35 Years of Structural Measurements at Brüel & Kjær

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Both Gade and Herlufsen started working for Brüel & Kjær when the modern era of structural measurements began in the early 1980s. In (Brown and Allemang, *Sound & Vibration*, pp. 19–25, January 2007), it is even argued that the modern era of experimental modal analysis already started one or maybe two decades earlier.

In 1982, we participated at IMAC I, the first international modal analysis conference in Orlando, FL – the time considered when modal analysis changed from being a pure scientific concept to be a practical engineering tool. Many tests were at that time limited to single-input/single-output (SISO) measurements.

In 1983, we were involved with the release of B&K's first dual-channel signal analyzer. Today dual-channel FFT analysis is the established method of performing frequency response function measurements used for what we might call classical mobility-based modal testing and analysis.

Over the years, we have seen progress and development in all fields of the measurement chain – from the input vibration transducers via signal conditioning to the analog to digital conversion, real-time and post-processing of functions followed by modal parameter estimation and applications of the modal model.

This article deals with what we see (and we both have been involved with from a B&K perspective) as some of the most important steps achieved in this progress. Today it is not unusual that modal analysis is performed using several hundred high-dynamic-range measurement channels connected to dedicated smart modal accelerometers (with built-in transducer electronic data sheets (TEDS) doing multiple-input/multiple output (MIMO) measurements with automated modal parameter estimation and model correlation with large finite-element models.

We were both employed during the first half of 1980 as application engineers at the B&K sales department/headquarters in Denmark. Some of our first responsibilities were to run frequency analysis and digital signal analysis courses both internally and for customers. Our reference books were *Frequency Analysis* written by Bob Randall,[1] who was also our colleague back then, as well as a Fourier analysis book written by Oran Brigham.[2] From these sources and our colleague/mentor Niels Thrane, we learned what we initially needed to know about analog and digital frequency analysis.

Using digital techniques was rather new to many of our customers and colleagues, so there was really a need for training people in topics like fast-Fourier-transform (FFT), sampling, aliasing, convolution, weighting functions, uncertainty principle, units/scaling, etc., and also to operate and demonstrate the new and more complex digital instrumentation. At that time our digital analyzers were single-channel instruments basically measuring auto spectra either by digital filtering (1/n octaves – acoustics) or FFT (narrowband – vibration) techniques, but B&K was in process of developing the Dual-Channel Signal Analyzer Type 2032, including preparing the largest release activity at that time. We were heavily involved with testing the functionality, learning and understanding the dual-channel concept, including reading/studying a newly released and very inspiring book of Bendat & Piersol,[3] and much more. In addition, we were writing application notes, sales training notes and even one of the manuals for the dual-channel analyzer.

On April 1, 1983, several application/sales engineers in groups of two went on a worldwide tour introducing the Type 2032 analyzer, which became an instant success for B&K, see Reference 4, Chapter 19. Carrying two 2032 analyzers with last-minute updates, Herlufsen and Gade started their tour in the UK by rushing in a Volvo station wagon from Copenhagen to Harwich to reach the ferry from Esbjerg just in a nick of time. We carried transducers (including a newly developed modal impact hammer), and we were on the road for quite some time covering several countries. Probably the most important new application we introduced and demonstrated was hammer-based mobility measurements and information about the easy extension from dual-channel FRF measurements to modal analysis.

Figure 1. Multichannel Analysis System Type 3550 with a typical dual-channel mobility shaker setup.

Cross-Spectrum Signal Analyzers

Besides a very large display, Dual Channel Signal Analyzer Type 2032 was unique in several ways. It was the first analyzer on the market that used the concept of measuring at any time what we called "total documentation," namely the two autospectra and the complex cross-spectrum (and the last block of the two input time signals). All other functions were just derived/post-processed (in real time) from these fundamental three spectra. The list of functions was long (actually 34), FRF, coherence, impulse response function, auto- and cross-correlation, cepstra and sound intensity, just to mention a few.

Type 2032 was using three processors in parallel that worked independent of each other, ensuring the same high real-time speed of 6 kHz (in dual-channel mode) no matter what kind of function was displayed during measurements. A measurement processor controlled by a measurement setup was processing the three basic spectra; a display processor controlled by display setup parameters made further processing of the three basic spectra ensuring a reasonable high-update live display performance of the desired functions. Finally, a zoom processor was used for decimation (including low-pass filtering and zooming) of data.

