Thirty Years of FFT Analyzers . . .

Sri Welaratna, Data Physics Corporation, San Jose, California

This is a story of passion, triumph and heartache. People, when their imagination is captured by an idea, can become energized and deeply involved, producing remarkable results and reaching new heights that lead to the creation of landmarks in the progress of man. The Fast Fourier Transform (FFT) was such an idea.

Cooley and Tukey published their historic paper on the computation of the Fourier transform in 1965. Overnight, in universities and laboratories around the world, scientists and engineers began developing computer programs and electronic circuits to implement the FFT.

The FFT is a brilliant technique for computing the (discrete) Fourier transform quickly. By recognizing that the Fourier transform of a sequence can be derived from the Fourier transforms of two half length sequences more economically than if the whole sequence is transformed directly and by carrying this concept through to its logical conclusion of evaluating only the direct transform of sequences of two terms, Cooley and Tukey showed that the FFT required only $N \times \log_2(N)$ operations while the direct form took N^2 operations. This meant that a 1024 term FFT would take one hundredth the time it would have taken before. Not only was it faster, it also could be evaluated in-place, requiring only half the amount of then scarce electronic memory. It is not difficult to see why the FFT captured the minds and hearts of scientists and engineers. In spite of the oft mentioned description of scientists as automatons, without touch and feel, we are all romantics at heart able to separate poetry from prose.

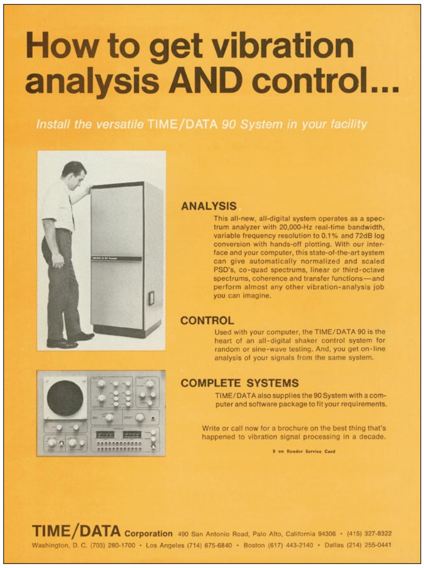
> *The Fourier transform today touches the lives of everyone. It does so in the form of superior automobiles, aircraft, telecommunications systems, chain saws, washing machines and myriad other aspects of modern life.*

Ed Sloan was an engineer working on tape recorders at Ampex in Palo Alto when he came across the Danielson and Lanczos technique for speeding up the computation of the Fourier transform published in the *Franklin Journal* in 1942. Having failed to get Ampex interested in the idea of a Fourier transform instrument, Ed rounded up a group of private investors (venture capitalists were not yet an identified breed) in early 1966, to finance his start-up company, Time/Data Corporation. Ed Sloan, often described as "a certifiable genius," with the help of another brilliant young engineer named Bruce McKeever, was discovering larger computational efficiencies over the "Frequency Folding" technique of Danielson and Lanczos when they were shown the Cooley-Tukey paper that had been published the year before. Heartbreak, over being beaten to the goalpost by someone else, soon gave way to enthusiasm to build an FFT machine; and Ed and Bruce rolled out their FFT instrument in October 1967. The Time/Data 100 consisted of two six foot racks of purpose built hardware, performed a 1024 point FFT in 1 sec, and was a tremendous technical achievement.

Unfortunately, the equally large commercial success it was expected to become didn't happen. Nearly thirty customers had been canvassed, all of them in medical applications, who had funding approved from the National Institute for Health when the Johnson government diverted the funds to the Vietnam war effort.

This time the heartbreak was difficult to deal with and only an accident of fate revived the fortunes of Time/Data. The F111 fighter aircraft that sported variable swept wings was in trouble – the wings fell off in flight! The Air Force had given an ultimatum to General Dynamics that no more aircraft would be accepted without proof of wing integrity. Faced with a field full of planes that were undeliverable, General Dynamics was ready to move heaven and earth in search of a solution. A young MIT graduate named Jim Green at General Dynamics remembered his grandfather testing steel rails by hoisting each rail in the middle, hitting each end with a calibrated hammer and listening to the ringing. His grandfather was able to detect cracks in the rails with remarkable accuracy. Jim convinced himself that this could be made into a science and called around for likely sources. He found Time/Data and after a weekend of analyzing tape recordings of aircraft wing impact tests with Bruce McKeever, General Dynamics discovered their measuring instrument. The acceleration signals measured from wings with cracked pivot holes showed characteristic frequency spectra, thus providing an unmistakable method of detection.

