

New Developments in Multi-channel Test Systems

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ABSTRACT

A significant challenge in successful implementation of large channel count dynamic test systems, like multi-channel modal systems, has been efficient and error free test set-up and data collection. Newly developed instrumentation that digitally communicates self-identifying information (including transducer type and serial number, calibration value and physical location) greatly enhances system performance and drastically reduces the opportunity for human documentation errors. Sensors featuring this **Transducer Electronic Data Sheet** (TEDS, consistent with the impending IEEE P1451.4 standard), in addition to such techniques as sonic digitization for geometry definition and automated data acquisition with computer controlled, bank switching signal conditioners are continually improving accuracy and reducing the per channel price of multi-channel dynamic test systems.

1.0 INTRODUCTION

In the experimental structural dynamics field, the definitive aim has always been to create a modal model for a particular structure. The means are tests and measurements, which must be designed so that they provide sufficient – yet economically compact – information, to extract reliable parameters on which to establish such a model.

With escalating global competition, today's manufacturers are met with ever increasing

customer expectations for improved product quality. This, combined with the fact that the ability to shorten time-to-market of new products is as crucial as ever, has posed great constraints on the large channel count test and measurement community. A quick and efficient test setup that nonetheless provides for accurate and reliable data, has truly become one of the greatest challenges faced by the test and measurement community. It is in this light that the evolution of a dedicated, structured and intelligent multi-channel test system has been executed: A test system that allows for accurate, reliable and consistent measurement data sets from which reliable mathematical models can be established.

2.0 HISTORICAL DEVELOPMENT

The last decade has seen a tremendous development in sensing technologies; low-cost, dedicated large channel count modal sensors - utilized simultaneously in what are now known as modal arrays - have become commercially available, allowing the test engineer to acquire data with greatly increased spatial definition.

In time, with the emergence of new modal sensing technologies, two other very important historical issues should be addressed in order to understand the present state of multi-channel test systems.

Firstly, all modern global parameter estimation techniques break down if, for example, the pole

locations are inconsistent through the data set. Shifted poles may be mistakenly curve fit as additional system poles, basically generating “noise” – whereby the process of pole estimation is further complicated. The practical implication of this fact is obviously that potential time variant sources in the data set must be taken seriously. Variations in transducer loading, temperature, changes in boundary conditions, etc., must be controlled to the absolute limit and the appropriate technique must be carefully chosen for the individual structure. Most often, this means the deployment of a large number of modal sensors, typically in a Multiple Input Multiple Output (MIMO) configuration.

Secondly, relying on accurate, consistent and truly representative data sets for the structure under test, sophisticated Multi Reference (MR) modal parameter estimation techniques have become commercially available. The ability to conduct Multi Reference testing with ease has meant a technological break-through in terms of solving dynamic characterizing problems, in particular within: Large structures, where the sheer size may create problems with regard to the amount of excitation energy it takes to ensure a sufficiently large signal-to-noise ratio, Bi-symmetrical structures (and sometimes even structures of arbitrary geometries) that may exhibit repeated roots, and finally, complex structures in general, where it can be impossible to find one adequate reference – that is, a Degree-of-Freedom (DOF) on the structure that has sufficient participation for all the modes in the frequency range of interest.

From a historical perspective, an interesting note is that obtaining the most consistent, highest quality experimental data sets, as is the case with any successful global parameter estimation technique, typically relies on large channel counts in a MIMO configuration.

The concomitant drive within the modal community toward larger multi-channel testing has meant an ever-increasing focus on intelligent channel management concepts and systems. As discussed in the foregoing, multi-channel vibration measurements are designed produce better mathematical modal models and ultimately better structural solutions. However, multi-channel measurements can also lead to a tangle of cables that will lead to an installation process that is both time-consuming and tedious (Figure 1). Over the course of several continuous hours of set-up, distractions become inevitable. Sensor directions are misread, calibration values are mis-keyed into acquisition software and channel

connections are confused. This loss of concentration leads to the introduction of avoidable human errors into the test setup and an increase in time, effort and ultimately cost.

