The Modern Era of Experimental Modal Analysis

One Historical Perspective

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Dr. Brown (right) graduated from the University of Cincinnati, Aeronautical Engineering Program with a B.S. degree in 1961. After graduation, as part of a university research contract, he worked at Wright Patterson Air Force Base in the ARL Hypersonic Wind Tunnel Facility where he was involved with both analytical and experimental hypersonic research. After he received his M.S. degree in 1963, Dave took a temporary leave of absence from the University for two years and worked on the Research Staff at General Electric in Cincinnati, studying hypersonic shockwave boundary layer interactions in hypersonic scramjet inlets as part of another Air Force Project. During his stay at GE, Dave took a self study class in advanced thermo-dynamics from the department head of the Mechanical Engineering Department and when he returned to the University of Cincinnati, he joined the University of Cincinnati Structural Dynamics Research Laboratory (UC-SDRL) in the Mechanical Engineering Department. This was the start of his long association with the UC-SDRL. His early work in UC-SDRL was studying cutting mechanics of the grinding process which evolved into "Grinding Dynamics" which became the main title of his Ph.D. dissertation work. During his study of grinding dynamics, Dave became very involved in the early practical development of Fourier analysis as applied to digital signal processing, acoustics, controls, self-excited and forced vibrations. This work set the stage for subsequent developments in experimental structural dynamics, the area that is often associated with UC-SDRL. During this early period from 1966-1970, Dr. Brown worked on the Research Staff and taught undergraduate and graduate courses in thermodynamics, acoustics and vibrations. In 1970, Dr. Brown became the Director of the UC-SDRL a position he held until he retired in the fall of 2004. During his tenure, Dave influenced and advised hundreds of students, gave many seminars, consulted with a large number of companies, was published extensively in the above mentioned areas and was invited to give numerous keynote presentations at conferences internationally. Dr. Brown is still teaching an occasional course and he continues to direct research in the areas of acoustics, controls and vibration. His students are his proudest legacy.

Dr. Allemang (left) is a member of the faculty of the Mechanical, Industrial and Nuclear Engineering Department, University of Cincinnati, where he currently also serves as Director of the Structural Dynamics Research Laboratory (UC-SDRL). Dr. Allemang has been actively involved in the area of experimental modal analysis for over thirty five years, pioneering the use of multiple input, multiple output estimation of frequency response functions, developing the concept of cyclic averaging, formulating the modal assurance criterion (MAC) and the enhanced frequency response function and reformulating modal parameter estimation algorithms into the unified matrix (coefficient) polynomial approach (UMPA). During this period, Dr. Allemang authored or coauthored over 140 technical articles, including chapters for 2 different handbooks and numerous refereed articles. Dr. Allemang has participated in over 50 invited seminars or lectures in the United States as well as in Taiwan, Japan, Korea (NSF), India (NSF), Belgium, Germany and France, including being asked to give the keynote address at both the Leuven International Seminar on Modal Analysis (ISMA, 1990) and the International Modal Analysis Conference (IMAC, 1993). During this period, Dr. Allemang has served as principal investigator or coprincipal investigator in over $2,500,000 of research with government (NASA and USAF) and commercial agencies (Boeing, General Motors, Ford, HP/Agilent, MTS, Brüel & Kjær, etc.). Dr. Allemang has worked as a consultant to a number of companies in many different structural dynamics applications since 1973. He continues to serve on the Advisory Board for the International Modal Analysis Conference (Chairman, 1986-1995), is serving on the Editorial Board of *Sound and Vibration* Magazine and has served as the Associate Technical Editor for *Mechanical Systems and Signal Processing* (MSSP) and Editor for the *International Journal of Analytical and Experimental Modal Analysis* (IJAEMA).

Dr. Allemang is currently involved in several areas of research which includes the experimental identification of nonlinear structural systems, the development of flexible MATLAB® based software for modal analysis and data acquisition research, the evaluation of impedance-based modeling methods and the correlation and correction of experimental and analytical dynamic models. He also served as President for the Society of Experimental Mechanics (SEM), 2003-2004, and on the Executive Board of SEM from 1998-2006. Dr. Allemang is very active in teaching in the areas of experimental methods, vibrations and automotive design and serves as Faculty Advisor to a number of student groups at UC including the Formula SAE Team (Bearcat MotorSports), Engineering Tribunal, Tau Beta Pi and Pi Tau Sigma.

With the celebration of the 25th anniversary of the International Modal Analysis Conference (IMAC) in February 2007 by the Society of Experimental Mechanics (SEM), *Sound and Vibration* asked the University of Cincinnati to chronicle how the modern era of experimental modal analysis developed to the jumping off point of the first IMAC conference back in 1982 in Orlando, FL. The University of Cincinnati was involved in one path of technology advances that contributed to Dick DeMichele and Pete Juhl deciding to work with Union College to put on the first IMAC. In fact, as is the case in many technology areas, the University did not start out with a mission of developing experimental modal analysis technology but instead was working on a machining problem for the U.S. Air Force. The application problem of machine tool vibration and machine surface roughness led to the need to become involved in the emerging analog and digital measurement technology and ultimately to the central role in the development of experimental modal analysis technology. This is our story.

In order to discuss the path to the first IMAC, the concept of the modern era of experimental modal analysis must be defined. There are a number of possible starting points for experimental measurements and modal analysis dating back to at least the Wheatstone

Bridge (1843) and certainly an argument can be made to go back even further to the developments by Fourier (1822) or Prony (1793) or even further. However, the modern era really can be restricted to more recent history when measurements of force and motion could be accurately recorded, the theory of experimental modal analysis had been developed in the literature and commercial implementations of the research technology began to make experimental modal analysis available to more than the research community. With this in mind, this gives the 1960s as the start of the modern era of experimental modal analysis. If a specific year must be chosen, 1967 will be our choice for a number of self-serving reasons that will be discussed later.

The rationale for this involves the confluence of many technologies that were developed earlier in the 1900s and began to become mature and somewhat integrated by the 1960s. To begin with, the modern era of experimental modal analysis could not begin until the theoretical background of modern test methods was formulated. This background was developed in the 1930s, 1940s and 1950s and was well established in the literature by 1963. Two competing methodologies were developed during this period and became known as *phase resonance* and *phase separation* methods. Phase resonance methods were being pioneered by researchers in the aircraft area and involved using multiple sine forces to excite the aircraft into a normal mode of vibration (resonance) by adjusting the location, signed magnitude (0 or 180° phase) and frequency of a set of multiple shakers. These methods continue to today as *forced normal mode* methods that are still used by some aerospace testing groups. The literature that first documents this approach somewhat rigorously was authored by Lewis and Wrisley in 1950[1] and De Veubeke in 1956[2] but many other authors contributed to this during the 1950s and early 1960s.[1-10] A good state of the art review was published by Bishop and Gladwell in 1963.[6]

Phase separation methods were more general in that normalized response functions and/or frequency response functions were measured at a succession of discrete frequencies, or via slowly swept analog frequencies using a single shaker, and analysis of the data was performed assuming one mode or a limited number of modes were present in a small frequency band. Literature discussing the theory behind this approach was published by Kennedy and Pancu in 1947[11] and was the first documentation of the need to use both magnitude and phase to separate close modes. While Kennedy and Pancu were also involved in the aircraft area, by the 1950s a number of other research areas began to utilize normalized response or frequency response functions to evaluate sound and vibration concepts. Even though some crude measurements involving transient inputs in automobiles and single frequency inputs in ships date back to at least the 1930s, by the 1950s, statisticians were beginning to define power spectra and a number of industries began to measure frequency dependent functions using single inputs, broad frequency ranges, and sensors with some form of electrical output in order to understand the dynamics of mechanical systems. These measurements were often made one frequency at a time utilizing filters to somewhat isolate the frequency content. The development of the tracking filter during the late 1950s was a key technical development that pushed early experimental modal analysis methods into the modern era. By the early 1960s, the phase separation methods were well known and beginning to be accepted as mainstream experimental methods used by automotive, aircraft and machine tool industries.

