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# Guest Editorial

## History of Multibody Dynamics in the U.S.

The following is the story of the growth of the technology now called multibody dynamics. However, more than that, it is the story of the times and some of the people who allowed that technology to develop.

The story starts in 1952 with a new graduate student from France arriving at the Northwestern University with the intent of obtaining graduate degrees in electrical engineering. His name was Jacques Denavit. Although he had originally hoped to do research on some microwave project, like many others, he found it necessary to seek financial support and he was guided to approach Professor Richard S. Hartenberg in the mechanical engineering department. From this first meeting grew a lifelong friendship during which Denavit received both his M.S. and his Ph.D. degrees in ME, the world received several seminal papers and a historic book, and a new notation and a transformation matrix analysis method were introduced which opened the door to the systematic description, and the kinematic and dynamic analyses of three-dimensional, articulated, rigid-body systems. After a short delay to serve a requirement in the French military, Denavit returned to join the ME faculty at the Northwestern University.

In 1960, Professor Denavit and Professor Hartenberg were awarded the first NSF research grant in the field of kinematics. The goal of this grant was to advance the Denavit–Hartenberg notation and to study how this could be developed into a numerical analysis tool for use with digital computers. Fortunately, in the summer of 1961, Northwestern University acquired an IBM 709 digital computer (the last of the large vacuum tube computers) from the Boeing airplane company as Boeing upgraded to an IBM 7094 system (the first of the new transistorized computers). This IBM 709 system had an amazing 32,768 words (128 kb) of 32-bit RAM memory and was programed by punched cards in the new FORTRAN II language; it was an amazing machine for its day, but really not as powerful as today's hand calculators. Still, it was far ahead of the IBM 650 system which it replaced.

Also, another new graduate student, John J. Uicker, arrived in the fall of 1961, who knew nothing of computers or of matrix algebra. However, during the next 4 years he overcame both of these shortcomings and he had general computer programs operating for displacement, velocity, acceleration, static force, and dynamic force analysis, as well as small amplitude vibration analysis of rigid-body systems. One might say that these were among the initial roots of numerical multibody dynamics. Also, during that 4-year span, Uicker met two more people who are important to the continuation of our story. First, Denavit learned of another young student by the name of Milton A. Chace who was pursuing very parallel research for his graduate degrees under Professor Joseph Shigley at the University of Michigan. Chace visited Northwestern for a few days, and he and Uicker became the best of personal friends and also the strongest of professional rivals, each determined to prove that his approach was superior, Chace with vector algebra and Uicker with matrix algebra. The other meeting of importance was with Professor Donald F. Livermore of the University of Wisconsin faculty, who came to the Northwestern University to complete his Ph.D. under Professor Denavit and Professors Hartenberg, and who extended the matrix method to include the search for static equilibrium on systems of the complexity of automobile suspensions. Uicker and Livermore shared an office and worked together in the programing of this equilibrium search software, becoming very close friends.

In 1964, Chace completed his doctoral degree at the University of Michigan and joined a group within IBM Corporation in Rochester, MN, which was releasing the first general software for the analysis of three-dimensional rigid-body devices. The program was based on Chace's M.S. thesis and was named Kinematic Analysis Method (KAM). However, in 1967, Chace left that position with IBM and joined the faculty at the University of Michigan.

In the spring of 1965, Livermore completed his Ph.D. degree at Northwestern and returned to his position on the ME faculty at the University of Wisconsin. A few months later, Uicker completed his Ph.D. degree and began to serve 2 years at the Frankford Arsenal in Philadelphia as Captain in the U.S. Army, an obligation resulting from an earlier ROTC commitment. At the end of his military tour, after interviewing a number of universities, Uicker began his 40-year career on the ME faculty of the University of Wisconsin. Part of his reason for this choice was to join his colleague, Livermore, with the hope of many years of joint research. Unfortunately, this was cut short when Livermore succumbed to ALS disease a few years later.

Still, Uicker arrived on the Madison, Wisconsin campus in the fall of 1967 to be joined by a very bright young Indian graduate student whom Livermore had already indoctrinated in the matrix method. His name was Pradip N. Sheth. He completed his M.S. degree with Livermore in 1968 and joined Uicker for his doctoral work which he completed in 1972. It was Sheth's M.S. thesis which first suggested the concept of generalized coordinate partitioning which was later more fully expanded in the doctoral research of Dr. Roger A. Wehage.