In contrast to other companies on the market, we decided to use the terminology *frequency response function* (frequency domain) rather than *transfer function* (Laplace domain), since at least in modal analysis application, it is important to clearly distinguish between these two domains. Most other companies called their similar instruments *transfer function* analyzers (TFA). Furthermore, it was the first analyzer on the market that offered several different FRF estimators, H_1, H_2 and H_3, to handle noise at either input or output. A 2034 version with reduced real-time speed was available for embargo reasons.

We knew there was a need for more than just two channels in modal applications, but it was not until 1991 before Multichannel

Figure 2. MIMO based on 16-channel Type 3550/3551 system.

Figure 3. Type LAN-XI 3660-D-100 frame (GSP support) with removable LAN-XI modules.

Analysis System Type 3550 (Type 2035 Signal Analyzer Unit in Dual Channel configuration) was ready for release. Type 3550 was based on the same principles and quite similar hardware as Type 2032 but visually extended with a floppy disk drive, see Figure 1. This analyzer had a number of advanced options such as order-tracking analysis, 100 kHz frequency range, multichannel option, etc. The maximum number of channels was 16, and the 3550 was able to do MIMO (Multiple Input Multiple Output0 measurements. In practical situations, MIMO was basically limited to two inputs (two shakers, see Figure 2) to limit the number of cross-spectra calculations and for not reducing the number of FFT lines from the "standard" 800 lines.

Meanwhile, personal computers entered the market, and Type 3550 was based on older technology. So we developed the so-called PULSE analysis system, which we introduced in 1996. It was unique in several ways. It was the first multichannel (up to a maximum of 32 channels at release) real-time analysis system on the market that was PC and MS Windows (Windows NT Ver. 3.51) based and being able to do multi-analysis, or the possibility of doing various analysis tasks simultaneously including direct reporting in MS Office. The number of FFT lines were selectable in binary steps from 50 to 6400 and nearly eliminated the need for zoom measurements.

The first release was based on the 3550 input modules, but today PULSE is using its fifth-generation of hardware (see Figure 3). Some of the major hardware improvements over the years include: First extending the original 32-channel limit several times, todays LAN-XI system architecture has in principle no channel limitations, any limit resides in the PC configuration. Real-time systems with up to hundreds of measurement channels have been tested and delivered to users. Other improvements are in terms of dynamic range going from 16-bit ADCs to 24-bit and finally in 2005 to 2×24 bit – called Dyn-X (dynamics extreme) technology[5] that efficiently offers 160 dB dynamic range in narrow-band analysis. For the user, it means that there is no attenuator setting to worry about (one range covers all), so no need to make preliminary measurements as long as transducers with a proper sensitivity have been chosen for the actual application.

Typically, one system has been used for measuring the basic FRF data (e.g. PULSE LabShop signal analysis software), and another system (modal analysis software) is used for modal parameter estimation, although both systems may be running in the same PC just exchanging data using export/import facilities. The PULSE Reflex Structural Measurement (released 2015) is a fully integrated system (hardware as well as software) performing all tasks (measurement, analysis, postprocessing, automated reporting) of modal testing. That includes MIMO measurements, modal parameter estimation, validating modal model, correlating test models with finite-element models to finally creating automated reports in MS Office.

The latest LAN-XI hardware frame Type 3660-C/D-100 (2014) supports synchronous measurement via the global positioning synchronization (GPS) clock due to built-in GPS receivers (see Figure 3). This is useful when performing a modal test on large structures, especially for operational modal analysis (OMA) applications. A number of completely independent (unconnected) PULSE data acquisition systems can make data recordings in synchronism with each other. One example of this would use an independent measurement system on each floor of a large building to make phase synchronous data recordings that can be used for cross-spectra (FRF) calculations between any channel from any frame and finally performing modal parameter estimation in reflex modal.

The PULSE Reflex software platform has recently changed from being a 32-bit to a 64-bit version (in year 2015). This ensures use of more memory capacity and supports larger datasets, especially when correlating and comparing large finite-element models against test models.

Modal Analysis Software

When B&K released the dual-channel Type 2032 analyzer, the company was entirely focusing on developing hardware products, so there was a need for working with modal software vendors to offer complete solutions. In 1980, we had one HP9825 computer and one programmer in the sales department so he could demonstrate to customers that it was possible to program and control our digital analyzers via the IEEE 488 interface.

