDT dynamics in single-point closure from the viewpoint for structure-based modeling.

The second paper by Clark and Zhou deals with the growth rate of Richtmyer-Meshkov mixing layers that are initiated by the passing of a shock wave over an interface between fluids of differing densities. The energy deposited by the shock passage undergoes a relaxation process during which the fluctuating energy in the flow field decays and the spatial gradients in the flow field decrease with time. This late stage of Richtmyer-Meshkov mixing layers is studied from the viewpoint of self-similarity. The authors note their past collaborations with Charles Speziale as well as his contributions to self-preservation of isotropic decay of turbulence in which he demonstrated that under certain conditions, a full self-preserving solution for isotropic turbulence can be obtained. The authors have extended this concept of self-preservation in shear layers to Richtmyer-Meshkov mixing layers in the present work.

The third paper by Margolin et al. concerns dissipation in implicit turbulence models. A series of computational experiments that employ nonoscillatory finite volume methods to simulate the decay of high Reynolds number turbulence are described for a broad range of physical viscosities and numerical resolutions. The authors have extracted the energy dissipation by physical viscosity and by the numerical algorithm and offer a preliminary analysis, including new insights into the (computational) transition between direct numerical simulation and large eddy simulation and the usefulness of the finite scale numerical solutions of Navier-Stokes equations as a physical model.

The work on non-canonical jets in cross flow by Plesniak presents a topical review and consists of a compilation of results previously reported, as well as some new ones. Experimental results acquired with particle image velocimetry along with RANS simulations of the flow for different aspects of the problem have been investigated, and the structural features of the flow within the hole and in the developing jet and crossflow interaction are analyzed. A significant result is that the vortical structures present in the hole, depending on their sense of rotation, tend to augment or weaken the primary counter-rotating vortex pair in the non-canonical jets, thus impacting global features associated with the jet trajectory and spreading.

The mechanism of drag reduction due to spanwise wall oscillation in a turbulent boundary layer is analyzed in conjunction with Stokes' second problem by Bandyopadhyay based on measurements and simulation data. A kinematic vorticity reorientation hypothesis of drag reduction is first developed and it is shown that spanwise oscillation seeds the near-wall region with oblique and skewed Stokes vorticity waves. The resulting Stokes' layer has an attenuated nature, with attenuation increasing as the wall is approached. The mean velocity profile at the condition of maximum drag reduction is similar to that due to polymer with maximum drag reduction when turbulence is suppressed. A kinematic drag reduction hypothesis is developed to characterize the measurements.

In closing, we are pleased that this collection of papers well represents the many interests of Charles in turbulence modeling and as such the issue is a worthy tribute to his work. We would like to express our thanks to the contributors and to the anonymous reviewers who made this special issue possible.

Dennis Siginer
Wichita State University
e-mail: dennis.siginer@wichita.edu

Siva Thangam
Stevens Institute of Technology
e-mail: sthangam@stevens.edu

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Addendum to the Foreword
Reflections on Charles G. Speziale

What I learned from Charlie: During the 1980s, at NASA Langley Research Center, control experiments at the Viscous Flow Branch and turbulence modeling efforts at the ICASE used to be pursued vigorously. I met Charlie in the confluence and saw what an intense researcher he was. He called me one day saying that he would like to discuss an experimental flow visualization paper on relaminarization in a coiled pipe that had just appeared in the inaugural issue of a journal. Although he did not say so, I believe he was looking to validate his physical insights into extremely rapid distortions that he was assembling into a new turbulence model. He had analyzed the relaminarization mechanism in great detail and the paper had fallen short in his expectation. He wanted to make sure with me that he had understood the experimental work correctly and was not rushing to judgments. I had to agree with him that the work needed to be more rigorous for the claims made. From that one brief encounter with Charlie, this is what I learned regarding robust turbulence methodology. In turbulence, techniques such as flow visualization, direct numerical simulation, turbulence modeling, and point or volume measurements are different windows to the same phenomenon. Due to the closure problem, the inference from each is to be validated against what has been learned in other techniques. Such a balanced approach is more likely to give us the true picture.

Promode R. Bandyopadhyay
Naval Undersea Warfare Center,
Newport, RI
e-mail: BandyopadhyayPR@Npt.NUWC.Navy.Mil

I first met Charles many years ago when I was one of the summer visitors to ICASE, sited at NASA Langley Research Center in Hampton, Virginia. ICASE was a wonderfully unique center of fluid dynamics research headed brilliantly for many years by Yousuff Hussaini. Charles spent a number of years at ICASE after he left academia, then returned, accepting an appointment at Boston University. We remained friends and collaborators until his death.

