Harvard Lomax: His Quiet Legacy to Computational Fluid Dynamics

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1 Harvard Lomax: 1922-1999

Harvard Lomax, one of the pioneers of Computational Fluid Dynamics, passed away early Saturday morning May 1, 1999. Harvard, who retired in 1994 after 50 years of government service, had just turned 77 on April 18, 1999. Harvard was beloved by everyone who came in contact with him over his many years at NASA Ames Research Center, Moffett Field, CA. Harvard received his BA in Mechanical Engineering from Stanford University in 1944 and his Masters in Engineering Sciences from Stanford in 1947. He joined the staff of the then NACA in 1944 and worked from 1944 to 1970 as a Research Scientist. From 1970 to 1992, Harvard was Chief of the Computational Fluid Dynamics Branch and helped to make it the premier CFD research group in the world. From 1992 to his retirement in 1994, Harvard was a Senior Staff Scientist. [1]

Harvard worked closely with some of the early legends at NASA Ames. He was a leading contributor in the area of linearized supersonic flow theory used in the design of early transonic and supersonic aircraft. He published over 20 articles in that area, culminating with Section D, "Supersonic and Transonic Small Perturbation Theory", co-authored with Max Heaslet, which comprises nearly one third of Vol. VI, General Theory of High Speed Aerodynamics in the Princeton Series. He pioneered in making CFD an aerodynamics design tool by developing computer programs for solving inviscid supersonic flow over blunt bodies, which were disseminated to over 60 organizations.

In the early 1970's, Harvard was probably the most influential person in the budding area of Computational Fluid Dynamics. At that time, Harvard became Chief of the Computational Fluid Dynamics Branch. His creative research and leadership molded the CFD Branch into a group recognized internationally as one of the foremost in its field. The Branch made significant, innovative, and ground breaking contributions in the areas of computer languages, numerical methods, turbulence simulations, and solution to inviscid and viscous flow problems. His research in small disturbance theory, transonic flow methods, Euler and Navier-Stokes solution techniques, turbulence modeling and simulation,and parallel computing were just a few areas where Harvard made an impact, either through his own research or by mentoring, leadership, innovation and his own style of managing research by getting the most out of everyone who had contact with him. The Baldwin-Lomax turbulence model[(60)] is the most widely used and best known turbulence model in the world and is still in wide use today, a testament to his ground breaking contributions. The highly successful areas of turbulence, Full Simulation and Large Eddy Simulation, arose in those early years under his tutelage. Most of the modern flow simulation codes in existence today employ the implicit methods he helped pioneer and develop.

Fig. 1 Harvard Lomax: 1977

Numerous researchers who started their careers under this tutelage have risen to responsible positions within and outside of NASA. Alumni include many university professors and aerospace researchers and executives both in the United States and around the world. One could create a huge list of people whose professional lives he has influenced. Harvard's real

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[1] A partial list of Harvard's references is included, (1)–(19),(19)–(78)

contribution was in creating an environment and attitude conducive to basic research, and he expected that all those associated with him strive to better understand the fundamentals of their research. Harvard produced an atmosphere of both professional and friendly competition which brought out the best and most productive efforts from those who worked for him[2].

Harvard also left a legacy as a professor and teacher at Stanford University. From 1950 to 1994, he was a lecturer and consulting professor in various departments, in particular the Department of Aeronautics and Astronautics. His "Introduction to Computational Fluid Dynamics" Course trained many of the world's leading CFD researchers and is still taught at Stanford today.

Harvard was the recipient of the NASA Medal for Exceptional Scientific Achievement (1973), the AIAA Fluid and Plasma-dynamics Award (1977), an AIAA Fellow (1978), Presidential Rank Award for Meritorious Executive, Senior Executive Service (1983), an Ames Research Center Fellow (1986), received the Presidential Rank Award for Distinguished Executive, Senior Executive Service (1987), a member of the National Academy of Engineering (1987) and the Prandtl Ring recipient (1996).

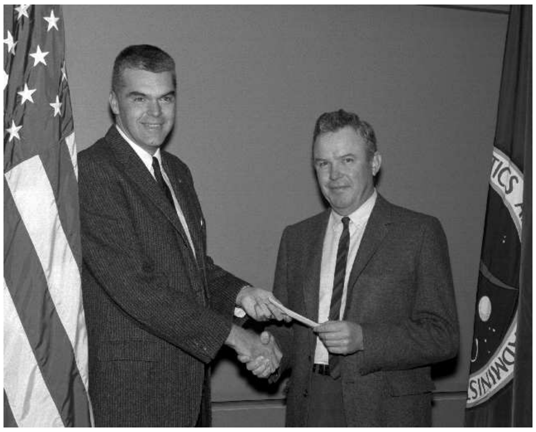

Fig. 2 Harvard receiving the NASA Medal for Exceptional Scientific Achievement from Center Director Hans Mark, 1973

In all, Harvard very successfully carried out over 50 years of research and leadership, resulting in over 80 technical papers and reports, numerous significant contributions and a legacy of high quality research, integrity and pride which will last all who knew him for the remainder of their lives. He will be sorely missed and widely remembered.