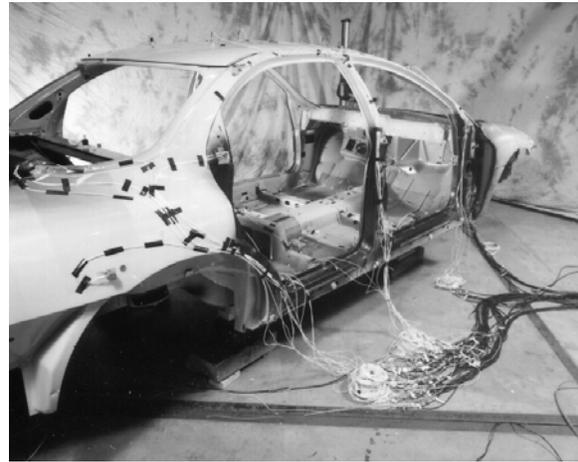


Figure 1 - Individual Coaxial Cables In A Multi-Channel Test
Create a Tangled Nest That Is Managed Efficiently

The first attempt to create a more systematic approach to large-channel-count data acquisition, was taken at the Structural Dynamics Research Laboratory at University of Cincinnati, where several techniques providing improved sensor channel management were developed in the beginning of the 1980's^{1,2}. Incorporating array calibration techniques, bar coding, auto identification and intelligent computer control, these techniques were designed to handle hundreds of parallel sensor channels.

The first practical results using early modal array concepts and multi-channel management concepts, were successful and encouraging for further development. The ability to obtain “snap shot” Frequency Response Function data sets, proved not only to be a tremendous time-saver, but also proved simultaneous acquisition, ensuring time invariance, enhances data consistency and improves over-all data quality^{3,4}. This helps obtain a more accurate mathematical modal model of the structure under test, allowing for better prediction of design alternatives and ultimately better design choices.

3.0 CURRENT STATE OF MULTI-CHANNEL TEST SYSTEMS

There are several enabling technologies which have contributed significantly to the current state of large count multi-channel test systems. Continual improvements in instrument quality

with reduction in system costs have increased the feasibility for test laboratories to assemble large channel count systems. From low cost analog-to-digital converters (ADCs) developed to serve the consumer audio market to automated fabrication of piezoelectric accelerometers, the trend for more high resolution channels at a lower cost continues to grow.

3.1 Data Acquisition Hardware

Driven by the huge consumer product market, consumer audio continues to drive rapid development of high fidelity, low cost ADCs in the form of delta-sigma ADCs and combined ADC/DAC coder/decoders (CODECs). Although developed three decades ago, only within the last 10 years or so has delta-sigma conversion achieved commercial implementation. These first high-performance, commercial converters were targeted at such demanding applications as high-end modems and digital audio. It has since become the foundation of a new generation of economical spectral analyzers rapidly growing in popularity in the experimental dynamic test and measurement market.

Utilizing oversampling and digital filtering, the delta-sigma technique achieves high performance in both A/D conversion and filtering at low cost. Precision analog components and powerful digital filters are integrated onto the same chip, creating the two basic building blocks of a delta-sigma ADC: an analog modulator and a digital filter. The modulator consists of a single-bit A/D converter embedded in an analog negative feedback loop with high open loop gain. This loop oversamples the analog input and provides single-bit output at an extremely high rate and in a form that the digital filter can process at higher resolution, say 16-bits, at a lower rate. Complete technical information on delta-sigma ADC's is available in the literature⁵.

The other significant driving force in the development of front end data acquisition systems was the creation of the "VXIbus Consortium" consisting of several leading manufacturers and the US Air Force. Their discussions aimed at creating a standard that would benefit both commercial and military test laboratories. In the late 1980's, the specification was submitted to the IEEE for consideration as a standard.