The modern era of experimental modal analysis could not begin until sensors were readily available and sufficiently stable and accurate to measure force and acceleration. By the 1960s, sensors were commercially available and becoming well accepted in experimental methods involving vibration and experimental modal analysis. With the development of the bondable strain gage into the elastic dynamometer by Hans Meier in the late 1930s, modern sensors for measuring force and motion were technically possible. Following this development, many companies in the 1940s built strain gages and sensors for their own use. However, many of the sensor companies still in business today (Kistler, Brüel & Kjær, Endevco) had their roots in the 1940s and 1950s in the initial development of strain based load cells and accelerometers and the follow-on development of the piezoelectric load cells and accelerometers.

Finally, the modern era of experimental modal analysis could not begin until equipment was readily available to measure the data required by the phase resonance and/or phase separation methods. This required equipment that was capable of measuring both magnitude and phase or the real and imaginary (coincident and quadrature components) of harmonic signals. With the development of the commercially available Dynamic Analyzer, Model SD101, also known as the tracking filter (1961), the Co-Quad Analyzer, Model SD109, and the Automatic Mechanical Impedance Measuring System, Model SD1002, also known as the Transfer Function Analyzer (TFA), by Spectral Dynamics in the mid 1960s, commercial equipment was finally available. In the late 1950s, Federal Scientific, later to become Nicolet Scientific, introduced the Coherent Memory Filter and later the Model UA-7, that used time compression technology developed for radar research with the USAF to perform frequency analysis. In the mid 1960s, Spectral Dynamics licensed this technology and developed their Real Time Analyzer (RTA), Model SD301, to provide broadband frequency analysis for the general commercial market. After the publishing of the Cooley-Tukey FFT algorithm in 1965,[12] the first FFT based data acquisition system was introduced by Time Data, Model TD-100, in 1967 followed closely by Hewlett Packard, Model HP-5450, in the late 1960s.

The modern era of experimental modal analysis, therefore, can be clearly traced to the middle 1960s when the theory had been developed and the hardware in terms of sensors and measuring equipment was commercially available. The year 1967 can be logically chosen as the start of the modern era of experimental modal analysis for two reasons that are clearly important to the authors of this article. First, 1967 was the year that the group of researchers led by Dr. Jason (Jack) Lemon at the University of Cincinnati left to form a small consulting company called Structural Dynamics Research Corporation (SDRC) and left the remaining researchers at the University of Cincinnati to work as what is now known as the Structural Dynamics Research Lab (UC-SDRL). Second, with 2007 as the 40th Anniversary of *Sound and Vibration* Magazine, this gives a nice benchmark for the beginning of the magazine.

Key Technological Breakthroughs

Most of the early developments with respect to experimental modal analysis came about due to the need to solve self-excited vibration problems. In the aircraft industry, this is the problem known as *flutter*. In the machine tool industry, this is the problem known as *chatter*. The University of Cincinnati was heavily involved in machine tool research and the problem of chatter in connection with the U.S. Air Force and other commercial companies. In order for the experimental work in these two areas to progress into the modern era, several technological breakthroughs were critical and allowed the University to become a central research group in the ultimate development of experimental modal analysis technology.

Tracking Filter (1961) – The development of the *tracking filter* by Spectral Dynamics revolutionized the ability to practically measure Frequency Response Functions and narrowband response spectrums. These capabilities were important for experimentally determining the chatter limitations of machine tools which was the initial problem of interest in UC-SDRL but had wide potential applications in trouble shooting vibration, controls and acoustic problems. The Transfer Function Analyzer (TFA) was ultimately developed which coupled the tracking filters with a sweep oscillator, log voltmeters, phase meter and x-y plotter in one package which automated the measurement of Frequency Response Functions (FRFs). The FRF measurements were important in characterizing the stability limits of machine tools. In order to alter the dynamics of machine tools and to minimize the possibility of chatter, procedures for modifying or improving the design had to be developed. This led to research at the University of Cincinnati in following areas:

- Experimental methods for measuring the modal properties of machine tools.

- Analytical modeling tools which could be used in the evaluation of modifications to the machine tools or in the design of new machine tools or components.
- Parameter estimation algorithms which could be used to extract modal parameters from measured FRFs (phase separation technology).

FFT Algorithm (1965) – The Fast Fourier Transform (FFT) algorithm and its ultimate development into a digital data acquisition system by Time Data and later Hewlett Packard permitted the use of broadband excitations (transients and random) in the estimation of FRFs. This development directly led to decreased measurement time and the ability to measure many channels of data acquisition at a significant savings of time and money.

Co-Quad Analyzer (1965) – This add-on module to the TFA developed by Spectral Dynamics automated the experimental measurement of the real and imaginary parts of the response with respect to the excitation sinusoid. This directly led directly to the development of digital data that could be used to represent mode shapes. Prior to the development of the automated Co-Quad Analyzer, the experimentalist would have to visually read the magnitude of the filtered input and output filtered sinusoids from meters and to separately read the phase angle from a phase meter, which measured the phase angle between the input and output sinusoids.

Real Time Analyzer (1967) – The UC-SDRL received a prototype of the Spectral Dynamics Real Time Analyzer, Model SD301, which used crystal delay lines to build a narrowband real-time spectrum analyzer. Since the signals were heterodyned to high frequencies using time compression technology, the quick stabilization of a high frequency, narrow band pass filter could be used to measure the frequency content from 0 to 40 kHz. This revolutionized narrowband spectrum measurements. The TFA could measure narrowband spectra but not in real time. Tape loops of recorded data had to be used with the TFA to process transient signals.

ICP® Sensors (1967) – Integrated Circuit Piezoelectric (ICP®) sensors incorporated integrated electronics into the sensor to eliminate problems associated with a remote charge amplifier. This technological development allowed the sensor to operate on a two wire, low impedance cable, significantly simplifying and reducing cabling problems and cost as well as the calibration sensitivity that comes with long cables.