Fig. 3 Harvard receiving the Presidential Rank Award for Meritorious Executive from Center Director Clarence Syvertson, 1983

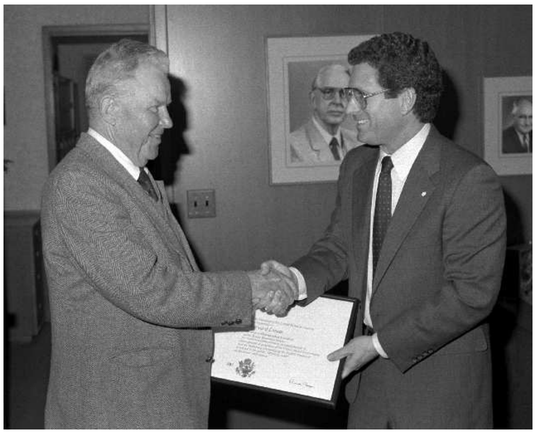

Fig. 4 Harvard receiving the Presidential Rank Award for Distinguished Executive from Center Director William Ballhaus Jr, 1987

2 Introduction: Tom Pulliam

It would be very difficult for any one person or group of people to really chronicle Harvard's life, career, and contributions. In fact, Harvard was a very private person, modest in a sense, and prone to discount his contributions. There are many interesting stories and anecdotes attributed to Harvard[3]. He had worked for many years under some very demanding individuals, who had strict policies and work habits[4], which Harvard adhered to. He would come to work every day at 6:00AM, take off his suit jacket and put on a tattered sweater[5], and in later days (to avoid the increasing

[2] It is an indication of the high esteem in whichNASA Ames management held Harvard that one of Dean Chapman's last acts before retiring as Director of Aeronautics was to promote Harvard to the Senior Executive Service, making him the only SES Branch Chief in all of government service.

[3] When Harvard was asked on numerous occasions what the qualifications were for being a Branch Chief, he would respond, "Only someone who doesn't want the job should get it."

[4] Harvard would often relate stories from his time working under Max Heaslet. "Heaslet was a strict disciplinarian, we had only one phone in the branch hallway and if it rang, Heaslet would stick his head out of the door to see who answered it and then stared them down until the retreated to their office

[5] One incarnation of his sweater was still hanging in his old office until last year

traffic) promptly leave at 4:10PM. The cars he drove always stimulated comments from his co-workers. The yellow Opel he drove for many years was a landmark in the parking lot of Building 202A[6].

Harvard had four major passions: his family (which always came first), his research at Ames, teaching at Stanford, and golf at the Stanford Golf Course[7].

Fig. 5 Harvard and some of his golfing buddies

The authors have decided to attempt to present a synopsis of his career as viewed from their own perspectives and interactions with Harvard during his tenure at NASA Ames. We therefore present three disjoint dialogs on Harvard which I will attempt to integrate. There are also many others who could and would have observations, anecdotes, and comments on Harvard and his career and therefore, we apologize for anything we may have overlooked or missed. We also apologize for any misinformation, oversights in referencing people and events, and general inaccuracies.

Unfortunately, it would be very difficult to delve deeply into technical details of Harvard's research and I only attempt it in a very rudimentary fashion. We have included, as a reference, as complete a list of Harvard's publications as we could compile.

3 Harvard's Background: Joan Lomax

Harvard Lomax came to California in 1940 from Broken Bow, Nebraska at the invitation of his Aunt Edith Stephenson who had encouraged him to apply to Stanford. Harvard graduated from high school in 1940, as class valedictorian. At his aunt's invitaion he made her San Francisco home his "headquarters". His ambition at that point was vauge, "To become a writer!". Aunt Edith was a very practical, sensible person; she made appointments for vocational guidence testing to learn where his real talent lay. His test scores were very high in mathematics. It must have been an accurate analysis for he not only excelled in Stanford math courses, but absolutely loved them.