Their goal was to create acquisition systems with increased test throughput, smaller packaging and

reduced cost, among other benefits. The group recognized the General Purpose Information Bus (GPIB, or IEEE-488) and VMEbus as the two most popular instrumentation standards for consideration. GPIB exhibited ease of integration while VME allowed high-speed communication. VMEbus Extensions for Instrumentation (VXIbus) took the best from both of these standards and created a well-defined environment in which different vendor's products can operate together properly. Finally, a common instrumentation language was developed, named Standard Commands for Programmable Instruments (SCPI), to simplify implementation and integration of VXI instrumentation⁶.

VXI is a highly standardized platform governing a truly open modular instrumentation architecture. Currently, it is the overwhelming favorite among dynamic test engineers. Its scalable, configurable solutions allow for adaptability to users' unique and/or specific measurement situations.

3.2 Signal Conditioning

A significant hurdle in successful large channel count multi-channel testing is transducer channel management. A signal conditioning system should not only supply power to the array of transducers, but also simplify the channel installation process. This involves easy channel identification and continuity check (via bias verification), cable management issues and computer control and communication features.

The system presented here is specifically designed for large arrays of Integral Electronic PiezoElectric (IEPE) sensors, such as PCB's ICP[®] transducers. ICP transducers output a low-impedance voltage signal, which operates over long runs of ordinary, low-cost coaxial or ribbon cable without degradation of signal quality. This design is ideal for modal analysis (i.e. large channels of transducers installed on a given test structure in controlled laboratory conditions).

A well-designed multi-channel acquisition system limits the length of (or completely eliminates) expensive single channel coaxial cables by collecting numerous cables at a central "hub", or patch panel. Ideally, low-cost ribbon cable is used, cut to length and neatly installed on the test structure to the appropriate transducer locations. These cables are terminated with economical, reliable, easy-to-install Insulation Displacement Connectors (IDC). The signal paths are then

condensed on distributed patch panels, which output multi-conductor extension cables. At this point attention need not be paid to which specific channel is run to the specific physical DOFs. (This will be handled later.) Signal conditioners designed with the multi-channel user in mind utilize these same multi-conductor cables and connectors. The elimination of the clutter of the test site by removing the "rat's nest" of multiple coaxial cables running from the structure to the signal conditioning / data processor area simultaneously removes one of the largest distractions that presents itself during a test (Figure 2). Additionally, system troubleshooting is simplified by using small clusters of transducers in patches of 16 units.



Figure 2 - Shielded Multi-conductor Ribbon Cables Gather Transducer Signals At a Central "Hub", With Single Channel "Spokes" Extending Over The Test Structure.

These dedicated signal conditioning systems (Figure 3) possess several features that greatly aid users in test set-up and channel management. Specifically, computer controlled channel identification/verification and computer-controlled bank switching allow for smooth, efficient tests.

Channel identification locates transducers, as they are installed, and indicates proper bias via an LED on the power supply. If the channel is shorted or open (either in the transducer or cabling), the LED will remain lit. This is why cabling can be laid out without close attention paid to the specific channel connection. The transducer verifies channel location and continuity as it is installed.

Bank switching is a cost saving technique that approaches true simultaneous data acquisition. Unfortunately, even with the new generation of low-cost delta-sigma ADC front ends, the acquisition channel itself remains the most

expensive component. Bank-switching allows the user to fully install all necessary transducers on a test structure, power these units simultaneously, and, via computer control, switch patches of transducers (say 16 at a time) into a smaller, more affordable front end acquisition system. The result is a complete system, capable of acquiring all data very rapidly, at significant cost advantages.



Figure 3 - Computer Controlled Signal Conditioning System Powers 96 Transducers (Bank Switching Into 32 Data Acquisition Channels) In A 19-Inch Rack Mount.

3.3 Transducers

Array accelerometer implementation can be traced in Figure 4. Dating back from the introduction of the PCB 330A Structcel®, modal accelerometers have matured with the implementation of ICP technology in the form of piezoelectric beam elements, and finally, the integration of the preferred shear mode piezoceramic accelerometers built within transistor cans⁷. These low-cost elements are packaged in composite housings designed specifically for the large channel laboratory test environment, shown in Figure 5.