FFT Fourier Analyzer System (1967-68) – The development of the Fourier analyzer System with the emergence of commercial Fourier analyzer systems (Time Data followed by Hewlett Packard) in 1967 and 1968, was a significant technology impact which ultimately led to the conversion of analog based measurement systems to purely digital systems. The Fourier transform-based systems could estimate FRFs and Power Spectra (PSs) directly from any input or output signals. From the measured FRFs and power spectra, the inverse Fourier transform could be used to estimate the Unit Impulse Response Function and Correlation Functions. From the time of this development until the first IMAC conference in 1982, significant advancements in digital data acquisition and experimental modal analysis methods were possible and the development of phase separation methods began to dominate the experimental modal analysis community outside of the aircraft industry.

The Early Years

The University of Cincinnati Structural Dynamics Research Laboratory (UC-SDRL) is one of the oldest and best known research laboratories in the Mechanical Engineering Program at the University of Cincinnati. Since the UC-SDRL has developed a national and international presence in the area of experimental modal analysis, a number of people have been curious as to how the lab got started, what the relationship is to the Katholieke Universiteit of Leuven (KUL) in Belgium and what the relationship is with the commercial company, Structural Dynamics Research Corporation (SDRC). This historical review of the origins of the Lab, and the people involved with its development and its mission, spans the period from its origin in 1964 and to the first IMAC in 1982.

The person most responsible for the development of the laboratory was Dr. Jason (Jack) Lemon who may be better known as the founder of the Structural Dynamics Research Corporation (SDRC). Dr. Lemon was an alumnus of the Mechanical Engineering Department, graduating in 1958 with a B.S.M.E. degree. During his undergraduate program, Jack participated in the mandatory cooperative education program in Mechanical Engineering by working (co-oping) at the Cincinnati Milling and Grinding Machines Company. (Often referred to in Cincinnati as "The Mill" – in the late 60s it became Cincinnati Milacron.) As an undergraduate student, Jack was married and already had an expanding family so it's clear that his wife (Marilyn) was an important influence on Jack's plans. After graduation, Jack continued to work for the Mill and at the same time continued his education by enrolling at Ohio State where in 1960 he got his M.S. and in 1962 his Ph.D. degrees. After his graduation from Ohio State, Jack worked in the research department at the Mill. One of the areas of interest concerned machine tool dynamics where significant advancements were being made in analytical and experimental methodology for analyzing machine tool chatter. This started Jack's association with the U.S. Air Force and *chatter* beginning with U.S. Air Force contract (AF33-657). It became clear to Jack that methodology developed to understand self-excited vibrations had the potential to significantly impact the broader area of analytical and experimental structural dynamics. Jack's vision was that this technology, if further developed, would significantly influence the engineering design and product development process in a large segment of industry (aerospace, automotive, etc.) which had requirements that extended far beyond those of the machine tool industry.

Figure 1. Machine Tool Test – Jack Lemon, Jim Sherlock, Ivan Morse and Al Peters, left to right (1964).

In 1964, Jack left the Mill and joined the UC faculty in Mechanical Engineering with goal of developing a university-industrial effort to implement this new technology. Figure 1 shows a very early machine tool test conducted by the university using the technology that Jack brought to the campus.

The timing for this sort of effort was right because two new technologies were just emerging – one analytical and the other experimental. Computer systems were getting powerful enough so that mechanical systems could be modeled in a 2D representation and later in a 3D Finite Element Modeling (FEM) sense. The technology was crude but it was a start. At the same time, experimental methods for automating the measurement of frequency response functions were emerging. This measurement which was critical for the analysis of self-excited vibrations such as machine tool chatter also had the potential for experimentally extracting the structural dynamic characteristics of mechanical systems.

Also, the timing was right at the University of Cincinnati, because in the early sixties the Mechanical Engineering Department was in the process of developing a more extensive graduate program. Dr. Daniel Schleef, the Department Head, hired Dr. Ivan Morse and Dr. Frank Tse, who had expertise in mechanical vibrations and measurements, to develop modern undergraduate and graduate courses in those areas. Mechanical engineering also added two new faculty members, Dr. I-Chih Wang and later Dr. Y. G. Tsuei, who added graduate courses in elasticity and analytical

Figure 2. UC-SDRL Party, including Jack Lemon (center), Bob Farrel and Vic Nicolas (1966).

methods. The Aeronautical Engineering and Applied Mechanics Departments had complementary courses which allow mechanical engineering students to define a program of study for both a masters and Ph.D. degree in the areas of controls, vibrations, and solid mechanics.

Dr. Lemon had a vision of developing a research laboratory where the university and industry would participate in mutual interest activities to develop new educational and engineering processes. Since Jack had worked as an undergraduate co-op student while attending the University of Cincinnati, he had experienced the positive affects of a university-industry educational experience. Jack understood that it was a win-win situation for both the university and industry if a student activity could be developed that would allow graduate students to be exposed to real-time industrial problems while industry was being exposed to new engineering design and product development processes. The result would be better trained engineers who could help implement these new processes practically in an industrial environment.

In the model that Jack envisioned, the analytical and experimental design processes are closely linked. The students in the university research laboratory would develop an expertise in one area, but should have a good basic understanding and appreciation of the other area. In reality, many graduates have moved from one area to the other depending upon the circumstances in their life and/or job.

Obviously, his concept of the university/industry partnership was proven fruitful because very shortly, after he joined the university, Jack generated tremendous industrial response and gathered the resources to put together a very good team of students and support personnel. Over the next year he recruited a wide variety of students. There were students from many different departments at the university, from other universities both national and international and from many different disciplines. He formed valuable alliances with universities in Europe and Japan. These relationships became very important to UC-SDRL after Jack left and formed SDRC.

By late 1966, the UC-SDRL had expanded to approximately 40 people, the majority being supported students. At this time, the financial support for the research was generated primarily by a major U.S. Air Force contract in manufacturing with the emphasis on the cutting process and cutting dynamics, together with support from industry partners with similar interests. Several U.S. Air Force contracts (AF61-052) funded international machine tools experts on their individual research. Other U.S. Air Force contracts (AF33-615) provided support for the research at UC which included funding to support members of this international research activity to become part of the UC-SDRL staff. These contracts provided financial support for an international collaboration with research activities in Belgium, Germany, Great Britain and Japan that developed relationships and became the model for research activity at the UC-SDRL for the next forty years.

The format for the industrial support process was accomplished by defining an industrial project where industry and the university cooperated in solving a specific problem. In this early phase, the educational process was truly mutual with industry mentoring students (developing an understanding of the industrial problems) and university personnel educating industry (developing an understanding of how new emerging technologies would meet their needs). The end result of this process was a solution to a difficult problem and the education of both the university and industy.

There were also students from a large number of disciplines (mechanical, aerospace, metallurgical, electrical engineering, physics, chemistry, etc.), and these students mentored each other on their various projects. This, coupled with a large number of social activities in the UC-SDRL (parties, picnics, etc.), helped to bond the students. It was an exciting educational environment. Lifetime friendships were developed which were later important in the continuing development of UC-SDRL and the formation of SDRC.