I met him at Stanford as a conscientious student, most appreciative of the Stanford education his aunt made possible. He was soon earning scholarships and eventually Phi Beta Kappa. I laugh to recall his course in machine shop, probably required for an aeronautical degree at that time. Harvard got a warning notice in that course. His manual dexterity was never very good.

He and other graduate engineers were put into the Navy and assigned to Moffett Field as engineers, had some sort of boot camp and wore sailor suits for six weeks. At the end of World War II, he had become a Navy lieutenant and afterward stayed on at NACA. We were married December 31, 1943.

Fig. 6 Harvard with his wife Joan, 1944

4 Early Years: Vernon Rossow

Harvard began his career with the NACA Ames Aeronautical Laboratory in 1944 as a Research Scientist in the 16-Foot High Speed Wind Tunnel, which could reach test section velocities very near mach one. In the mid-1950's, the tunnel was converted to the 14- by 14-foot transonic wind tunnel. It was soon recognized that Harvard had significant theoretical ability. In order to better utilize his talents, he was transferred to the Theoretical Aerodynamics Branch and began a very fruitful collaboration with Dr. Max Heaslet on a wide variety of aerodynamic problems. In addition to his work with Max, he also developed a variety of

[6] This model of the Opel had the disturbing feature of a passenger seat switch for the enforcement of seat belt use. The mechanism broke at one time, making it impossible for someone to sit in the passenger seat while Harvard drove. It was not uncommon to see Harvard chauffeuring 2 or 3 passengers stuffed into his back seat.

[7] At one time some of the more energetic students in the CFD Branch tallied the total mileage on Harvard's car and compared that with the Lomax triangle distance, i.e. the travel distance between Harvard's home, NASA Ames and Stanford. The story has it that the two numbers were in equilibrium

Fig. 7 Left to right: Harvey Allen, Max Heaslet, Walter Vincenti, Max's wife, and Milton Van Dyke at Heaslet Retirement, 1967

theoretical tools for aerodynamicists on his own. Of these theoretical research efforts, the one that proved most valuable to the aircraft industry, and that won him considerable recognition, was his development of a method for the determination and minimization of the wave drag of arbitrary aircraft configurations in the high subsonic and low supersonic velocity ranges. His method was a significant extension of Richard Whitcomb's area-rule theory at transonic speeds in two ways. First, Harvard's method made it possible to design aircraft for minimum wave drag on the basis of design parameters that included both volume and lift distributions, and, secondly, his method made it possible to do the evaluations and optimizations at Mach numbers other than one.

The method was adopted by all of the major aircraft companies of the time for the design of high-speed aircraft, military and commercial. This research was the primary basis for his recommendation (by Glen Goodwin of Ames in 1977) and promotion to the level of Fellow of the AIAA in 1978.

The wave-drag mathematical technique developed by Harvard for the minimization of the wave drag of aircraft configurations at speeds from high subsonic to well into supersonic Mach numbers involved a large number of computations, which were first carried out on electro-mechanical computers, which was very tedious. Harvard was well aware of the efforts at Ames Aeronautical Laboratory to develop a numerical computation capability through the use of automated electronic digital computers. The intended uses were aircraft dynamics, data reduction for wind tunnels, and possibly to expedite aerodynamic analyses in progress here at Ames. Harvard recognized the possibilities available if theoretical aerodynamics and high speed computing machines could be utilized. Therefore, early in his studies Harvard expanded the application of his new theory by adapting his theoretical method to the electronic computers available at Ames, which greatly improved the usefulness of his method. From that time onward, Harvard's endeavors were more and more closely tied to the use of digital electronic computers for the solution of a wide variety of aerodynamic problems.

In the late 1950's, an IBM 650 came to Ames to be used primarily to reduce data obtained with the Unitary Wind Tunnel, but other researchers could use the machine while the wind tunnels were preparing for tests. Harvard, and a few others at Ames, wrote programs in machine language to generate numbers for various theoretical analyses in order to expedite that research. At the time, the machines were devoted to grinding out numbers for analytical solutions to aerodynamic problems that often required a large number of iterations, and not to numerical analysis for directly solving differential equations for flow fields; e.g., finite-difference solutions. When the IBM 704 (the last tube computer we had here) arrived at Ames just before 1960, Harvard taught a class of prospective users how to program for the machine in the ABC language. A number of us then found out that Harvard was a really good teacher as the class was outstandingly good. Harvard taught the course because he had stayed at the forefront on the use of electronic computers for the solution of aerodynamic problems. Several years later, the transition was made to transistor-type computers and FORTRAN.