Our first partner was Structural Measurement System, SMS, a company founded by Mark Richardson, Ken Ramsey, Don Kientzy and Dave Formenti in 1979. The SMS people had great experience from developing the first modal analysis software for Hewlett Packard, the Type HP5423A Structural Dynamics Analyzer released in 1979. The first SMS modal software structural testing and analysis system, STAS, was running in HP computers, where you had to load the Basic 2.0 operating and programming software followed by loading the STAS software using 5.25-inch floppy disks[16] before any work could take place. No built-in HDD or SSD, of course, were available at that time. Communication between analyzer and HP computer took place over the IEEE 488 cable and interface. STAS was command driven, so you had to learn all necessary commands and parameters by heart, or you had to have the manual open next to you at all times. This was not very user friendly by today's standards – but was the state of the art at the time.

SMS created the first Windows-based modal software (STAR Modal, Structural Analysis and Reporting System) in 1985, but had to wait until IMAC V, 1987 for its first official release. This became a very popular platform due to its intuitive user interface and sold by B&K to many users worldwide. The STAR software is today a product of Spectral Dynamics.

When we entered the multichannel market around 1990, B&K and Leuven Measurement Systems (LMS) started cooperating on multichannel systems. B&K delivered multichannel hardware (a Model 3550-based front-end system called 3551), and LMS the necessary software, the UNIX based CADA-X. For smaller systems (dual channel), B&K delivered the Type 3550 analyzer together with a LMS Windows-based modal software called CADA-PC Modal. One important issue was that B&K was constantly behind the market with respect to the number of measurement channels in the early '90s due to long development times. When the market needed

Figure 4. Type 8208 impact hammer.

Figure 5. Type 4826 modal exciter.

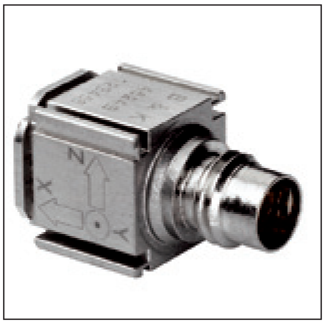

Figure 6. Type 4524 triaxial accelerometer with mounting slots.

Figure 7. The 4506 triaxial accelerometer mounted on swivel base.

Figure 8. Type 4506 triaxial accelerometer with data matrix code.

16 channels B&K, offered two channels. Then we made 16 channels but now there was a need for 32 channels. When the 32-channel front end was ready, the market needed 64 channels and a 32-channel front end was the last system we offered on that platform, although there was a need for 128 channels we were told.

Finally, cooperation with LMS ended since LMS was regarded to be a competitor rather than a partner. B&K introduced its next-generation multichannel hardware, Intelligent Data Acquisition (IDA) in 1995 to be used by the PULSE LabShop system from 1999. IDA multichannel systems offered a considerable cost reduction per measurement channel compared to the 3550/3551 hardware solutions.

After the LMS adventure, B&K went back again to cooperate with Mark Richardson, who had sold the STAR Modal software to Spectral Dynamics and founded a new company Vibrant Technology, Inc. in 1991. Their main product was the modal software ME'scope (later ME'scopeVES). For many years, ME'scope became the preferred modal software supporting our Type 3550 and PULSE systems.

In 2001, we released the first version of a new analysis technique called "output-only" modal analysis, also known as ambient modal or operational modal analysis (OMA) for *in-situ* measurements.[20] The software was developed by Structural Vibration Solutions A/S, SVS (Palle Andersen) in cooperation with and support by B&K (product manager Niels-Jørgen Jacobsen) and is today the preferred "output-only" software on the market with many users worldwide.

SVS calls the product ARTeMIS (ambient response testing and modal identification software). The primary use was for extracting modal parameters of civil engineering structures and soon for mechanical structures under operating conditions as well. The advantage of the method is that no artificial excitation needs to be applied to the structure or force signals to be measured. The parameter estimation is based on response signals only, minimizing the test preparation work.

Two very different estimation techniques are included: a nonparametric (and patented) frequency domain decomposition (FDD) technique, and a parametric data driven stochastic subspace identification (SSI) algorithm. Instantly the FDD became a popular method because it was fast, simple to use, and easy to understand. The SSI method was difficult to understand and required, in the beginning, extensive computer calculations. (Typically an analysis of even a small test required calculations for several hours.) There have been many improvements over the years, so today the parameter estimation method is fully automated, making the SSI method as fast as and as well accepted/understood as the FDD method. Modal parameter estimation using current PC technology takes just a few seconds even for large-scale testing.

B&K took over the Test for I-deas product portfolio in 2006 after MTS Corporation's Noise and Vibration Division closed down. Structural Dynamics Research Corporation (SDRC) originally developed Test for I-deas. Over time, it was decided to move this modal product from the UNIX platform to Windows and is presently supported on maintenance contracts. PULSE Reflex Modal software was first released in 2009. Today, the Reflex Structural Analysis solution is a mature product and comprises modal analysis (including structural measurements), model correlation, operating deflection shapes (ODS) and shock response analysis. Reflex modal and correlation software are offered in exchange today free of charge on a one-to-one basis for Test for I-deas users on maintenance contracts.