As the Laboratory learned how to implement the technologies being developed in various industrial projects, a demand began to emerge for a consulting activity to routinely solve these types of problems. It was clear that an engineering service business could be formed which could perform this service and provide the type of response that industry demanded. However, this type of short-term, time-critical response is in general not compatible with having students perform the work while they are pursuing a degree and must attend class. Requiring graduate students to provide these engineering services on a continuing basis took too much time from both their university education and their research efforts. Jack's solution was to form an engineering service company outside of the university to provide a service which industry clearly needed. His initial concept was that UC-SDRL would continue to educate graduate students and interact with industry by concentrating on developing the newer technologies, and the service company (which became the Structural Dynamics Research Corporation, SDRC) would provide the service to industry while funding projects at the University which were more compatible with the University's education and research mission.

At that time, Jack planned to stay actively involved with the UC-SDRL. Unfortunately, this was not possible, and Jack formally left the university to form SDRC in 1967. SDRC became one of the dominant industries in the engineering services business internationally as well as providing education and the development of state-of-the-art analysis software for industry. SDRC also became one of the university's largest cooperative engineering employers and spawned a number of spin-off companies. Figure 3 is a schematic that represents a number of the companies that are or were active in the area of structural dynamics that can trace their roots back to the research activity at the University of Cincinnati that began in 1964. Over the years, hundreds of students from the University of Cincinnati, and to a lesser extent from other universities, have been involved in this cooperative experience with companies that trace their history to the University of Cincinnati structural dynamics legacy.

When Jack left the university in 1967, six other people who were instrumental in UC-SDRL joined Jack in starting SDRC (Helen Conners, Bob Farrel, and four students – Al Peters, Vic Nicolas Ted Comstock, Jim Sherlock). Figure 4 is photograph taken at Helen Conner's retirement party with 6 of the 7 original founding members of SDRC. Vic Nicolas and Ted Comstock continued on part time at the university and completed their Ph.D. degree programs in the late sixties. As Jack started SDRC, he lined up financial support from U.S. Steel and Spectral Dynamics, two industrial companies that heavily supported the research activities at the University.

One example of the significant research developments in the UC-SDRL during the 1960s was the application of the analytical and experimental philosophy to improve the design of machine tool structures by using steel weldments. Based upon this early application of analysis and test, steel weldments were used to replace the cast iron components (beds, etc) in existing machine tools

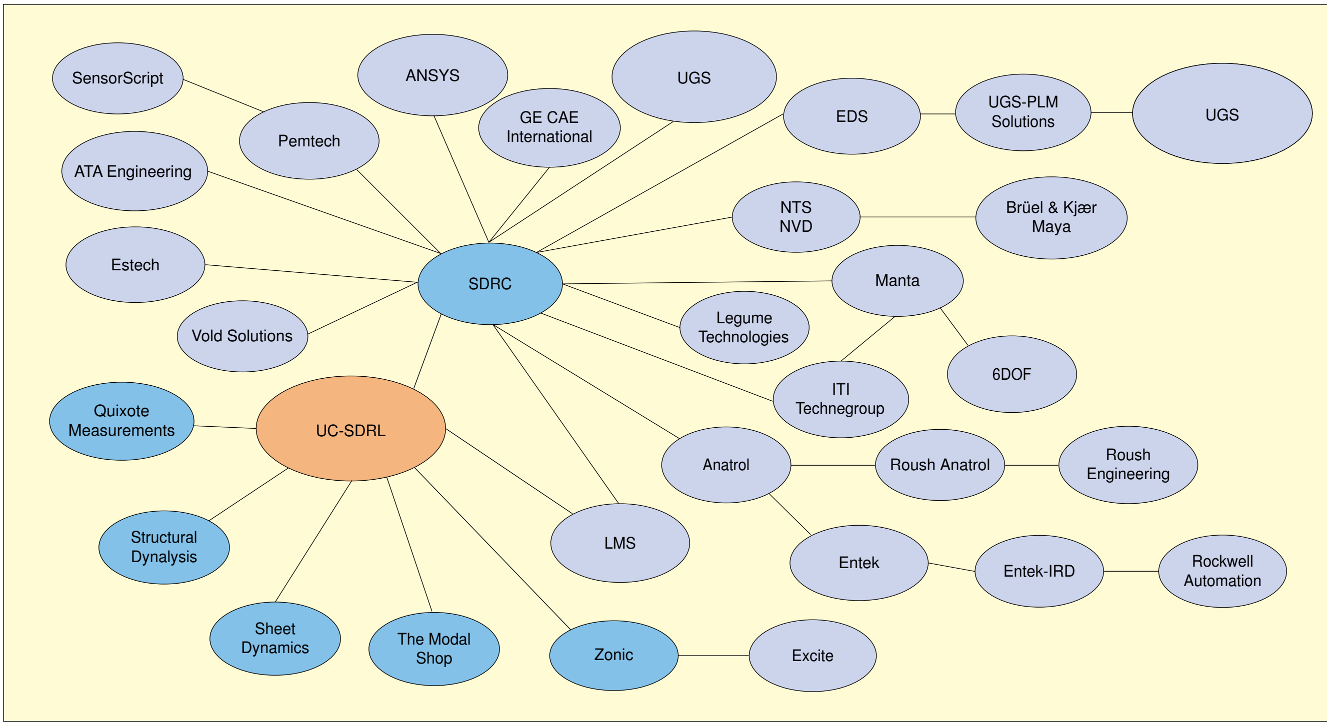

Figure 3. Multi-generational relationships of companies that can be tracked back to UC-SDRL and/or SDRC.

Figure 4. Original SDRC employees at retirement party for Helen Conners: first row – Bob Farrel, Helen Conners and Jack Lemon; second row – Al Peters, Jim Sherlock and Ted Comstock (1999).

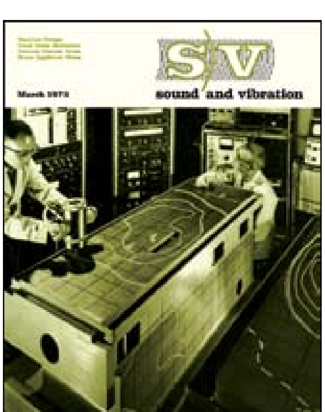

Figure 5. Steel weldment testing at UC-SDRL on cover of S&V (1973).

with significant improvements in performance and reduction in cost. In Figure 5, the work performed at the UC-SDRL in 1963-66 is shown on the front cover of *Sound and Vibration* Magazine (1973).

When SDRC was formed, the application of this technology to a wider industrial base became their main focus. Their initial business was troubleshooting of control, vibration and noise problems; however, their ultimate goal was to develop application software that would significantly impact the product development process in industry. During this time, Dr. Lemon is credited with being the first to use the term Computer Aided Engineering (CAE) to describe the process that was being used to solve engineering problems. Over the next several years SDRC hired other students and staff members from the University and the UC-SDRL. Many of those who joined SDRC during this early expansion would later significantly impact structural dynamics and CAE technologies worldwide

Shortly before SDRC was formed (1966), the university won another large Air Force contract (AF33-615) for analyzing and measuring the cutting dynamics of large 5-axis milling machines. This contract involved traveling around the United States to gather data from these large and expensive machines to establish their current state-of-the-art machining characteristics. These data were used by the Air Force to set procurement specifications for other major machine tool purchases. The database included a complete modal survey of all the machines tested which made it very useful in characterizing good design practices. A large mobile laboratory then was outfitted with measurement equipment and a communication link (video, voice and analog data link) to the test site where the test was conducted. The data analysis occurred in the van. This arrangement streamlined the test setup and procedures. The photos in Figures 6-8 show the van located at various test sites during some of this testing. and test engineer at test site.