Charles was a very private person, with a number of strongly held beliefs and passions, which he loved to debate. There was always time to discuss these in the evenings as, every evening a group of six or so of us visitors and permanent staff, in fact (or de facto "bachelors"), went off to dinner in a local restaurant with little else in Hampton to entice us away from a leisurely meal intermixed with spirited discussions. I remember fondly how Charles, after ordering the same fried shrimp dish (Hampton, near Chesapeake Bay, is noted for its seafood) he had ordered at many previous such evenings, felt obligated to make the case for the dish, precisely delineating the qualities he found so irresistible.

Charles was an incredibly gifted and creative scientist. One felt there was no question about turbulence he could not answer, and when not, give a learned discourse about. He freely shared his wisdom and insight, and was always fully prepared to debate any and all scientific issues, particularly in turbulence.

Like, I suspect, many others, I did not know the full extent and seriousness of his medical problem. Had I known, I like to think I would have phoned Boston as often as he called Berkeley. Sadly, rather than having someone to look after him, he was the caretaker for a widowed father who lived with him. (All his friends remember the times Charles left a group of us for a moment, when away at ICASE or elsewhere, to check up on his father by phone.) And like many, I will carry the burden of not following his example, not being as good a friend as he was a son.

Stanley Berger
University of California at Berkeley,
Berkeley, CA
e-mail: saberger@me.berkeley.edu

I met Charles around 1991 in CTR (Center for Turbulence Research, Stanford University and NASA Ames). For a couple of weeks we were an enthusiastic team, together with Nagi Mansour, focusing on rotating turbulence, a subject Charles was intensely interested in throughout his career. I was surprised by what I naively felt as the "old British" appearance of Charles, in contrast with his Italian-origin family name. This impression was strengthened by his very quiet attitude and his use of humor and understatement; even his touch of east-coast accent sounded British to my unacquainted French ear (my own English with a French accent is terrible). Of course this feeling carries all basic stereotypes you can imagine!

In a more serious vein, it gives me pleasure to recall his deep-seated interest in fundamental aspects of fluid dynamics, and his efforts to build a bridge to applications to intelligent models of turbulence in engineering. As a first example, he mastered the analogies with constitutive laws in continuum mechanics, with possible applications of "objectivity" and "material indifference," while being aware of their limitations; eventually he showed the limited applicability of the latter principles to "rotational" turbulence, only retaining Galilean invariance for, e.g., improving calibration of some subgrid-scale models. As a second example, linkage of stability analysis to turbulence modeling drew his attention. This aspect gave my colleague Aziz Salhi and me the opportunity for a new, unfortunately very short, collaboration with him, which partly justifies our modest contribution to the present special issue.

Finally, I was very sad to hear about the passing of David Tritton not long after Charles', a terrible loss for our research community. Since I began with CTR and my and Charles' association with it, I could not possibly not mention the passing of Bill Reynolds a few years later. All three scientists made valuable contributions to turbulence research, and especially to rotating turbulence, over the last two or three decades.

Claude Cambon
Ecole Centrale de Lyon,
Lyon, France
e-mail: Claude.Cambon@ec-lyon.fr

My first meeting with Charles Speziale occurred in 1995. By that time, I had just finished my Ph.D. in France and I was spending one year at ICASE in NASA Langley Research Center (LaRC). I was new to this marvelous institution, but I later came to know that Charles was used to visiting ICASE several times a year to work with fellow researchers.

By the time I met him I had already known the work of Charles for more than four years, as all my graduate work was in turbulence. It was a real pleasure to meet the author of so many papers that had been so interesting to read. His work was plain novelties, and although quite young he had already become an ol' man of physics. Talking with him was also a pleasure.

Charles was really a genius, but he was also very kind and cheerful every time I got to see him. He enjoyed sharing the big as well as the little troubles of our scientific community. He collected stories of errors and disputes as we all learn from our mistakes. One day I even realized that I owned the key to one of those still unknown to him. He was also delighted to hear about the birth of a new child of fluid mechanics and all the happy events such as weddings which outline the differences between equations and human beings.

Charles Speziale taught us a different point of view on fluid mechanics and turbulence. I am most grateful and I regret that he left us so early.

Francoise Daumas-Bataille
Université de Perpignan,
Perpignan, France
e-mail: francoise.daumas-bataille@univ-perp.fr