Around 1960, Milton Van Dyke introduced a finite-difference numerical method for the solution of the blunt-body problem. Harvard then applied his computer skills to the development of automated computation on electronic computers. He also extended the method to include the supersonic flowfield downstream of the blunt body region. Since knowledge of the flow fields of blunt-nosed bodies was crucial for the development of intercontinental ballistic missiles, and many supersonic vehicles, Harvard led the development of computer codes that accurately solved the differential equations for a wide variety of configurations. These codes were widely distributed in the United States, and became noted for their accuracy.

In the early 1960's, Robert Crane, the organizational director for aeronautics at Ames, recognized the importance of computational tools for the solution of problems in aeronautics. On the basis of past successes by Harvard's group, Bob Crane used the Center's research funds to purchase a high-speed electronic computer (IBM 1401) that was dedicated to Harvard's group within the Theoretical Aerodynamics Branch at Ames. With full-time access to a computer, the productivity and size of the group increased rapidly. It also became Center policy to cycle researchers from other Branches at the Center through Harvard's group so that they could learn the new computational technologies being developed. Having learned the new techniques, they would return to their former Branches to utilize the new knowledge. This interactive exercise had a very large and favorable affect on the theoretical and computational capabilities of all of Ames Research Center. In 1970, it was decided to form a Computational Fluid Dynamics Branch at Ames, and Harvard was appointed Branch Chief, with Robert MacCormack and Mamoru Inouye as assistant chiefs. Thereafter, the Branch grew rapidly in size and in reputation.

5 The Intermediate Years (1968-1980): Paul Kutler

A work-study program was conceived and established by Vernon Rossow between NASA Ames Research Center and Iowa State University, in the late 1960's. That program enabled graduate students having completed all of the requirements for their Ph.D. (except the research for and writing of their dissertation) to work at NASA Ames under the tutelage of Ames scientists. Vernon Rossow was the Assistant Branch Chief of the Theoretical Branch within the Thermal and Gas-Dynamics Division at that time.

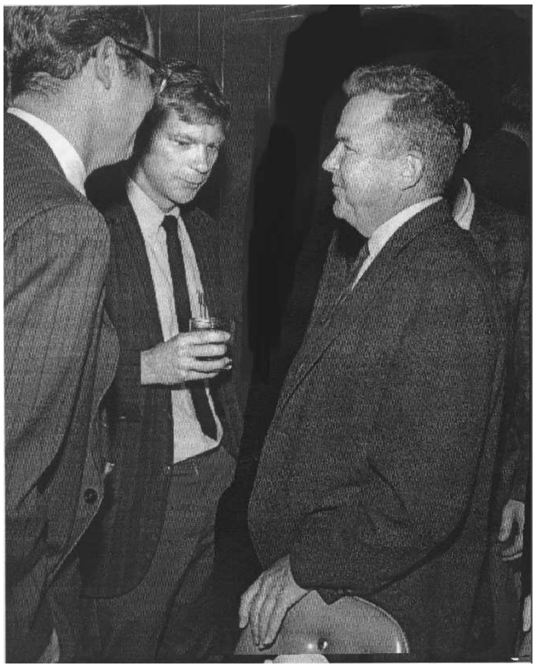

Fig. 8 Left to right: Joe Steger, Ron Bailey and Harvard at Frank Fullers Retirement, 1970

Joseph L. Steger and Paul Kutler were the first two graduate students to participate in the program and began their research at Ames in the Fall of 1968[8]. A variety of research topics were available for them. The topic that interested them most was the numerical solution of the equations describing fluid flows (later termed Computational Fluid Dynamics (CFD)), and the Ames scientist that led the effort was Harvard Lomax. Lomax's research, at the time, was focussed on development and analysis of algorithms for solving the gas-dynamic equations. This stemmed from his previous research mentioned earlier in this paper. He was also interested in the application of that technology to problems of practical importance to NASA's mission in aeronautics and space. Thus, it was a perfect fit for the two graduate students from Iowa State. Other NASA scientists on Harvard's team included Margaret Covert, Jean Hyett and Yvonne Scheaffer [9]. A number of converted aerodynamicists trained for fluid dynamics and structures were also included, notably Harry E. Bailey, Richard Beam and Robert Warming.

Two aeronautics problems of importance at that time were the transonic airfoil problem and the sonic boom problem. No one had been able to develop a procedure for numerically solving the transonic flow problem because of the sonic point difficulty. Steger and Lomax were interested in developing an algorithm for doing this that offered fast convergence compared to existing time-dependent procedures.