The Transition Years

After SDRC was formed in 1967, the activity at UC-SDRL decreased significantly with a limited number of new projects coming into the lab. However, the students still at the University involved with the UC-SDRL had continuing support for several years from the activity in machine tool dynamics connected with the U.S. Air Force contract and related work with industry. David Brown was one of the students supported by UC-SDRL who remained at the university after SDRC was founded. Dave was part of a small grinding research team headed by Dr. Kenjo Okumura, a Professor from Kyoto University in Japan (1966). The team consisted of a student from Japan, a student (Bill Bael) and a post doctorate researcher (Mond Snoeys) from Katholieke Universiteit of Leuven (KUL) in Beligum and two students (Jon Gerhart and David Brown) from UC (Figure 9).

Dr. Raymond (Mond) Snoeys, the post doctorate from KUL, had just finished his Ph.D. dissertation on grinding dynamics. After Mond joined the group, Dave worked with him on extending the grinding dynamics problem. This became Dave's Ph.D. dissertation

Figure 6. Mobile test van, machine tool test (1969).

Figure 7. Test director conducting test from mobile test van.

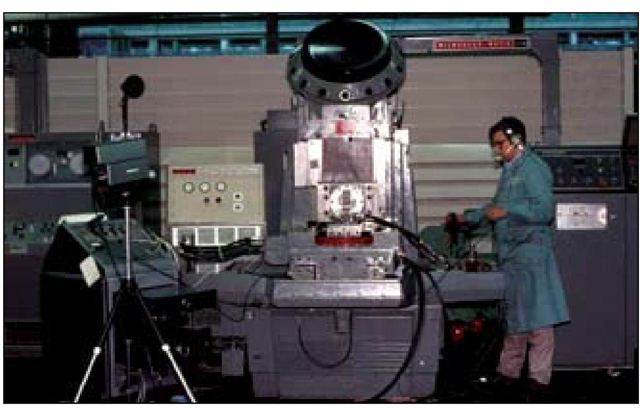

Figure 8. Test site setup. Audio-video-data link to test van and test engineer at test site.

Figure 9. Original UC-SDRL grinding group: front – Bill Bael; back – Dr. Okumura's daughter, Jon Gerhart, Dr. Okumura's wife, David Brown and Dr. Okumura (1966).

topic as well. The relationship between Mond and Dave was important to future developments at the UC-SDRL laboratory, as well as the close relationship that developed over the years between UC-SDRL and the Mechanical Engineering Department at the KUL.

After SDRC was formed, Dave worked on the Air Force contract (F33615-67-C-1727) with a new faculty member, Bill Shapton, and an electronic technician named Jerry Giesen. Other students would very often travel on the testing trips for the practical experience, including two current UC ME Distinguished Alumni, John Coy and Bill Grissom, who were Ph.D. students at the time. Andy Siebert (past Department Head and Professor at the University of Kentucky, Department of Mechanical Engineering) was an undergraduate co-op student working on the Air Force contract. It was during this program that many of the concepts for using

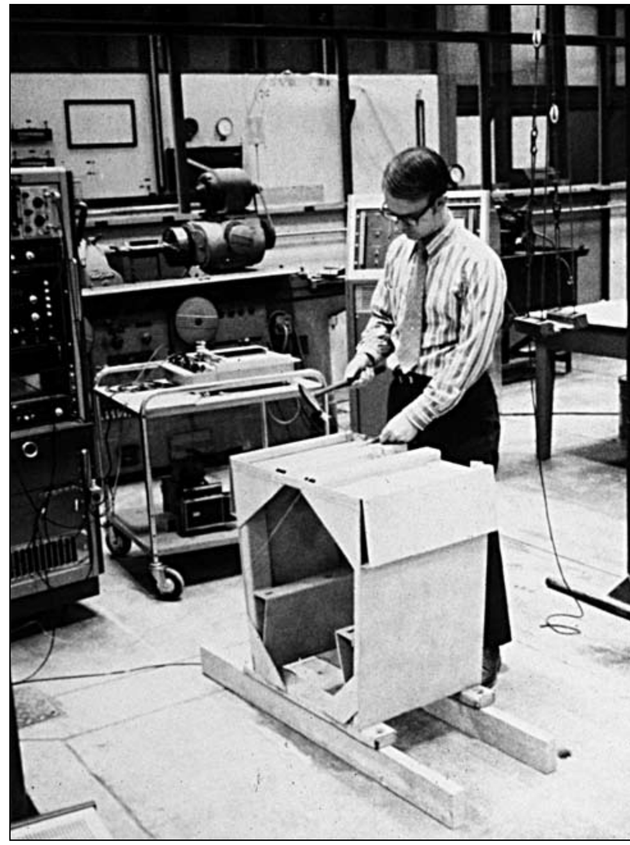

Figure 10. Evaluation of impact testing using Spectral Dynamics Realtime analyzer, Bill Zimmerman (1967-68).

Fourier analysis and digital signal processing were formulated for measuring and characterizing mechanical structures.

As mentioned earlier, the students in the laboratory would interact on their research projects, which often yielded good results. One example involved the M.S. thesis project of Bill Kramer (General Tool). Bill was trying to develop a machine tool testing procedure based upon impact excitation using the analog test equipment of the time. Unfortunately, due to the limitations of the analog approach, the method was impractical. A few years later, the technology to solve the problem became available and it was this impact-excitation problem that started the initial interest in digital signal processing. Discussions between David Brown and Al Klosterman, both Ph.D. students, led to the idea to use Fourier analysis for processing transient data. This coupled with Bill Kramer's thesis problem ultimately led to using the Fast Fourier Transform to make impact testing of machine tools practical. In the late sixties, Dave used a prototype Spectral Dynamics Real Time Analyzer (Model SD301) to check the feasibility of using Fourier analysis (despite the fact that the RTA was based upon a hybrid process using time compression technology and a bank of narrow band filters). A photograph of Bill Zimmerman, a student working with Dave making measurements on small machine tool base is shown in Figure 10.

The results were encouraging, so Dave programmed the FFT algorithm into an IBM 1130 computer connected to an Applied Dynamics analog computer located in the Electrical Engineering Department of the University of Cincinnati. This analog computer provided the analog signal processing and the analog-to-digital conversion, while the IBM computer performed the Fourier analysis and computed the power spectra, frequency response and coherence functions. The analog computer occupied a complete room at the University at that time. Small experiments could be performed in the room but real data had to be recorded on an FM tape recorder and played into the computer. It was not practical for real test work.

