Brief Narrative Career Account – David W. Zingg

I defended my Ph.D. in January of 1988 and began my career as an Assistant Professor that same month. My M.A.Sc. thesis topic involved the development of procedures for airfoil design. For my Ph.D., I studied higher-order boundary-layer approximations in the context of viscid-inviscid matching techniques for the numerical solution of aerodynamic flows. I was hired at the University of Toronto Institute for Aerospace Studies (UTIAS) to initiate research in the field of computational fluid dynamics (CFD), subsequent to an external review that determined this to be an important research area in which UTIAS was not active. For four months during the summer of 1988 I visited the world-renowned CFD Branch at the NASA Ames Research Center, where I worked with one of the pioneers of CFD, Harvard Lomax. This began a long and fruitful association with NASA that continues to this day.

My initial research concentrated on three areas, 1) accuracy issues, 2) high-accuracy finite-difference schemes, and 3) computation of flows about high-lift aerodynamic configurations. I performed several studies in order to develop a better understanding of the nature of the errors in aerodynamic computations, including both modelling and numerical errors. I also examined the mesh density requirements for a specified level of accuracy in, for example, drag prediction. This work was quite influential. I am told that it figured in the development of the editorial policy with respect to numerical error of the American Institute for Aeronautics and Astronautics (AIAA) Journal, and it is featured prominently in the influential book by Patrick Roache, *Verification and Validation in Computational Science and Engineering.*

Given the understanding gained about the mesh density requirements for well-resolved numerical solutions of the compressible Reynolds-averaged Navier-Stokes equations governing turbulent aerodynamic flows, I became interested in techniques for obtaining accurate solutions more efficiently. This led to the development of high-accuracy and optimized finite-difference schemes, which can produce accurate solutions on meshes of reduced density, thus reducing the computational effort needed. Optimized schemes are those which do not maximize order of accuracy; rather some other criterion is used to define the coefficients of the scheme. We (my graduate students and I) initially applied such schemes to Maxwell's equations governing the propagation and scattering of electromagnetic waves and demonstrated large improvements in efficiency through careful mesh refinement studies. I also developed special Runge-Kutta methods that exploit the linearity of the Maxwell equations. Later on, we applied higher-order schemes to the computation of turbulent aerodynamic flows, reducing the computing expense by a factor of four.

High-lift multi-element airfoil configurations are used for take-off and landing of aircraft. We developed an automated multi-block mesh generation technique that permits the flow about such geometries to be computed with little or no user intervention in generating the numerical mesh. This led to the development of the TORNADO high-lift flow solver which we transferred to Bombardier Aerospace. TORNADO has been repeatedly compared with other solvers and shown to rank among the best in the world for high-lift applications. It was used by Bombardier in the design of the flap system of the Q400 commuter airplane and in my group in the design of a new flap for the Found Bush Hawk, a Canadian-made light utility airplane, which greatly improved the performance of the airplane. Over the years, TORNADO has been continuously improved through various algorithmic developments.

My summer visits to NASA Ames became an annual event. Harvard Lomax taught a course called *Introduction to CFD* at Stanford University for many years which was taken by several of the world's top CFD researchers. I based my CFD course at the University of Toronto on his course notes. Eventually

Dr. Lomax asked me to work with Dr. Thomas Pulliam, also a widely-recognized CFD authority at NASA Ames, and him to write a CFD textbook based on his notes. This was a great honour which I was happy to accept. The book, which is called *Fundamentals of Computational Fluid Dynamics*, was published by Springer in 2001. It is a unique textbook in its detailed coverage of fundamentals and unifying approach to the subject and appears on the reading list for many CFD courses world-wide.

In the mid 1990's, I began to develop a Newton-Krylov algorithm for solving the nonlinear algebraic equations resulting from a spatial discretization of the Reynolds-averaged Navier-Stokes equations as an alternative to the approximate factorization algorithm developed at NASA Ames used in TORNADO. A Newton-Krylov algorithm combines an inexact-Newton strategy with a preconditioned Krylov solver for nonsymmetric linear systems. Through a series of innovative ideas, we developed a Newton-Krylov algorithm for the compressible Navier-Stokes equations that is both fast and reliable. Based primarily on the success of this work, I was invited to present a paper at a small international conference held in 2000 in honour of CFD pioneer R.W. MacCormack. Using our Newton-Krylov algorithm, we can now accurately solve for the turbulent flow field about a single-element airfoil on a desktop computer in well under a minute. This represents the state of the art in numerical analysis of aerodynamic flows.