The Air Force commandeered the first available Time/Data 100, bumping others in line and the company received a tremendous boost in the marketplace. Soon, vibration applications would be added to the list of uses for the FFT instrument, which had up until then, found most of



Time/Data 90 FFT Processor, November 1969.

Hewlett-Packard 5451A Fourier Analyzer, December 1972.

its uses in medical applications including the Stanford sleep studies of 1967. The Time/Data 100 was followed by the Time/Data 90 which provided speedup of the FFT in a general purpose minicomputer system. An improved version, based on the PDP11, was marketed as the Time/Data 1923 in 1972.

When the private investors wanted to cash out, General Radio bought Time/Data. Since the new owners probably never understood what they had bought, they failed to provide the environment in which Ed Sloan, Bruce McKeever and the scores of other bright men who followed could have realized their dreams. Bruce still drives around in a car carrying the registration FFT. While the passion has subsided, he has not entirely forgotten the heady excitement of the early period.

About the same time, at the Santa Clara division of Hewlett-Packard, an unassuming young engineer named Ron Potter set out to develop a waveform calcu-

Nicolet Scientific Corporation 440A Mini-Ubiquitous® real-time spectrum analyzer, September 1975.

Spectral Dynamics Corporation SD360 Digital Signal Processor, November 1975.

Computational Systems, Inc. Wavepak® FFT Signal Analyzer, September 1985.

lator that would allow computations on waveforms and their spectra rather like a hand held calculator could do with individual numbers.

Ron Potter had studied electronics at the University of Illinois and taught himself to program on the ENIAC, which had 1024 words of 40 bit memory, no drum nor disk storage, but did have a CRT display and a camera. He was able to plot the cubic polynomial he had derived as the step response of a two pole amplifier and published one of the earliest papers on the use of a digital computer in *Radio Applications*. Ron Potter is a true genius; there have been few men who have understood the measurement and analysis of physical phenomena as well as he and everyone who worked with him knew "he walked on water."

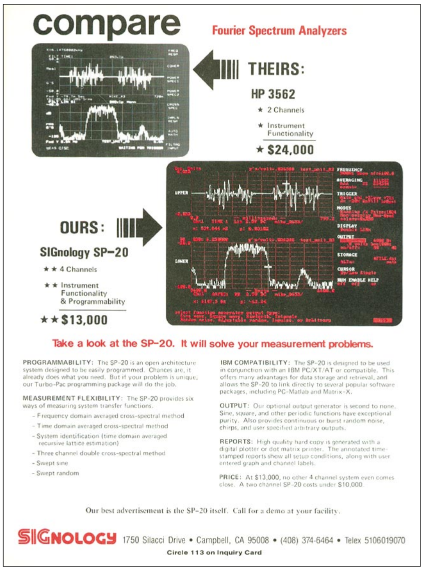
Correlation was gaining momentum as a technique for pulling signals out of noise and studying physical systems. The evaluation of a spectrum took too much computational effort to be practical and there was a debate on as to what was better. When the Cooley-Tukey paper appeared, Ron understood the algorithm and its significance immediately. The cornerstone of his new instrument would be the FFT. Ron Potter worked out the mathematics, Ago Kiss worked on the hardware and Pete Roth joined to build the ADC (Analog to Digital Converter).