There's hardly a need to mention that there has been a tremendous improvement in modal-parameter estimation (earlier called curve-fitting) algorithms, but it is outside the scope of this article to go into detail. We have seen the market moving from simple manually controlled local mono-reference SDOF (single degree of freedom) curve fitters to advanced fully automated global polyreference MDOF (multi degree of freedom) parameter estimation methods.[21]

Modal Test Software

One of the first dedicated applications on the PULSE LabShop platform was Modal Test Consultant (MTC) released in 1999. This has also been one of the most popular PULSE applications over the years. MTC is an application on top of the PULSE measurement platform and guides the user through a complete modal test. Typical steps include selecting hardware and transducers, creating geometry, defining degrees of freedom (DOFs) and measurement sequence. Predefined setups are then chosen for hammer or shaker testing, including ratio calibration to perform geometry-driven measurement. Finally measurement validation is carried out: this is done via FRF-based geometry animation and exporting the data (measurements, DOFs and geometry) to a user-selected modal software or to disk in, for example, the widely accepted universal file format (UFF). MTC has dedicated measurement templates for hammer, shaker (including MIMO), ODS and OMA tests.

As mentioned earlier, support of structural measurements has been added to the Reflex platform with a great number of improvements and enhancements compared to MTC. Included (2016) is the use of geometry driven SIMO and MIMO stepped sine excitation and analysis, which has a number of advantages in structural testing including forced vibration analysis and check and control of non-linearities. It is especially used for testing of larger and/or complex structures.

Modal Test Transducers

Besides introducing a wide range of modal hammers (Figure 4, for example) and shakers (Figure 5 for example) over the past 35 years many advances have taken place in the design of modal response transducers (accelerometers) and signal conditioning. Actually B&K introduced its first accelerometer as early as 1943.[18] Typical accelerometers in the early 1980s were charge accelerometers connecting to the analyzer input via a charge-conditioning preamplifier, such as the widely used B&K Charge Amplifier Type 2635. This offered high-quality measurements with a wide frequency range, high- and low-pass filters, adjustable gain, etc, but was an expensive solution per measurement channel.

The introduction of accelerometers with built-in charge-to-voltage converter reduced price per measurement channel considerably without compromising accuracy for modal analysis, which is a typical low-to-mid-frequency-range application. This technological development allowed the accelerometer 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. Kistler already introduced the principle as early as 1965. These types of vibration transducers have a variety of names depending on the manufacturer. Names like Piezotron™, ICP® (integrated circuit piezoelectric), DeltaTron®, CCLD (constant-current line drive), IEPE (integrated electronic piezoelectric) are often seen. B&K was late on the market with CCLD because it had developed a slightly different principle called CVLD (constant-voltage line drive), but it was the CCLD principle that became the de facto standard.

In 1999, smart accelerometers were introduced by Brüel & Kjær. These are transducers with a small built-in chip containing transducer information such as manufacturer, type, serial number, sensitivity, calibration, polarity and resonance frequency. The user can also type in information like measurement position ID (DOF information) using an editing program. The information is then automatically identified/read by a smart-transducer-compatible measurement system. The benefits for the user are less setup time, fewer mistakes and significantly more confidence in measured data, especially for a high channel count. Smart transducers are also called TEDS (transducer electronic data sheet) transducers, and the information in the chip is designed according to the accepted IEEE 1451.4 TEDS standard that was finalized in 2004. B&K developed the template-based protocol structure that is used in TEDS.

Modern dedicated modal accelerometers are of cubic design, giving the possibility of mounting the accelerometer on any of the five measurement surfaces, making it easier to align an accelerometer according to a global rectangular coordinate system, for example, by use of a swivel base, a mounting clip and a spirit level (see Figures 6 and 7). Typical size and weight are 1 cm × 1 cm × 1 cm and 5 grams. There is a wide variety of cubic modal accelerometers with different sensitivities, different cable mounting and there are uni- and tri-axial versions. B&K introduced its first cubic modal accelerometers in 1997 and in 2016 introduced data matrix codes (similar to QR codes™) on accelerometers (see Figure 8). This simplifies and automates multichannel test setups and gives instant access to specifications, calibration and DOF information using a smart phone.[18,19]

IMAC Conference

Brüel & Kjær has joined all IMAC conferences from the very beginning (1982), and both Gade and Herlufsen have participated most years. We normally have one of the largest exhibition booths, and we offer a hospitality event for our customers on (typically) Wednesday evening. Every year B&K presents a couple of conference papers (with quite a few given by Gade and Herlufsen over the years).