In April 2001, I was awarded a Tier 1 Canada Research Chair in Computational Aerodynamics. Tier 1 Chairs "are awarded to experienced researchers whose peers acknowledge them as world leaders in their field."[1] I was also successful in convincing the University of Toronto to classify scientific computing as a strategic area and to form a research cluster in computational technology, which I lead. The cluster consists of seven professors and about fifty graduate students who are performing research in all aspects of computational techniques for solving problems in science and engineering. Research areas of cluster members range from blood-flow simulations to multi-disciplinary optimization in aircraft design. We were successful in obtaining a large grant from the Canada Foundation for Innovation to purchase a large Beowulf-class high-performance computer. In 2001, I also became an Associate Director of the Institute for Aerospace Studies.

With an efficient and reliable algorithm for aerodynamic analysis, such as our Newton-Krylov algorithm, it becomes feasible to consider the shape design problem in which we seek the aerodynamic shape which minimizes a specified objective function while satisfying prescribed constraints. Previously, the design of aerodynamic geometries was accomplished using CFD together with a designer's experience and intuition to determine a suitable geometry. An automated design optimization technique searches the design space and allows the designer to focus on the specification of suitable objectives and constraints. The creative human element is thus concentrated where it is most needed in the design process. Optimization techniques permit the optimal geometry for a given set of conditions to be found rapidly, thus facilitating trade-off studies and assessment of new concepts. Efficient algorithms for aerodynamic optimization are a major breakthrough. In aircraft design they are invaluable in reducing the design cycle time and can lead to safer, more efficient, greener aircraft. Furthermore CFD-based optimization can be used in many areas where fluid flow affects the design. For example, we are currently working on the design of an enclosure for a very large optical telescope that requires airflow to reduce density gradients associated with heating of the primary mirror without causing excessive wind-induced vibration.

Development of algorithms for aerodynamic optimization was an active area of research throughout the 1990's. Popular strategies include gradient-based algorithms in which the gradient is efficiently computed using an adjoint method and evolutionary algorithms which do not require gradient information. Our

[1]From the Canada Research Chairs web site.

Newton-Krylov algorithm proved to be ideally suited for gradient-based optimization. Its excellent convergence properties are an asset, and furthermore the preconditioned Krylov solver is an efficient technique for solution of the adjoint problem. As a result, we have developed one of the fastest and most reliable algorithms for aerodynamic optimization in the world. We have also worked with Dr. Thomas Pulliam at NASA to explore the trade-offs between evolutionary and gradient-based algorithms. Our research in aerodynamic optimization algorithms was included in the magazine *Aerospace America* among the highlights of 2002. The success of this research led to an invitation to give the opening keynote address at ICCFD2, the Second International Conference in CFD held in Sydney in July 2002. I have also been asked to chair ICCFD3, which will be held in Toronto in July 2004. The ICCFD series is perhaps the most prestigious international conference series in CFD.

At the present time, much of the government support available for research in Canada is tied to industrial support. Over the past 16 years, I have received considerable support from Bombardier Aerospace, Pratt & Whitney Canada, and other companies that has been matched by government funds. To the credit of these companies, this support has been for interesting research of a long-term nature. The difficulty with the current policy in Canada is that the research community is subjected to the same market cycles as industry. This is especially true in aerospace, which has always been a cyclical industry and is currently in a protracted period of poor economic performance. I currently hold two government grants that are not linked to industrial support. The Tier 1 Canada Research Chair brings $200,000 annually to the University of Toronto for seven years beginning April 1, 2001. Some of these funds contribute to my salary, and I receive $10,000 for research per year. The cluster in computational technology is also funded through my Chair, and I receive a portion of those funds for research. Finally, I hold a Discovery Grant from the Natural Sciences and Engineering Research Council of Canada of $45,000 per year (April 1, 2002 – March 31, 2006). The average such grant for my category is about $25,000 annually.

I have been very fortunate to supervise a large number of excellent graduate students, 49 over my 16-year career, 14 Ph.D. candidates and 35 M.A.Sc. candidates[2]. Many of my former students hold senior positions at Canadian aerospace companies, such as Bombardier and Pratt & Whitney, as well as other high technology companies in Canada and the USA. Two are now Assistant Professors, and two have held post-doctoral fellowships at the NASA Ames Research Center. Four of my Ph.D. graduates have been awarded the G.N. Patterson Award given annually to the top Ph.D. candidate at UTIAS.

To sum up, the following are the key milestones and accomplishments of my career to date:

- Made significant contributions in computational aerodynamics, particularly in higher-order schemes, Newton-Krylov algorithms, and optimization, that have advanced the state of the art.
- Co-authored an important and successful textbook in CFD.
- Made significant contributions to Canadian industry, primarily through the TORNADO high-lift flow solver used at Bombardier and through the design of a new flap for the Found Bush Hawk.
- Contributed to the education of 49 graduate students.
- Awarded a Tier 1 Canada Research Chair in recognition of the high quality of my research accomplishments.
- Collaborated extensively with researchers at the NASA Ames Research Center.

[2]Note that an M.A.Sc. involves a research thesis at UTIAS.