In the typical product development style of HP, they assembled a simulator in a six foot rack of equipment comprising of a PDP minicomputer, an ADC for capturing the signals, a CRT device for waveform display, a paper tape reader for program input and a teletype for interacting with the system. In those days, Bill Hewlett and Dave Packard personally reviewed every new product idea. After being presented with a demonstration of the waveform calculator in gestation, it was Packard who suggested that they sell the simulator as the product itself. HP was just getting into the computer business at that time and Ron received one of the first prototype computers from the Cupertino division. It quickly replaced the rival Digital Equipment Corporation's PDP computer; the HP 5450 Fourier Analyzer was born. Ron Potter who had made history as the father of the Fourier analyzer had briefly left the company and it was Pete Roth who was in charge when this revolutionary instrument/computer system was brought to market. There were a number of other bright engineers who wrote the software and developed the hardware: Skip Ross, Steve Cline, Chuck Hershkowitz and Charlie Heisman among them. But, if not for Al Bagley, the Frequency & Time Division Manager, who acted as the inspiration and supported Packard's idea, the Fourier analyzer may not have been born, at least not in that form.

The first customer for the HP Fourier Analyzer was the Walter Reed Hospital in Maryland, where they were studying neural responses of monkeys. Dave Snyder, another bright engineer who had just joined the team, went east with Pete Roth to install and train the users. They never imagined that eventually the product would find its focus in noise and vibration applications. There were to be many false starts in a number of applications before HP would discover a market for the FFT technology. Bob Perdriau, who joined the digital signal analysis group at HP Santa Clara to produce the HP5453 telephone test system, the first derivative of the Fourier Analyzer, remembers the excitement and fervor among the team members. The HP5453 never took off and the politics and economics of business left behind a few more young men with hearts full of sorrow. Fortunately, a significant business grew around the HP-5451 Fourier Analyzer with applications in closed loop shaker control for vibration testing, modal analysis of mechanical structures and machine signatures of rotating equipment.

Far away in Yonkers, New York's Harlem (fondly referred to as upper Manhattan), Henry Bickel had started a business named Federal Scientific Corporation with four professors from Columbia University to develop long range missile detection technology for the Defense Department. Federal Scientific carved out a niche for itself with the 'Ubiquitous®' series of real-time analyzers based on time-compression techniques. Their largest success was a contract to supply submarine detection instrumentation for the fleet of P3 Orion Aircraft. It was after Nicolet had acquired Federal Scientific and the FFT business was in full swing that Federal made its first single channel FFT analyzer called the 'Mini-Ubiquitous®' 440A. The 440A, its progeny and its companion, the two channel 660, were to make their mark during the second wave of FFT analyzers.

Yet another young man, Laurie Burrows left the Convair Instrument Division of General Dynamics, which had fallen on hard times, to start a company in San Diego with Hugh Ness and a couple of others. They named their company Spectral Dynamics after General Dynamics and bought the rights to the tracking filter that Laurie had developed while at General Dynamics for use in the 880 and 990 aircraft. Laurie's tracking filter used a low cost HP oscillator in place of an expensive precision oscillator to cut the cost to a tenth of the rival instruments. Initially, Spectral Dynamics made tracking filters, but later they built real-time analyzers using the time compression technology patented by Victor Anderson who worked for the Naval Research Lab in San Diego. While they did not build a first generation FFT instrument until 1975 when the SD360 was introduced, they joined the fray in full force with the



SIGnology SP-20 Fourier Spectrum Analyzer, January 1987.

Data Physics Corporation DP420 FFT Analyzer, June 1989.

Scientific Atlanta SD390 Dynamic Signal Analyzer, February 1993.

SD380 which commanded a significant segment of the FFT market in the second wave.

There was a sense of excitement in the air at all these places, the feeling that once a waveform was captured in digital form and available in a computer, there was no limit to the measurements that could be derived. In effect, this was a universal instrument, making obsolete all others. Of course, nothing is quite so simple and the measurement of physical processes demands a lot more than a digitizer and a computer.

The first FFT analyzers came in a six foot high, 19 in. wide rack with a visible minicomputer, CRT display device, analog to digital converter, optional digital to analog converter, paper tape reader, and a teletype. At Hewlett-Packard, every project to create a faster FFT device with dedicated hardware FFT ran into competition from the ever faster computer. Dave Snyder remembers how his microcoded FFT in the 5451B made obsolete in one stroke, the 5471 hardwired FFT box. At GenRad, Bruce McKeever acknowledges that having first made a dedicated hardware FFT system in the Time/Data 100, they quickly changed to a general computer system for the Time/Data 1923, though still using a speedup box for the FFT. At HP, Webb McKinney invented band selectable Fourier analysis to yield higher frequency resolution from a limited available memory. Zoom transform, as it later came to be called, was a significant milestone.