At the first of many IMACs, B&K supported the classical modal analysis pre-course (run in the past by modal society celebrities such as David L. Brown, Randall J. Allemang, Peter Avitabile and David Ewins)[7] with hands-on at afternoon sessions. We offered participants hands-on exercises using four complete modal analysis test (both hammer and shaker) and analysis systems using a significant amount of B&K instrumentation, (see Figure 1) as well as highly qualified instructors (Thrane, Døssing, Herlufsen and Gade). Since 2007 Gade and professor Carlos Ventura (University of British Columbia) have been running an IMAC pre-course called Operational Modal Analysis, Background, Theory and Practice. B&K is also involved in the "Basics of Modal Analysis for the New/Young Engineer" sessions organized by Mike Mains. The IMAC homepage is located at https://sem.org/.

IOMAC Conference

After the OMA techniques became mature enough, we decided to exchange and share our knowledge more efficiently by introducing a new international conference with the name International Operational Modal Analysis Conference, IOMAC. About 150 participants have attended each of these conferences. The driving forces behind the two first conferences were the two companies SVS (Rune Brincker) and B&K (Nis B. Møller). The conference is held in Europe during odd years. (The other European modal conference, ISMA, International Conference on Noise and Vibration Engineering, is held on even years in Leuven, Belgium.) The IOMAC locations have been Copenhagen, Denmark in 2005 and 2007, Portonovo, Italy 2009, Istanbul, Turkey 2011, Guimarães, Portugal 2013, Gijón, Spain 2015 and the next IOMAC in 2017 will be held at Ingolstad, Germany, May 8-12. B&K (S. Gade) is a member of the permanent IOMAC committee. Prior to all these conferences S. Gade and C. Ventura have been running an OMA pre-course. The IOMAC homepage is located at http://www.iomac.eu/.

Modal Seminars

In the early 1980s, there was a need for B&K to offer a modal analysis seminar covering all aspects of modal topics.[6] The contents of a generic three-day modal seminar were developed by Niels Thrane, Ole Døssing, Henrik Herlufsen and Svend Gade, and the high-quality lecture material was produced by the B&K literature department, initially as overhead transparencies and later transferred into PowerPoint presentations.[4] The seminar is still on the agenda and held twice every year in Nærum, Denmark, by Gade and Herlufsen (on request at other locations).

Day one introduces mechanical mobility measurements (FFT principles, input/output analysis, excitation techniques and mobility, etc.), and day two introduces modal analysis (SDOF and MDOF models, MIMO and parameter estimation, etc.). Only day three, which is about model scaling, validation and the use of modal model, has seen major changes over the years. Today the focus is on modal model correlation and updating finite-element models as well as more elaborate validation techniques. Ole Døssing made two B&K primers that cover the topics from day one and day two of the course.[11,12] These can be found on B&K's homepage http://bksv.com/.

Computers

Remember that a large amount of the progress for all scientific disciplines is heavily impacted by the continuous development of better and faster computers.[13] The introduction of the personal computer occurred in 1981 with the birth of the IBM PC[14] along with MS DOS and the disk operating system by Microsoft. But we had to wait another four years until 1985 before we saw the release of MS Windows Version 1.0.[17]

IMAC V, in 1987 at Imperial College, London, was the first time B&K brought Windows-operated PCs for our modal exhibition and for the afternoon hands-on modal exercises. According to the legendary Moore's Law from 1965,[15] the increase of processing speed (original number of transistors in circuit boards) is predicted to be doubling every 18 months. A prediction that was still reasonably accurate after the first 10 years in 1975, when Moore's law was re-introduced. This means that the speed of PCs (according to Moore's law) may have been doubled about 25 times for the last 35 years. Two raised to the power of 25 is more than 30 million times!

Summary and Conclusions

Both of us have been working for more than 35 years as application specialists at Brüel & Kjær. We have both been involved in a very wide range of applications within the world of sound and vibration, but we have especially had a focus and interest in modal analysis over the years. So we thought it was time to review the activities we have been involved in for this application area.

Even though the basic principles of modal analysis is nearly unchanged, there have been significant advances in theories and practical implementation as well as in instrumentation of modal testing. We have tried to preserve a great amount of our achieved knowledge in a number of *B&K Technical Reviews* 8,9,10, along with technical papers at conferences and articles in magazines.

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