During this period, the airframe manufacturers in this country were embarked on the design of a supersonic transport. One of the environmental problems associated with that aircraft dealt with the sonic boom. The accurate prediction of the shock waves generated by such a vehicle and their propagation to the ground could be used to help improve the design to minimize the effects of the sonic boom. This was a good supersonic application of the algorithm technology that Lomax and others (e.g., Robert MacCormack) were developing. The flows contained discontinuities, such as shock waves and slip surfaces, that would test the algorithms ability to predict or "capture" them. Hence the evolution of the term "shock-capturing" [10]. Kutler, whose Master's Thesis involved supersonic blunt body flows solved using the method of lines, applied a variety of algorithms to pedagogical problems involving discontinuities.

Lomax and MacCormack, working in two different

[8]Searching the Horizon,[79] page 174, "In 1970, after chairing a committee to define the future computer needs at Ames, (Dean) Chapman created the Computational Fluid Dynamics Branch, using as a core the old Theoretical Branch. Harvard Lomax became chief, assisted by Robert MacCormack. Those two, plus two graduate students (probably Joe and Paul), had been the only researchers who could claim to be involved in computational fluid dynamics. Chapman's immediate task was to enlarge this cadre." Harvard Lomax was an integral part of this effort. His reputation and experience in this area of research soon attracted a large group of both converted aerodynamicists and fresh out students from various universities.

[9]During Harvard's years of theoretical work and initial computational efforts, he developed a large group of "computors"', mainly women who applied calculating machines (e.g. Monroe's) to the long list of number crunching tables. Harvard quickly converted these researchers over to the use of electronic computers.

[10]In fact, the concept of "shock capturing" developed into a rather controversial rivalry between the researchers at Ames and their counterparts at NASA Langley (notably Gino Morretti). Harvard was a staunch supporter of the Ames philosophy and didn't back off from such scientific battles.

branches at NASA, were both working on the numerical solution of the gas-dynamic equations. The senior management at Ames, Hans Mark and Dean Chapman, saw the potential of the discipline based on the recent accomplishments of Lomax, MacCormack, et al. and made a strategic decision to enter this new field. It was felt by them that computers offered far more potential for modeling flows about aerospace vehicles than wind tunnels. The Ames senior management believed that for any research program to be successful, it required three key elements. Those included, talented people, world-class facilities and a good working environment.

As a result of that vision and senior management principles, the Computational Fluid Dynamics (CFD) Branch was formed with Lomax as the Chief and MacCormack and Inouye as the Assistant Chiefs. Kutler and Steger were the other two "CFD'ers" that were charter members of the branch. Others, that had the necessary mathematical background and interest in the new challenge, were added to the branch. For this group to be successful, it was necessary to make available to them the latest in computing technology.

In the latter part of the 60's, Lomax had for his computing requirement an IBM 7094. He also had an IBM 1800 that was linked with an IBM 2250 cathode ray display tube. For input, it utilized an alphanumeric key board, function pad and light pen. The 7094 high-speed processor and 1800 were not linked. The 1800/2250 capability was used to display the numerical solutions. The system software necessary to display the numerical solutions was written by Lomax and his programming team[11]. The solutions generated could be stored on disk or 16mm film for later playback. Color film images were obtained by pasting color gels over the blue-light cathode-ray tube.

Since the 1800 was a rather slow machine and the equations being solved were somewhat complicated, solutions generated on this machine took hours to produce. But the results obtained vividly demonstrated an algorithm's capabilities. Instabilities could be observed and the appropriate action taken to eliminate them. The use of computer graphics clearly resulted in a substantial savings in person hours by providing a real-time observation of the solution being generated. It eliminated the time-consuming process of plotting data from paper output. A week's work could be accomplished in a matter of hours using this capability.

There is always a computing bottleneck when generating CFD solutions. In this case, it was the high-speed processor. The IBM 7094 was eventually replaced with an IBM 360/50 and subsequently an IBM 360/67. These machines were directly connected to the IBM 1800, and thus this computing bottleneck was eliminated. Grid sizes could be enlarged and numerical solutions could be generated in a matter of minutes. As the discipline began to prove successful, additional computing capability was added.

In the early 70's Ames obtained a CDC 7600. It served as the main Ames computer until 1976. The one disadvantage of the 7600 was that it could not be linked to an on-line graphics terminal, and the scientists were back to plotting their results from paper output. Ames acquired the Illiac IV in 1972; it became reliably operational in 1976.[(79)] It was 300 times faster than the IBM 7094. This machine established Ames as the center for computational fluid dynamics within the agency and possibly the country.