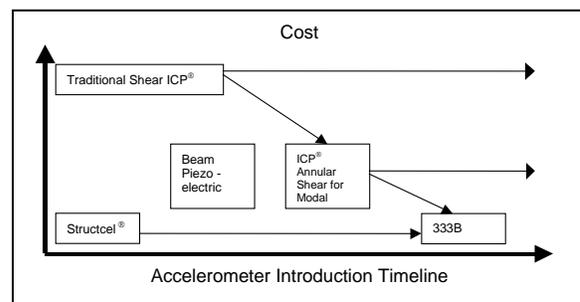


Figure 4 -Tracing Development of Accelerometers Suitable For Multi-channel Testing Through Time.

The development of improved element design and assembly automation techniques have provided the opportunity to use piezoelectric shear mode accelerometers. The implementation of shear mode sensing elements should not be overshadowed by the

developments in digital transducer communication outlined elsewhere in this paper. With the introduction of low cost annular shear sensing elements, which exhibit improved ruggedness and reduced sensitivity to low frequency temperature transients, the beam design has effectively been obsoleted. The annular shear design provides the means needed to achieve both low-cost and high performance, compromising only the performance characteristics that have typically not been utilized by the large channel user, such as high frequency (>2000 Hz) response and non-laboratory environments (>150° F).

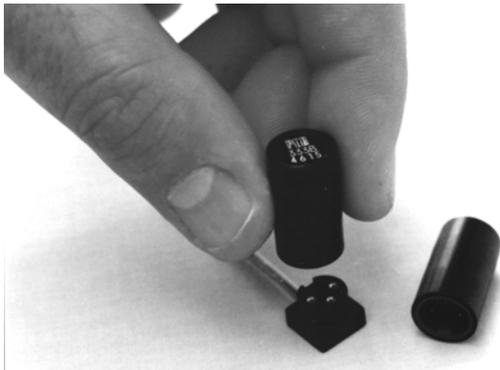


Figure 5 - PCB Model 333B Modal Array Accelerometer System Focuses On Large Scale (hundreds) Multi-channel Laboratory Testing.

3.4 Test Accessories

The introduction of 3 Dimensional Digitizing capability has improved the efficiency and accuracy of pre-test set up by automating the documentation of transducer placement across a structure (Fig. 6).



Figure 6 - 3D Sonic Digitizing Automates The Structure Geometry Definition Process

Using arrayed ultrasonic transducers, the timing ultrasonic pulses emitted from a digitizing probe which is located at a structural test point identify test points on a structure. Simply put, the location of the probe tip relative to the microphone array is "triangulated" in 3 space. The tri-ordinates are then cataloged in the data acquisition / data analysis software⁸. This automation of test point data acquisition dramatically reduces test set-up time, with nearly 80% time reduction in geometry definition⁹.

4.0 Smart Sensor Revolution

The method of pairing a transducer to its calibration data has remained unchanged for an extensive era. A technician measures output of the transducer under test against that of a traceable reference and records the data on a certificate. The transducer's model number and serial number serve as a unique identifier, and the data on the certificate serves as a record of the transducer performance. This paper certificate is then filed, waiting to be called upon for some or all of its information. Most often, the location at which it is practical to locate the calibration / performance data is very separate from the useful location of the transducer.

The effort to bring the sensing unit into closer contact with its description is not new. However, the success found in the practical implementation of this idea is. As early as 1994, sensors have been fabricated which accurately and reliably identify themselves and their characteristics while still retaining the analog performance for which they had been designed¹⁰. However, package sizing and obstacles to practical manufacturing encumbered the deployment of this sensor technology. Recent efforts by a consortium of concerned citizens in the sensing community, organized under a standards committee of the IEEE, have produced systems that show great promise and have already been deployed successfully¹¹.