At the time of this development, Dave and Bill Zimmerman, a graduate student working for Dave, were working with Ford Motor Company's Manufacturing and Development Division on

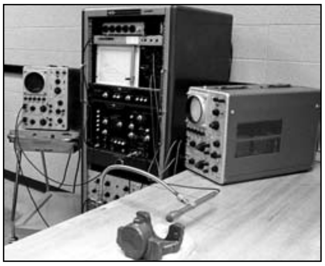

Figure 11. Signature analysis test setup (1969).

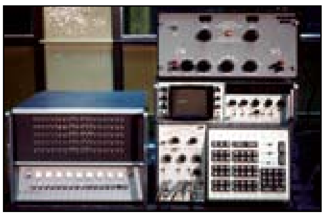

Figure 12. HP 5450 system (1970).

a signature analysis project (today called feature extraction) for detecting cracks in cast iron parts using spectrum analysis. This involved using the Spectral Dynamics RTA to measure frequency and damping of cast iron parts (Figure 11). These parts had very low damping and a crack would increase the damping of selected modes. The modes which had increased damping could be used to give a rough location of the crack. This method work very well for rocker arms and could be easily implemented in production.

However, the next year, Ford shifted to stamped rocker arms and the method was never implemented in production. But, Ford was so impressed with the work that they wanted to duplicate the procedures and equipment for their laboratory. To make a long story short, Dave suggested that they look at a new commercial Fourier Analyzer System that was just introduced on the market. Ford took his suggestion and approached Hewlett Packard, but Hewlett Packard did not have the expertise to apply their new Fourier analyzer to Ford's problem. Ford suggested that Dave Brown could help them and this led, in 1970, to the UC-SDRL obtaining the HP-5450 Fourier Analysis System, a small (relative term – it was the size of refrigerator but much smaller than the Hybrid Computer Room) portable Fourier analysis system (Figure 12). Over the next year or so Dave developed the signal processing expertise to use Fourier Analysis to supplement and finally replace the analog measurement capabilities of the TFA and the RTA.

The Focus on Experimental Modal Analysis

Around this time, early 1970s, Dave became the Director of UC-SDRL. In developing a unique research capability, Dave decided, as his predecessor Jack Lemon had done, to develop a mutual interest relationship with industry involving education, research and problem solving, but to concentrate more on the development of next generation experimental tools (measurement and parameter estimation) needed for product development. UC-SDRL would use commercial analysis tools and work on developing better measurement and experimental data analysis tools.

The most important resource at a university is the student; the biggest challenge is to develop their true potential. In order for the students to perform state-of-the-art research in an experimental area, they needed state-of-the-art measurement and test tools. This equipment is very expensive, so the plan was to develop a mutual interest relationship with companies that manufactured test equipment. As a first step, the UC-SDRL could help the companies educate their customers in the science and art of using testing to solving real problems. The second step was to perform research on new testing methods and help the equipment manufacturers develop new testing equipment/software to implement these new methods. In return, the equipment manufacturers would donate equipment and provide support either directly and indirectly for students. Again it was the right time (digital signal processing was just developing); equipment manufacturers were just starting to make the transition to digital technology and the University already had significant expertise in this area. In order to attract the interest of the equipment manufacturers, the UC-SDRL consulted with some of their large customers and educated them to the point where customers were pushing the equipment manufacturers for products to implement the new digital technology.

UC-SDRL already had good support from Spectral Dynamics who made state-of-the-art analog test equipment but were reluctant to go in the digital direction in the late sixties and early seventies. Hewlett Packard (HP) was investigating a prototype measurement system based upon the Fourier transform and they were looking for applications for this system. The UC-SDRL had already developed Fourier testing techniques for analyzing mechanical systems by using the hybrid computer in electrical engineering. However, in order to make the testing techniques practical, the UC-SDRL needed a portable measurement system, and the HP prototype system satisfied this requirement. Once Ford made the initial introduction between HP and the UC-SDRL, this became a strong mutual interest relationship. Over the years Hewlett Packard ended up donating millions of dollars in equipment to the University of Cincinnati. The UC-SDRL developed new testing methods and educated students in industry on how to use these new methods. One of the very interesting and positive aspects of the UC-SDRL relationship with HP was that there were no constraints placed upon the University about working with other companies in the signal processing area. The UC-SDRL could share freely any information that was developed at the University with the general public. HP in turn only shared information with the university that was non-proprietary to HP.

This mutual interest relationship also worked well with other equipment and sensor manufacturers as well as several industrial partners. As a result of these relationships, the UC-SDRL has had the best state-of-the-art measuring systems for our students to work with for the past 40 years.

At about the same time that the research was starting to move to digital data acquisition and the FFT (the early 1970s) Dave started teaching dual level (senior undergraduates and graduate students) courses in acoustics, and vibrations). The Vibrations III course was a spring quarter, advanced vibration course which involved a project. The projects for this course involved using Fourier analysis to examine realistic problems encountered in typical industrial situations. The students were divided into groups of two to three students. Since Fourier analysis was in its infancy, many of these problems involved ground breaking applications. The problems included signature analysis (health monitoring), forced vibration problems, self excited vibration problems and modal analysis. The following examples are representative of some of those early student projects (1971-1972) that focused on experimental test methods which show applications that were state-of-the-art at that time:

Response Ratio Test Method – A large machine tool isolation block located in the UC-SDRL was tested using a response ratio method, where a fixed accelerometer was used as a reference to a roving accelerometer. A steel wire was attached at a fixed point and the wire was loaded by an over-head crane until it broke. In this case, the force was not measured. The FRF between the reference accelerometer and the roving accelerometer was estimated along with power spectra (PS) of the two signals. At the frequency of the resonant peaks in the power spectra, the real part of the response ratio FRF was used as a measure of the modal contribution.

Step Input Excitation – This application is an example of using transient testing to measure the modal parameters of a simulated shear model of a multi-story building (Figure 13). Sewing thread was attached in a grid pattern on the model and accelerometer was mounted on one of the upper corners of the model. The thread was connected to a load cell and pulled until it broke. This simulated a unit step function force input. Frequency Response Functions were computed between the input force (sewing thread breaking) and the output accelerometer. These FRFs were used to obtain estimates of the natural frequencies, damping and the mode shapes.

Impact Testing of an Operating Machine Tool – This research project developed the first impact hammer as it is used today. While impact testing had been documented before this,[16] the load cell had to be placed on the test object and impacted with a hammer. In testing an operating machine tool, the goal was to measure the directional frequency response function. This required that the impact force be applied to the turning spindle of a drill or lathe or rotating cutting tool of a grinder where the load cell could not be mounted to the spinning object. This project involved mounting the load cell on the hammer and impacting the rotating spindle or cutting tool through a plastic flap (in order to minimize the tangential force of the hammer during this strike) (Figure 14). This

Figure 13. Step input test of building model, student project group: Jerry Nessler (left) and Ray Zimmerman (1972).

project was very successful and resulted in an ASME publication a year later.[17]

These examples indicate that applications of Fourier analysis to the areas of vibrations, controls and acoustics were so new that student projects associated with dual level course work was ground breaking. A large number of students that took this course in the early 1970s went to work in industry, where they had a chance to immediately apply the information learned in their coursework directly to problems encountered on the job. Other students from this era went to work for consulting firms such as SDRC.