This computing capability enabled more complicated problems to be solved. These included transonic airfoils, wings and wing-body combinations, supersonic wedges, cones and conical wing body combinations, spherical and indented blunt bodies and flows about approximated space shuttle configurations. Additional scientists, such as Ron Bailey, Bill Ballhaus, E. Dale Martin, G. Steve Deiwert, Unmeel Mehta, Ching Mao Hung and later Terry Holst and Tom Pulliam, joined the Branch to further expand the algorithm development and demonstration capability of CFD.

Lomax's CFD Branch was very successful at developing algorithms and demonstrating them on pedagogical problems. What was lacking was the practical application of that technology to problems in aerodynamic design. Therefore, in 1978, the Applied Computational Aerodynamics Branch was formed in the Thermo- and Gas Dynamics Division with Bill Ballhaus as the Branch Chief. This Branch was to develop user-oriented computer codes for solving such problems. It bridged the gap between the fundamental technology developed in Lomax's CFD Branch and the design codes required by the aerospace industry.

The demonstrated success of CFD and the demand for solving more complicated problems dictated the need for more computing capability. Thus was conceived in Lomax's Branch the idea for the Numerical Aerodynamic Simulation Facility. It would contain a computing machine capable of providing one billion floating point operations per second. The proposal was presented and accepted by NASA Headquarters in 1979. Two contracts were awarded in 1980 to Burroughs Corporation and Control Data Corporation to build such a computer. As the project progressed, the strategy changed from building a special purpose machine to purchasing a first-off-the-line, production supercomputer. This approach resulted in a series of Cray supercomputers that provided cycles for a variety of problems in fluid flow, meteorology, gas dynamics and computational chemistry.

[11] MacCormack in his paper "A Perspective on a Quarter Century of CFD Research"[(80)] states that: He (Lomax) once quickly stopped aimless speculation at a meeting by softly saying, "You don't understand it unless you can program it".

6 Harvard's Legacy "The Numerical Wind Tunnel": Tom Pulliam

By 1974[12], the CFD Branch was a fully functioning research group making initial breakthroughs in algorithms and applications. I had the great good fortune to work closely with Harvard. He was both a mentor and a friend through over 25 years of my career, which is just half of Harvard's total service.

Harvard's career at Ames spanned 5 decades and a radical change in the way aerodynamic research is performed. A close look at his early research and publications shows that he had a keen mind for theory and the application of mathematics to the practical solution of problems in aerodynamics. The development of linearized transonic and supersonic theory which culminated with Section D of Volume VI, General Theory of High Speed Aerodynamics in the Princeton Series, "Supersonic and Transonic Small Perturbation Theory", co-authored with Max Heaslet,(19) demonstrated his ability to perform analytical research and development. That work became the standard, including being the basis of aerodynamic theory taught at many of the major engineering universities in the world. Where Harvard transcended his contemporaries was in his ability to transition into the use of computational tools applied to the pertinent problems of the day. As mentioned above by Vernon Rossow, Harvard quickly became the local expert in the use of the new numerical techniques, both in terms of the theory and application (to the point where he was teaching programming).[13]

In October 1969, Harvard presented a paper at the Symposium for Analytic Methods in Aircraft Aerodynamics, held at NASA Ames, entitled "An Analysis of Finite-Difference Techniques Applied to Equations Governing Convective Transfer".(44) This began a series of survey papers: in 1975 at the AIAA 2^{nd} CFD meeting in Hartford, Conn. on "Recent Progress in Numerical Techniques for Flow Simulation";(58) in 1981 at the AIAA 5^{th} Computational Fluid Dynamics Conference, Palo Alto, CA on "Some Prospects for the Future of Computational Fluid Dynamics";(61) and finally in 1991 at the AIAA 10^{th} Computational Fluid Dynamics Conference Honolulu, HI on "CFD in the 1980's From One Point of View".(73) In each of these papers, Harvard set the standards and ignited the imagination of those of us who were inspired to perform research in CFD.

In the 1969 paper,(44) Harvard introduces his simplified approach to analysis and design of numerical algorithms, which he taught at Stanford in the Aeronautics and Astronautics Department over the next 25 years. It is based on linear matrix analysis, where a consistent development from PDE to ODE to OΔE (Ordinary Difference Equation) is employed. MacCormack's method is highlighted here, is contrasted with the (at the time popular) Lax-Wendroff method and is even demonstrated for a 3D conical flow problem. In this work, Harvard demonstrated his ability to develop a mathematical approach to CFD which didn't overwhelm one with complicated mathematical proofs or analysis, but at the same time produced an approach and understanding which could easily be applied by the new crop of aerodynamicists, or engineers turned CFD'ers.