I did not interact much with the late Charles. I used to run into him at conferences and summer events. Occasionally we discussed issues of common interest. I recall vividly, however, the summer of 1995 when we both took part (with a number of other visitors) in the ICASE summer program (at NASA Langley). The place was very crowded and small offices were packed by three or even four visitors (program participants). Without any doubt, Charles was the most papular guy around, not only because of his well-known publications on the matter, but also because of his reputation of a broad erudition, excellent theoretical background, and readiness to discuss any topic. Many people wanted to talk to him. However, in most cases a simple question would lead to a long monologue by Charles. With office doors kept open, we could all hear him and listen to his "lectures" in another office. And he was tireless. But no one seemed disturbed. On the contrary, most people opened their ears widely trying to figure out what he was talking about. The last time I saw him was on the occasion of the ICASE/NASA LARC/AFOSR Symposium on modeling complex flows in August 1997. It was held in a big hotel (I do not recall the location; the proceedings, edited by M. D. Salas, J. N. Hefner, and L. Sakell, were published by Kluwer Academic Publishers in 1999). Charles came only for a day to deliver his lecture. I talked to him briefly and he told me that he had been in an accident (he slipped and fell over on ice), broke his arm, and suffered from various complications. Apparently it took him a long time to partially recover. He looked weak, but was still optimistic. Shortly afterwards, I learned that his recovery was rather slow and not very successful.

Kemo Hanjalic
Delft University of Technology,
Delft, The Netherlands
e-mail: hanjalic@ws.tn.tudelft.nl

What was most striking about Charles Speziale's personality was the intense devotion to his work that underlay a friendly and informal manner. Other than that, like me, he grew up in New Jersey and was fond of quality watches. I knew very little about him beyond his work.

I first met Charles at the Ithaca APS meeting, where after the briefest exchange of pleasantries, he launched into a lively discussion of the principle of exchange of stabilities. I knew nothing about it, not even the name. But it was not a matter of being lectured to; I think he really wanted me to share his enthusiasm over a new discovery.

Somehow, the importance and the quantity of Charles' ICASE reports in the late 1980s and early 1990s led me to assume that ICASE was housed in a very large and impressive building. I was really surprised at how wrong I was when I first visited ICASE at Charles' invitation some years later.

For all his single-mindedness, Charles was far from dogmatic: he could be persuaded he was wrong and he could change his mind. It was through him that I met the group at Los Alamos working on two-point closures; they were often very critical of the kind of turbulence models Charles devoted his research to.

One personal detail I would like to note was his fondness for Captain George's Seafood Buffet on (unattractive) Mercury Boulevard in Hampton.

A personal connection that I must mention is that Charles was among those who brought me to ICASE in 1995. For this turning point in my professional life, I will always be grateful to him.

Robert Rubinstein
NASA Langley Research Center,
Hampton, VA
e-mail: bobr@cfdlab.larc.nasa.gov

I met Charles during the Twelfth Southeastern Conference on Theoretical and Applied Mechanics (SECTAM XII) held at Callaway Gardens, a golf resort in Pine Mountain, Georgia in May 1984. He approached me after my presentation and engaged me in a lively discussion. I will always remember that first encounter and the warmth that permeated our conversation. What struck me at the time was his genuine interest in the discussion not to be proven right but to develop a better and deeper understanding of the subject. Over the years we kept in touch and became friends. My research is specifically in non-Newtonian fluid mechanics and more broadly in continuum mechanics and I do not work in turbulence per se. But Charles' broad range of interests made for interesting conversations.

I followed the career of my friend and the impact of his research with pride. He was one of the most insightful researchers I have known, brimming with ideas and with an open mind. I also would like to emphasize the human side of Charles. He was a true friend, always ready to extend a helping hand.

My last conversation with him took place a couple of months before his passing. He was in Boston and we must have talked for more than an hour, nothing much about research, but mostly philosophical about the deeper meaning of our existence on this tiny speck of dust we call Earth. It must have been ominous as I do not recall dwelling on the subject with such emphasis before.

He will be remembered fondly and missed by many. His prolific output and his seminal contributions, in particular to turbulence, paved the way to much progress. I will miss him and I wish him well in his journey beyond.

Dennis Siginer
Wichita State University,
Wichita, KS
e-mail: dennis.siginer@wichita.edu

Charles' contributions to fluid mechanics are too many to recall individually. Indeed, a lot of Charles' papers have become seminars. Broadly speaking, in my view, the most important legacy Charles left behind is that he transformed turbulence modeling from an art into a science. Using his superior command of continuum mechanics, Charles demanded that a good turbulence model should be constructed to satisfy the proper properties and limits. This may sound obvious in the modern turbulence community, but when Charles entered the field, such consideration was not on the radar.

I remember vividly many intense, but always friendly discussions with Charles on different aspects of turbulence research. I also vividly recall how sharp Charles' mind worked and how clearly he formulated his arguments. While the volume of Charles' publications was very high, his papers were always well written.

I also remember the frequent phone calls from Charles. These extended calls usually lasted one, two, or even three hours and almost always came in the middle of my dinners at home. As a late-working person, Charles was at his peak performance at the office whereas I usually had to work hard to keep up with his discussion after eight hours of work. While these overtime conversations were very taxing, they usually were very productive and will be remembered fondly.

Ye Zhou
Lawrence Livermore National Laboratory,
Livermore, CA
e-mail: zhou3@llnl.gov