As a result of his contact with students in these courses, Dave was able to recruit other excellent students to join the UC-SDRL where they were supported by grants, projects and contracts from a number of industries (automotive, disk drive, etc.) and government agencies (NASA, USAF, etc.). Randall Allemang (Randy), who was a student in the ME Class of 1972, got involved in the UC-SDRL as an undergraduate student beginning in 1970 and continued on for M.S. and Ph.D. degrees. Randy joined the UC-SDRL research staff in 1972 and later became a faculty member as an Instructor in the Mechanical Engineering Department. Over the years Dave and Randy have become a team of space cadet and pilot – Dave bounces from one technical idea to another while Randy keeps us on course. From an administrative point of view, Randy has managed the laboratory (for the past 25 years) as Associate Director.

Leading Up To IMAC

Education was central to the mission of the UC-SDRL in 1964 and remained so in the 1970s. The definition of education within the UC-SDRL structure has always included a combination of classroom learning, theoretical and applied research in experimental methods, consulting on industrial projects and giving seminars for industry. In general, when students first come into the laboratory, they are encouraged to concentrate on their course work and to become familiar with the research activities of other students. After they established themselves, they are exposed to, and participated in, short-term industrial trouble shooting or consulting projects to gain practical experience. Older students are strongly encouraged to act as mentors to the younger on these projects. After their initial indoctrination, the students are encouraged to select and develop a research area of interest and the UC-SDRL trys to find support for them in their area of their interest. Fortunately, the students have always responded positively and as a result, UC-SDRL has remained one of the more active laboratories in developing methodology useful to experimental structural dynamics.

Part of the education process involves the giving of short courses or seminars to industry. In the early 1970s, many of these seminars were sponsored by Hewlett Packard and included locations in the US, Europe and South Africa. Frequently, these seminars involve lectures and demonstrations utilizing a real test object at the industry location. UC-SDRL has given seminars of this type all over the world. The research students would participate in these seminars by giving lectures and conducting tests. Beginning in the late 1970s, many students have had a chance to visit Europe, Japan, etc. to participate in these seminars as an integral part of their training. Many of the seminars after 1975 were supported, in part, by various industries and/or universities.

Figure 14. Impact test of lathe, student project group: Chris Powell, Randy Allemang and Tom Graef, left to right (1972).

Figure 15. Mond Snoeys (left) and Dave Brown at an early KUL Seminar/Conference.

The focus on seminars as part of the education process began in 1972 when Dave was invited to give a seminar on the "Applications of Fourier Analysis" at the University of Birmingham, England during the 13th International Machine Tool Design and Research Conference. As part of this seminar, Dave borrowed an HP5451A Fourier Analysis System from HP Europe and demonstrated impact testing of a machine tool.[16] After the conference at Birmingham, Dave traveled to visit his friend and collaborator, Professor Raymond 'Mond' Snoeys at the Katholieke Universiteit of Leuven (KUL) in Beligum where he gave another seminar and demonstration. Dave and Mond had been collaborating since his visit to the UC-SDRL laboratory in 1966.

This trip was instrumental in acquainting another part of the world with Fourier analysis and some of its mechanical applications. In the following year, Dave gave a series of one-day seminars throughout Europe. He stopped to visit Mond Snoeys where he gave a special seminar. In 1975 Dave brought his family to Europe and spent two months at the KUL to work and collaborate with research students. During this stay, Dave suggested to Mond to work with industry in the same manner as the UC-SDRL did in the US. In order, to evaluate the possibility of developing this type of relationship with industry, Dave traveled to Germany to visit an automobile industry (Opel) with several assistants in Snoeys' research group. This group made arrangements to obtain an automobile which was then modal-tested at the KUL in the presence of technical representatives of the car company. This was a successful experiment and was the start of KUL working with industry in a manner similar to UC-SDRL. Over the next two decades, research assistants from the UC-SDRL and from KUL would spend time and collaborate with each other on various research topics while visiting each others' research labs.

After a few years of KUL working with industry, the project work became significant enough that a small company was formed to provide engineering services, and ultimately software, to the European and world marketplace, just as SDRC was doing in the U.S. That company was LMS and it was started with the support of Mond Snoeys and KUL by a small group of research assistants from his research group. Dave's assistant when he was at KUL, Maurice Mergeay, took the lead in forming LMS. There are many similarities between the way SDRC and LMS got started, and in the early business model that was used by both groups.

Dave returned to Leuven annually and assisted the KUL in the International Seminar on Modal Analysis (ISMA) which continues today as the ISMA Conference on Noise and Vibration Engineering (Figure 15). One year after the first KUL conference, the UC-SDRL started a series of short courses for industry in the areas of Signal Processing, Measurements and Modal Analysis that were co-sponsored by HP. These courses continue in an updated form to this day, as well.

During the rest of the 1970s and early 1980s, developing an understanding of the problem-solving and research potential of Fourier analysis and experimental modal analysis, as well as developing methods for educating engineers in these methodologies, became the major thrusts of the UC-SDRL. While many vendors and research groups were working on these issues as well, the UC-SDRL focused on making the best experimental measurements possible to reduce the overhead associated with the modal parameter estimation process that was often performed on slow and memory-limited mini-computers. Some of the research activities and milestones that mark the 1970s for the UC-SDRL are:

- Impact excitation for estimating frequency response functions (1971)
- Acoustic signature analysis of machined/cast parts (1971)
- Animated mode shapes (1972)
- Color spectrogram display for time and RPM spectral maps (1973)
- Development of the time domain Complex Exponential (CE) algorithm for estimating modal parameters (1974)
- Development of the time domain Least Squares Complex Exponential (LSCE) algorithm for estimating modal parameters from multiple FRFs (1975)
- Development of excitation procedures for making FRF measurements [transient, random, periodic, operational] (1976)
- Development of specialized digital signal processing methods to reduce signal processing errors (cyclic averaging, etc.) (1977)
- Experimental modal analysis review for The Boeing Company and the USAF (1978)
- Development of the Modal Assurance Criterion (MAC) (1978)
- First application of multiple input, multiple output, frequency response function (MIMO FRF) estimation (1979)

One of the activities that began during this time period that today has become the major focus of experimental modal analysis was the verification of analytical models utilizing experimental data. The UC-SDRL was involved in a number of projects from the experimental side including very successful projects with Cadillac Motor Cars, NASA-Plumbrook (now NASA Glenn), and NASA Marshall Space Flight Center. The NASA Plumbrook project involved the verification of a finite element model of a wind turbine that was being constructed at the NASA Plumbrook site near Lake Erie (Figure 16). This project was, politically, very visible at that time due to the energy crisis and the need to change to possible alternate forms of energy production. This project, together with the pictures of the wind turbine and test site, was featured in an issue of *National Geographic*. The pictures were taken while the UC-SDRL was on site for the testing.