Also of note in this 1969 paper are the comments and responses to Harvard opening remarks, "A survey of the presentations made at this conference points clearly to the fact that the development of numerical wind tunnels for practical airplane shapes is emerging as a reality." The paper includes a transcript of the post-paper discussion, in which some noted aerodynamicists of the day (Raymond Sedney of the Martin Company and Peter Lissaman of Northrop Corp.) took issue with this rather provocative statement.[14] Now while the management at Ames was pushing this concept to the point of controversy, one can see in Harvard's responses a sense of realism, which coming from him help lend some credibility to such (at the time) wild statements.

As a result of the impressive strides made by researchers (in particular, at NASA Ames) in the discipline of computational fluid dynamics the article "Computers vs. Wind Tunnels" was written by Chapman, Mark, and Pirtle of NASA Ames in 1975.(81) They stated that, "Because within a decade computers should begin to supplant wind tunnels in the aerodynamic design and testing process, the nation needs integrated planning of both to acquire the most effective overall capability for the 1980's and beyond", proclaiming that the computer would eventually replace the wind tunnel. It caused a furor by the experimentalists and generated an unbelievable challenge for the CFD'ers.

Harvard Lomax was given the task of making this bold statement come true and was given the resources both in terms of manpower and facilities to accomplish it.

In 1975, Harvard summarizes the state of CFD research in the leadoff paper at the 2^{nd} AIAA CFD Conference, entitled, "Recent Progress in Numerical

[12] I first joined the CFD Branch in 1974 as a graduate student from Stanford University Applied Mechanics Department.

[13] This is not surprising to us self styled hot shot programmers. My experiences programming with Harvard revealed a well organized and sophisticated capability. In programming for the Illiac IV, we had to map the data structure to the rotating disk. Harvard produced an efficient and practical mapping scheme using offset blocks and a pencil data base system(65) which comes up periodically as an option for current day parallel computation.

[14] Raymond Sedney starts out his comments by saying, "I hate to in any sense detract from the interesting material you presented, but I have to raise a strong objection to the rather provocative opening statement about numerical wind tunnels being on the verge of appearing."

Techniques for Flow Simulation". In this paper, he introduces a number of the emerging techniques being developed in his group and around the world: higher order methods (e.g. Pade schemes), direct solution methods, splitting schemes (e.g. Beam-Warming approximate factorization), and pseudo-spectral methods. He states his philosophy on the use of numerical algorithms, (which is indicative of his own approach), "the author believes that the use and understanding of sophisticated numerical algorithms should become as natural to the physicist as are the use and understanding of calculus." He also introduces in this paper, the concept of alternative (to FORTRAN) programming languages and formats. He discusses matrix notation and language constructs which were novel concepts at that time[15].

By the end of 1978, the group Harvard had put together was making enormous strides in both the development and application of CFD to realistic aerodynamic problems. Beam and Warming had developed an approach to solving the Euler and Navier-Stokes equations which rivaled MacCormack's algorithm (the main workhorse at the time). F. Ron Bailey and William Ballhaus Jr had performed landmark transonic full potential wing computations. Joseph L. Steger, under Harvard's guidance and tutelage, had carried these ideas forward by creating some of the first practical computer codes for the solution of flow past airfoils and wings. The Baldwin-Lomax turbulence model[(60)] was developed in this time frame and went on to become the standard model for CFD development and application. As a result of Harvard's efforts and the group's successes, there was a rapid growth in the development of numerical methods and codes for the solution of the Euler and Navier-Stokes equations. The CFD branch was growing rapidly, adding young PhD students from various Universities (which had began developing academic programs in response to the successes of Harvard's efforts and the demands of the aerospace and aircraft industry). Ames became a world class center for CFD research, development and application under the guidance and scientific leadership of Harvard Lomax.

There were two major advances in the late 1970's into the early 1980's which had a fundamental impact on CFD research. One was the area of parallel computing and the other was the emergence of turbulence research. In both of these areas Lomax played a key role either through his own research or though his management and scientific leadership.

In 1972 the prototype parallel computer the Illiac IV arrived at NASA Ames[16]. Even though the hardware eventually became somewhat reliable[17], it's lack of user-friendly software required users to develop a whole new set of tools to use the machine. Harvard assembled a talented group to deal with this problem, (notable in this group are Robert Rogallo, Ken Stevens and Alan Wray), even to the point of developing an extension to FORTRAN (called CFD) for parallel constructs. Harvard also developed new techniques (employing a pencil data mapping system[(65)]) to map the large computational data sets onto the limited memory of the processors. These were truly the early days of parallel processing and Harvard was at the forefront of the developments. He had grown up on the low memory IBM's and had to learn to shoehorn large problems onto those machines. Those lessons were not lost on Harvard and he used that experience to get the most out of the resources given to him.