An unsung hero of the FFT revolution, Norm Rodgers was a quiet engineer working at GenRad who one day announced to his colleagues that he had something to show. It was a breathtaking revelation. He had all by himself invented an entire programming system, inclusive of language, that would allow users to build new measurements extending the basic instrument. TSL (Time Series Language) was born and became the backbone of many new applications that were developed later, including modal analysis and vibration exciter control systems.

The first ten years were exciting but painful. The market remained small and narrow, both Hewlett-Packard and GenRad found it difficult to make the business grow in the model of the rest of their business. Spectral Dynamics and Nicolet had entered the fray, competition was becoming fierce and attention turned to applications. Dick Watts had worked on correlators at HP South Queensferry in the UK and had moved to Santa Clara. While Dick was marketing manager for FFT products, HP tried a bold experiment to create a specialist sales and application group to promote the products. This achieved instant success and attracted another band of enthusiasts who embraced the science with the same fervor, but HP always had difficulty dealing with primadonnas and eventually disbanded the special sales force in order to normalize its instrument sales operations, breaking the hearts of those who by then were bitten by the bug and enjoying their Camelot.

The Second Wave. The second wave of FFT analyzers came almost exactly at the end of the first decade. Gone were the visible computers. The weight was down to around 70 lbs. The most noticeable change was the lower price, instead of costing $50,000 to $100,000, they were now much more accessible at $20,000 to $50,000. The HP5420, GR2508, SD360 and the Nicolet 446A and 660B dominated the scene. Brüel & Kjær from Denmark, the undisputed leader in acoustical instrumentation had held out for a long time against the digital revolution, but the FFT analyzer was too large a force to resist and when they did join the bandwagon, their offering was significant. The B&K Type 2032 was the first to incorporate a larger capture buffer in the front-end allowing reanalysis of captured data with selective overlap.

The biggest surprise came from an unexpected quarter, another division of HP at Loveland, CO, brought out the two channel HP3582 at around $12,000 and in a small package, but weighing 55 lbs. The HP3582 changed the FFT analyzer business overnight, selling four times as many units as its nearest competitor; it was a runaway success. Nicolet and Rockland found the competition very tough and bowed out. Another romantic, George Fox Lang, left the ashes of Nicolet to carve out a niche informing and amusing us through *Sound and Vibration* magazine.

For a while HP, GenRad, B&K and Spectral Dynamics shared the spoils. One of the biggest casualties was the Santa Clara Division of HP, which had been the Mecca of digital signal analysis at HP. The Loveland Division had packaged the zoom transform on four chips. This function occupied at least four large printed circuit assemblies in every other instrument. The HP3582 was a very good instrument. Although it was short on memory and therefore lines of resolution, it became a workhorse in the industry. What they had done was nothing more than another milestone in the inevitable march of electronics towards smaller and faster devices. This was what HP was good at, but to the faithful at Santa Clara it was a bitter pill. Progress had come not from the development of applications but miniaturization and reduction of cost.

The second decade of the FFT analyzer was also dominated by the emergence of the applications into significant sciences. Four distinct areas of application of the FFT analyzer emerged.