The history of experimental modal analysis during the 1970s is mostly found in papers presented at numerous conferences and in journals and articles published by vendors or in articles published in technical magazines like *Sound and Vibration*. Examples are the original paper presenting the Least Squares Complex Exponential algorithm in the SAE Transactions and the complete discussion of impact testing in *Sound and Vibration*.[17,18] During one point in the late 1970s, an animated mode shape was even part of a car commercial on television. Nevertheless, there was a need for a conference that would focus on this important experimental aspect of structural dynamics. In 1979, the UC-SDRL was visited by two engineers from General Electric, Peter Juhl and Dick DeMichele, who tried to convince us that UC should start such an international conference. Recognizing that the organizational requirements were well beyond what the UC-SDRL was good at and having way too much fun working on our own projects, the UC-SDRL committed to supporting such an endeavor. Pete and Dick ultimately received the same response from a number of vendors and organizations and proceeded, with the assistance of Union College, of organizing the first International Modal analysis Conference (IMAC) in 1982.

Figure 16. Model correlation test of NASA Plumbrook wind turbine (1976).

From there, the rest is history and the documentation of the next 25 years is a matter of public record. The Conference took on a professional society affiliation with the Society of Experimental Mechanics (www.sem.org) in 1988. Since 1982, the history of experimental modal analysis, the progress that has been made and role the UC-SDRL has played, is well documented from the year-to-year contributions to the IMAC Proceedings. In recent years, the UC-SDRL research assistants, in carrying on the tradition of cooperating with industry and promoting education, have also staffed a Technology Center Booth at a number of international and professional society conferences, beginning with the IMAC Conference. The Technology Center Booth is a display area for UC and other universities to showcase the latest technology that is being developed and encourages these universities to continue to collaborate just as was done in the 1960s.

Conclusions/Summary

The modern era of experimental modal analysis developed with the University of Cincinnati playing a central role through a bit of serendipity and the coming-together of a number of talented individuals with vision and passion for their work. The serendipity of the process was that the technical insight needed to first understand the self-excited vibration problem in machine tool dynamics known as chatter; experimental modal analysis was one necessary tool for working on the problem. The talented individuals were the international team from throughout the world that brought their technological expertise and passion for their work together under charismatic leadership that had the vision for the developing technology beyond the scope of immediate research problems. This vision continued from the 1960s to the 1970s to the present day in the development of experimental modal analysis technology at the University of Cincinnati, through international cooperation with both university and industry groups throughout the world. Further history of the UC-SDRL may be found at www.sdrl.uc.edu.

Addenda

Dr. Jason Lemon passed away on December 27, 2006 while this article was being prepared by the authors. Although few knew of his battle, Jack fought his illness for many years as he continued his life-long passion for his work in structural dynamics and Computer Aided Engineering at ITI TechneGroup. Only 71 when he died, Jack left a tremendous impact on the technology, a large number of companies and countless numbers of individuals who worked with him over the years. We will all remember his vision, energy and enthusiasm for his life's work. Condolences may be sent to the Lemon Family, 8125 Kugler Mill Road, Cincinnati, OH 45243 USA. Memorial donations may be sent c/o Dr. Dan George at Duke Comprehensive Cancer Center, DUMC 3828, Durham, NC 27710 U.S.A.

References

1. Lewis, R .C.; Wrisley, D. L., "A System for the Excitation of Pure Natural Modes of Complex Structures," *Journal of Aeronautical Sciences*, Volume 17, Number 11, 1950, pp. 705-722.
2. De Veubeke, B. F., "A Variational Approach to Pure Mode Excitation Based on Characteristic Phase Lag Theory," AGARD, Report 39, 1956, 35 pp.
3. Trail-Nash, R. W., "On the Excitation of Pure Natural Modes in Aircraft Resonance Testing," *Journal of Aeronautical Sciences*, Volume 25, Number 12, 1958, pp. 775-778.
4. Asher, G. W., "A Method of Normal Mode Excitation Utilizing Admittance Measurements," Dynamics of Aeroelasticity, Proceedings, Institute of the Aeronautical Sciences, 1958, pp. 69-76.
5. Stahle, C. V.; Forlifer, W. R., "Ground Vibration Testing of Complex

Structures," Flight Flutter Testing Symposium, NASA-SP-385, 1958, pp. 83-90.
6. Stahle, C. V., Jr., "Phase Separation Technique for Ground Vibration Testing," *Aerospace Engineering*, July 1962, 1962, 8 pp.
7. Pendered, J. W.; Bishop, R. E. D., "A Critical Introduction to Some Industrial Resonance Testing Techniques," *Journal of Mechanical Engineering Science*, Volume 5, Number 4, 1963, pp. 368-378.
8. Pendered, J. W. Bishop, R. E. D., "Extraction of Data for a Sub-System From Resonance Test Results," *Journal of Mechanical Engineering Science*, Volume 5, Number 4, 1963, pp. 368-378.
9. Pendered, J. W.; Bishop, R. E. D., "The Determination of Modal Shapes in Resonance Testing," *Journal of Mechanical Engineering Science*, Volume 5, Number 4, 1963, pp. 379-385.
10. Bishop, R. E. D.; Gladwell, G. M. L., "An Investigation into the Theory of Resonance Testing," *Philosophical Transactions*, Royal Society of London, Series A, Volume 225, A-1055, 1963, pp. 241-280.
11. Kennedy, C. C., Pancu, C. D. P., "Use of Vectors in Vibration Measurement and Analysis," *Journal of Aeronautical Sciences*, Volume 14, Number 11, 1947, pp. 603-625.
12. Cooley, J. W., Tukey, J. W., An Algorithm for the Machine Calculation of Complex Fourier Series," *Mathematics of Computation*, Volume 19, 1965.
13. Comstock, T., Lemon, J. R., "Control of Forced Vibration in Machine Tool/Metal Cutting Systems," USAF Technical Report AFML-TR-67-88, April 1967, 165 pp.
14. Shapton, W. R., Morse, I. E., et. al., "Dynamic Machine Tool Testing," USAF Technical Report AFML-TR-70-79, April 1970, 233 pp.
15. Morse, I. E., Shapton, W. R., Brown, D. L., Kuljanic, E., "Applications of Pulse Testing for Determining Dynamic Characteristics of Machine Tools," 13th International Machine Tool Design and Research Conference, University of Birmingham, England, 1972, 11 pp. (HP Application Note 140-3).
16. Allemang, R. J., Powell, C. D., Graef, H. T., "Dynamic Characteristics of Rotating and Non-Rotating Machine Tool Spindles," ASME Paper Number 73-DET-29, ASME Transactions, *Journal of Engineering for Industry*, Vol. 96, Series B, No. 1, pp. 343-347, 1974.
17. Halvorsen, W. G., Brown, D. L., "Impulse Technique for Structural Frequency Response Testing," *Sound and Vibration*, November, 1977, pp. 8-21.
18. Brown, D. L., Allemang, R. J., Zimmerman, R. D., Mergeay, M.,"Parameter Estimation Techniques for Modal Analysis," SAE Paper No. 790221, SAE Transactions, Vol. 88, pp. 828-846, 1979. SV

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