At the same time that the Illiac IV was just becoming useful, a bright young group of graduate students under the guidance of Stanford Professors Bill Reynolds and Joel Ferziger joined Harvard's group at Ames. Armed with the power of the Illiac IV, the new research area of full simulation and large eddy simulation took hold and became powerful tools for understanding the fundamentals of turbulence. It was in this environment that Parviz Moin and John Kim made their detailed simulation of turbulent flow in a channel at a Reynolds number of 13800[18]. The success of the program of turbulence research started under Harvard's leadership lead to the creation of the Center for Turbulence Research, arguably the leading turbulence research group in the world.

In the 1981 AIAA 5^{th} CFD Conference,[(61)] Harvard summarizes the state of CFD research with the paper, "Some Prospects for the Future of Computational Fluid Dynamics". Here he encapsulates the state of the art and projects the future direction of CFD research. He clearly and prophetically identifies characteristic flux-splitting methods, multigrid techniques and zonal methods as the new and promising directions for CFD.

These early accomplishments in CFD and parallel

[15] An outgrowth of these ground-breaking ideas was a type and form of programming for the Illiac IV which made it possible to produce some of the first successful parallel codes for CFD.

[16] The Illiac IV was a 64 processor parallel computer. It was capable of performing SIMD or MIMD operations, but was usually used in SIMD mode. It had limited internal distributed memory 2048, 64-bit words per processor, and required data mapping from a large rotating drum 7 million word disk system.

[17] In the early days, the Illiac IV hardware was notoriously unstable. It was not unheard of for users to run two to four jobs in parallel partitions of the machine, periodically checkpointing the results to see if hardware errors occurred. If errors occured, the machine was taking down for a round of re-soldering connections.

[18] Harvard states in his 1991 review paper, "When the results (Moin and Kim) were presented in the form of moving pictures showing the computed path of particles in a turbulent flow, the majority of the viewing experimentalists could immediately identify with their own experimental observations and lost their skepticism about the potential power of computers to make fundamental contributions to their research." This turned out to be a milestone in turbulence research.

computing were just what the management at Ames had wanted. Armed with these results, they successfully advocated for the formation of the National Aerodynamic Simulation Facility (NAS), which was created as a pathfinder in the development and utilization of "supercomputers" to realize Chapman, Mark and Pirtle's dream. NAS formally came into existence in 1979 and was centered around the work of the CFD Branch under Harvard's leadership. As a series of CRAY computers arrived at Ames, the focus shifted to vectorized computation. The CFD Branch and its spinoff group, the Applied Aerodynamic Branch, continued the development and application of numerical algorithms to fluid dynamic and aerodynamic problems. The focus has now shifted back to parallel architectures, but the ground- breaking work of Lomax and the CFD Branch still influences present day codes and applications. Finally in 1991, leading off the AIAA 10^{th} CFD Conference(73) with "CFD in the 1980's From One Point of View", Harvard traces the advances in algorithms and turbulence research over the ensuing decade. At this time, Harvard gives us his views on a future where unstructured mesh methods and computational turbulence research are the leading research areas, something which has come to pass.

7 Harvard Lomax

There are many more things one can say about Harvard's life and career. He was truly a unique individual and had many contributions which cannot be measured just by papers and accomplishments. He touched all who had contact with him either directly through his contribution to their careers or indirectly through his leadership in research and science[19].

Throughout the last 25 years of Harvard's career in CFD there had been a recurring theme, "The Numerical Wind Tunnel". Although it was originally received with much controversy and skepticism, most of the research community has grown to accept this concept. Harvard Lomax had a profound impact on that acceptance; through his scientific leadership and his quiet approach to CFD development and research, he has left us the legacy of "The Numerical Wind Tunnel".

He will be sorely missed and widely remembered.

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[19]MacCormack(80) says of Lomax: "As Chief of the CFD Branch at Ames for more than two decades, he led a star studded group of scientific talent and was an excellent mentor to new employees by giving them their initial directions in research. The key was that he gave his employees room to maneuver in the creative environment he provided and did not subject them to our own limitations on how to proceed."

Fig. 9 Harvard Standing in Front of the Connection Machine, a 64,000 Processor Supercomputer, 1992

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