Sometime in 1968, Uicker and Livermore realized that they were in desperate need of an industrial contact who could help them to pose meaningful problems, help them to obtain accurate data, and provide them with a basis for comparison of attempted solutions. Uicker approached another University of Wisconsin colleague, Professor Phillip S. Myers, who had a long-standing reputation with the automotive industry for his research on IC engines, and was the newly elected chair of the worldwide Society of Automotive Engineers (SAE), and asked how he could make a contact within Ford or General Motors Corporation Myers asked which and, without even looking up a number, dialed the telephone. The following week, Uicker was in an office in Detroit, talking with the Vice-President of Ford Motor Company about his research vision. That meeting led to many years of cooperative research. Pradip Sheth spent the following summer of 1968 working with Ford, and Uicker did the same in the summer of 1969.

Now, at that time, there were no PC's or desktop workstations. All the computers were large mainframes and all the computing required financial payment; every addition or multiplication, every character read, and every character printed had a charge

attached. Since Uicker and Sheth were still waiting for a reply to their proposal to NSF, they had no access to the financial resources necessary to continue their research. Fortunately, they were successful with a smaller proposal that Ford Motor Company allowed them full access to the interactive Ford Philco 212 computer, communicating via a teletype over long-distance telephone lines, and that, in trade for the software developed, Ford would somehow forget to send the billing at the end of each month. In this way, Ford was assured access to working software, while Uicker and Sheth had access to excellent computing facilities.

While still waiting for a response to their NSF proposal, Uicker and Sheth worked feverishly to program their first software system for generalized analysis of articulated multibody dynamic systems. This software was named the Integrated Mechanisms Program (IMP), and the first version was operational in 1972. Starting from an MIT report on an early computer graphics project titled SKETCHPAD, they developed a hierarchical data structure and the problem-oriented IMP language, while programing entirely in FORTRAN IV. The system was far beyond anything else of its type at that time, and more modern, C-language versions of IMP are still available to this day, now on the web as open source code. The initial Uicker NSF proposal was finally approved in 1972, at about the time that Sheth was completing the first version of IMP, and Sheth's prodigious effort resulted in a 572-page doctoral dissertation. Hundreds of copies of that thesis were disseminated throughout the U.S. by the University Microfilms Corporation.

Ford was very pleased with the progress being made on the IMP program and wanted very much to employ Sheth upon the completion of his doctorate. In fact, Sheth had a letter containing a very generous offer of employment which he fully expected to accept. Unfortunately, in 1972 the U.S. economy went into a difficult period and Boeing, among other U.S. companies, was required to make significant layoffs. When Sheth sought a work permit and the U.S. Labor Department found that Ford wanted to hire an Indian national, rather than an unemployed American, significant pressure was brought to bear on Ford to change their mind. Unfortunately, no other U.S. citizen, except for Uicker, fully understood IMP, and Uicker was not moving. To make the best of the situation, Ford withdrew their fine offer to Sheth. However, in its place, they offered to fully finance Sheth to do a postdoctoral research at the University of Michigan, along with Uicker's arch-rival, Professor Milton Chace!

At Michigan, Chace had early success in attracting funding and had put together a strong research team. In fact, they had completed a two-dimensional software system, first named Dynamic Analysis of Mechanical Networks (DAMN), but later renamed Dynamic Response of Articulated Machinery (DRAM), which was completed as a part of the research of Dr. Donald A. Smith, who then joined the faculty of the University of Wyoming. This program was complete and already being marketed, and development had commenced on the three-dimensional successor system which later became known as Automatic Dynamic Analysis of Mechanical Systems (ADAMS). When Sheth arrived at Michigan in 1972, this research was well along under a doctoral researcher named Nicolae Orlandea. The ADAMS system was completed and first marketed in 1973 by a new company, formed by Chace and his former students, named Mechanical Dynamics, Inc. (MDI).

When Sheth finished his work at Michigan, he joined the Research and Development Department of Allis-Chalmers Corporation and, several years later, joined the Mechanical Engineering faculty of the University of Virginia. He passed away in 2009.

After finishing his doctorate, Dr. Orlandea joined the Deere Company from which he has recently retired.

Uicker was awarded an ASEE fellowship for a residency in engineering practice and spent the academic year 1973–1974 at the Ford Motor Company. His position was set up to help engineers throughout the Ford Company to learn and make effective use of IMP. Simultaneously, Uicker was awarded a follow-on NSF grant to distribute IMP to any American company and/or university who wished to receive a copy. With their feedback, IMP became more easily used and grew more robust and was widely used in many applications. At the end of 1974, Uicker received a letter from a Ford manager stating that IMP had saved over 10,000 man-months of drafting board time in the design of new vehicle front suspensions.