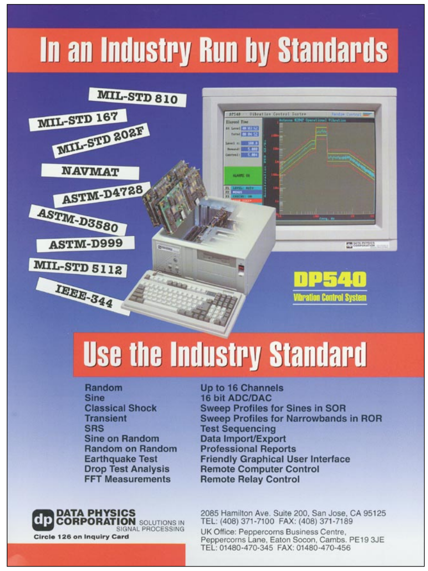
Modal analysis, popularized by Dave Brown at the University of Cincinnati, captured the imagination of engineers. The ability to identify the modes of vibration of a structure and extract individual mode shapes from a set of frequency response functions was a remarkable achievement. The ability to display each mode in animation made them ecstatic. The HP5423 Structural Dynamic Analyzer was the first of many instruments dedicated to modal analysis. Unfortunately, HP's search for success in the traditional packaging of technology to create ever increasing markets did not leave room for technologies that could not yield market size. The HP5423 marked the end of HP's direct involvement in modal testing applications. They chose instead to remain a supplier of general purpose FFT instruments.

Four modal aficionados left to form Structural Measurement Systems led by Mark Richardson. In Belgium, a University of Leuven alumnus, Maurice Mergeay started Leuven Measurement Systems (LMS) which would eventually dominate the field, though by then he would have left the company, not fitting into the politics within. Dave Formenti, one of the four founders of SMS remembers the sweet agony of labor, relentlessly pursuing modal analysis applications. Ten years after its founding, SMS was acquired by the Structural Test Products division of GenRad where SMS failed to flourish because once again GenRad failed to understand what they had bought.

Digital vibration control, though it did not have as much 'sizzle,' emerged as a significant application. A shaker could be controlled to reproduce a vibration environment in the laboratory with remarkable accuracy. Random vibration experienced in a vehicle on the road, shock experienced in dropping something on the floor or the periodic vibration produced by an engine speeding up – all could be simulated in the laboratory saving tremendous man hours of product qualification. The first applications appeared as software add-ons to the GR1921 and the HP5451 but by 1980 dedicated vibration controllers had taken over with the HP5427, GR2511 and the SD1700 series dominating this burgeoning business.

The growth of digital vibration control, which had brought large improvements in accuracy and speed over the analog systems with banks of parallel filters, fueled growth at Spectral Dynamics, GenRad and HP. Spectral Dynamics had their own Camelot in the period following the first wave and was a haven for many committed signal analysis professionals, until they were acquired by Scientific Atlanta. GenRad continued to sell vibration controllers long after HP and SD had left the field thus becoming the company with the largest installed base.

Signature analysis of rotating equipment was a distant third in appeal and size of application. The three dimensional RPM-spectral map is a remarkable method of separating vibration due to



Data Physics Corporation DP540 Vibration Control System, November 1994.

Data Physics Corporation DP104 FFT Analyzer, November 1996.

structural resonance from that due to rotating masses. The derived plots of order tracks provide a means of identifying vibration causing mechanisms. Engine run-up and coast-down waterfall maps became available with the first Fourier analyzers and have since become a standard feature in the majority of analyzers that followed.

Acoustic intensity was a new measurement technique in 1979. Two microphones spaced a few mm apart could be used to measure not only the magnitude of sound intensity but also its direction. The FFT-based cross power spectrum computation between the two microphone signals could be used to derive the sound intensity. This technique has been successfully used to identify sound-radiating components in internal combustion engines and other machines. B&K, with their superior position in acoustical applications and dominance of precision measurement microphone technology, has been the best proponent of acoustic intensity measurement. While the number of users of this measurement technique remains modest, it has, nevertheless, become an important feature in FFT instrumentation.

The growth of any business lies not in making and selling clever instruments, however fascinating the inventions may be, but in making a contribution to the business of the users who pay for them. The FFT analyzer was no exception. It was the growth of the applications that made a growth business for its suppliers. An editorial comment in the October 1969 edition of *Sound and Vibration* by its publisher, Jack Mowry, is worth repeating ". . . the man who recognizes your applications, understands what he's selling and fits his products to your needs, is going to get the order. One buys a hammer to pound nails, not just to have a hammer." An astute commentary by a young man at the time, Jack knew what he was talking about.