As Uicker prepared to return to academia, Ford introduced him to the Dr. Jason Lemon, president of Structural Dynamics Research Corporation (SDRC), and suggested that they could provide the ongoing software training and support that industry needs and that an academic cannot provide. Thus, a nice partnership was formed with SDRC providing marketing and support for IMP while Uicker and his students continued the research. This partnership continued until 1984.

In those days, a few companies had purchased the original KAM software described above and had become very disillusioned when they found that the example problem of a backhoe simulation, which appeared in the KAM manual, could not be solved with the KAM program; instead, it caused the host computer to hang! Thus, many companies became convinced that such systems could never be analyzed on a computer by any software. Therefore, it became imperative that both IMP and ADAMS prove that they could be used to analyze such problems. Both easily passed that test using the data from the KAM manual as a demonstration.

In 1974, the Strain History Prediction Committee of SAE was formed with the intent of determining how well software of that time, including finite-element software, could truly simulate dynamic problems, such as an automotive front suspension as it encountered a bump or a pothole. The universities of Michigan and Wisconsin, Ford, General Motors, John Deere, Caterpillar, International Harvester, Clark Equipment, and several other companies were members of the committee. General Motors provided data for a particular front suspension, and they also ran several sets of experimental tests for which data were also distributed. Each member of the committee was asked to attempt these simulations and report back to the committee on how well the simulations matched the experimental tests. It was almost a year later that the two universities presented their results, both with amazingly good results, and both with comparable deviations, though with quite different costs. The several companies involved listened intently, but each found a reason not to report their own success or lack thereof.

Uicker spent the summer of 1980 at the Boeing Commercial Airplane Company helping them to implement IMP on their network, and to learn its workings. They formed a small group within their CAD support department who fully understood the theory behind the matrix methods in IMP, and its use grew within Boeing for several years. It was fundamental in the development of the landing gear and the wing-flap and elevator actuation systems of the Boeing 747, 757, and 767 airplanes.

Uicker spent the summer of 1984 at the home office of SDRC and their sister company, CAE International, in Cincinnati, OH. At the end of that summer, however, as he prepared to return to Wisconsin, a feud developed between Uicker and SDRC over ownership of the IMP software and the question of whether Uicker would be allowed to have its source code at the university, where a student might see it, and find out how it worked! SDRC claimed that this was their code and must be protected as their trade secret; Uicker claimed that source code was essential for such research to continue and this was how IMP was created in the first place. Upon his return to Wisconsin, Uicker brought a copy of the code in spite of SDRC objections, and quickly retained legal counsel. He was told that, in spite of his ideas of justice, he would lose any legal battle that might ensue since he did not have the financial resources to continue a legal battle. However, his attorney was successful in generating a legal agreement that both SDRC and Uicker signed which declared the existence of two IMP programs owned by the two parties, identical at that time, and declared their intent to work independently from

that time forward, without contesting the history of ownership of the IMP code.

As time went along, SDRC did continue to make IMP available. However, they had little in-house expertise on its workings, and they did little to advertise or advance it. Uicker, now fully back in academia, continued the development of IMP, but had no marketing agency or interest. Therefore, with continuing graduate student research, IMP continued to grow in capability, but faded from the public view and has become overshadowed by ADAMS, with the MDI Company, now owned by MacNeal Schwindler Corporation, marketing and supporting it.

Soon thereafter, coming from the research of Professor Edward C. Haug at the University of Iowa, an even newer system by the name of the Dynamic Analysis and Design System (DADS) has entered the scene, with the newly formed company named CAD Systems Incorporated (CADSI), now a part of LMS International, marketing and supporting it. Incidentally, the first CEO of CADSI was Dr. Rexford Smith, who left SDRC to take that opportunity.

Two more individuals worthy of note received their doctorates during this period. One is Dr. Roger A. Wehage who studied under the leadership of Professor Haug at the University of Iowa. After a period on the faculty at Iowa, he spent his career at the U.S. Tank Automotive Center in Warren, MI, and then at Caterpillar Corporation in Peoria, IL.

The other is Dr. Ahmed A. Shabana, Professor of Mechanical Engineering at the University of Illinois at Chicago who studied under the guidance of Dr. Wehage. Dr. Shabana is author of two textbooks on pertinent topics; the second, now in its fourth edition, is titled *Dynamics of Multibody Systems*, Cambridge University Press, 2005.

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