The Third Wave. The third decade brought about the FFT analyzer on a card to be plugged into a PC. IBM had introduced the PC, setting in motion a revolution in the way we would make measurements. In the beginning, many FFT analyzers could be connected to a computer by an IEEE488 or RS232 interface cable, providing connectivity between the measurements and further analysis programs. The inclusion of the measuring instrument within the computer would benefit all, and the advent of the digital signal processor would make this possible. DSP (Digital Signal Processor) chips are remarkable; they are nearly complete computers, optimized for vector operations and especially, the computation of the FFT. The second generation DSP chips that became popular in FFT analyzers around 1986 could perform a 1024 point FFT in under 10 msec. Miniaturization and the commensurate reduction in cost had taken its next jump. A complete two channel FFT analyzer appeared on a single PC I/O card, the price of which came down to a range of $10,000 to $20,000. Even the instruments in conventional boxes came down to under 25 lbs in weight.

CSI Wavepak®, Data Physics DP420 and the SD390 PC-based analyzers took their place among the traditional FFT instruments from HP and B&K. SIGnology introduced a DSP solution in a separate box attached to the computer. In addition to the normal attributes of FFT instruments, the PC-based analyzers were able to provide better graphics and vastly improved user interfaces. As graphical user interfaces became popular in PC applications, HP and Tektronix also produced their own PC-based analysis systems, but with the data capture and signal processing hardware in an external box connected to the PC. The rapid development of the PC in speed and capacity has brought about corresponding improvements in the analyzers built upon them. The formula of modifying a general purpose computer to make an FFT analyzer claiming the benefits of the independent development of computer technology had come full circle to that of the first generation.

The FFT processor card within the PC also proved to be an ideal solution for the vibration control application. The Data Physics DP540 debuted in 1990, redefining the price/performance standards of a shaker controller. Initially used primarily in defense applications, the price reduction from the $60,000 to $100,000 range to the $20,000 to $50,000 range brought the technology within the grasp of a larger number of commercial applications.

The Future. A decade later, as we celebrate the 30th year of *Sound and Vibration* magazine, the FFT analyzer is about to register its next quantum leap. A complete analyzer weighing only 1.8 oz. has been introduced by Data Physics providing phenomenal performance: 20 kHz trispectrum real-time rate, 64k max transform size and 100 dB dynamic range. This tiny module plugs into any type III PCMCIA slot in any notebook computer running Windows 95 and provides a full repertoire of time, frequency and amplitude domain measurements. As you might expect, the cost of the FFT analyzer has made a corresponding leap downward. The entire package of notebook computer and FFT analyzer weighs about 6 lbs, painting visions of vibration engineers spending the day with their lightweight instrument and then writing their reports on the way home using the same system.

Those who began their careers with the first FFT analyzers and remember lugging huge bays of instruments around in wagons and trailers would look at this latest FFT analyzer in your palm and either cry for joy or shed tears in regret. But, none would fail to be amazed at what is truly a remarkable journey of technological accomplishment.

Epilog. The author wishes to thank all those who gave of their time and volunteered information about the early days. It has been the most enjoyable task I have undertaken in a long time, listening to colleagues reminisce about the glorious past and indulging in my own nostalgia. Some of you poured your hearts out, surprising me with the intensity of feeling for your work going back thirty years. The satisfaction of intellectual endeavor, the exhilaration of scientific discovery and the warm glow that comes with erudition when your mathematical models fit the physics – thank you for sharing your experiences with me. I am sorry time and space did not permit the inclusion of every name and event, some of them omitted in error. This account is highly personal and it probably does not do justice to all. Unfortunately, we cannot see history except through the eyes of the historian. I alone am responsible for the errors and omissions.

Reference. Cooley, J. W., and Tukey, J. W., "An Algorithm for the Machine Calculation of Complex Fourier Series," *Mathematics of Computation*, Vol. 19, 1965.

Sri Welaratna came across the Fourier analyzer in 1970 while doing research at the University of Bradford in England and went to work for Hewlett-Packard, first in Europe and then at Santa Clara. After a brief stint at SMS he founded Data Physics Corporation with Dave Snyder, another alumnus of HP Santa Clara. One of his hobbies is collecting loose ends, loosely defined as wandering signal analysis professionals, who lost their moorings in the shifting tides of corporate mergers.