By utilizing this technology in the field before protocol finalization, users can make their preferences known to the IEEE committee prior to the standard's protocol ratification. At the time of this writing, the standard remains in the preliminary stage, although hardware designs have been finalized and are useful, if still waiting for protocol standardization. This finalization of the hardware components allows the preliminary deployment of smart sensor systems.

Understanding the operation of an IEEE P1451.4 capable measurement system is fundamental to implementing a state of the art multi-channel sensing system. The P1451.4 section of the standard defines a Transducer Electronic Data Sheet (TEDS) which carries the calibration information for that particular transducer. Not only does it carry the performance information of the transducer, but it also contains application specific deployment information such as position and orientation. This TEDS information is stored "on-board", that is to say, INSIDE the transducer itself. The introduction of the TEDS circuitry gives the transducer the ability to operate in two separate modes: traditional analog sensing mode or digital transmission mode. The digital transmission mode is operated over the same two-wire cable used by the analog circuitry. By supplying a negative excitation voltage to the transducer, analog measurements are suspended and digital communication is initiated. Once the digital communication is terminated, the digital circuit is disconnected and the analog sensing circuit is engaged. The implementation of this TEDS hardware scheme is complimentary to ICP signal conditioning and does not obsolete existing hardware. IEEE 1451.4 TRANSDUCERS WORK WITH TRADITIONAL ICP® SIGNAL CONDITIONERS. TRADITIONAL ICP® TRANSDUCERS WORK WITH IEEE 1451.4 CAPABLE SIGNAL CONDITIONERS.

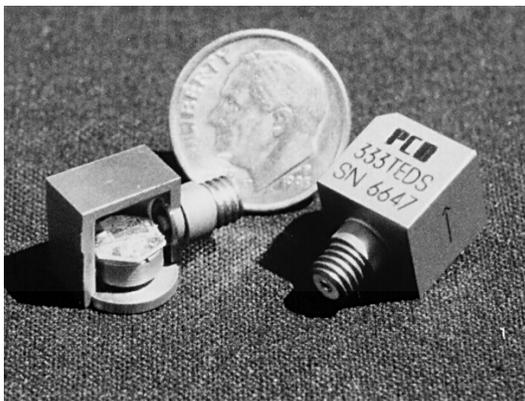


Figure 7 - These ICP accelerometers with IEEE P1451.4 communication retain their traditional analog performance, while maintaining their original package size.

The P1451.4 standard also defines the protocol and interface used. There is no presumption of a particular measurand, transducer design, or signal conditioning. The finalized IEEE 1451.4 standard will apply to all sensing system designs.

TEDS information is written to the transducer by a digital bit stream. This bit stream is produced by any interface device that complies with the

standard. These interface devices have already been implemented into commercially available 16 channel ICP signal conditioning units (Fig. 4). These "smart" signal conditioners communicate with the host computer over RS-232 and can completely identify hundreds of transducers in a single test set up with a single request. The serial connection is an arbitrary choice, utilized for both its convenience and performance.

Once the TEDS data has been passed to the data acquisition system controller, manipulation is performed at the software level by accessing the serial communication port. The data is then entered into the channel ID/transducer ID/calibration value database of the data acquisition software without delay, error, or time commitment.

The potential benefits of adapting this standard are impressive. When coordinated with the 3D digitizing capabilities that already exist, IEEE 1451.4 offers the possibility of eliminating the tedious "bookkeeping" portion of large channel testing. The end result is an environment in which transducers simply plug in to the data acquisition system, identify themselves, and then simultaneously have their position / orientation defined by a 3 dimensional coordinate digitizer in several seconds. This calibration and position / orientation definition is then retained by the transducer itself indefinitely, making itself available to be redefined at the next test set up and/or calibration.

5.0 Future Systems

The smart sensor revolution is fast approaching. With the impending IEEE 1451 smart sensor standard, the traditional lines separating analog transducer from acquisition front end are quickly blurring. Distributed acquisition nodes communicating over various means (i.e. RS-232, USB, Ethernet, or wireless schemes) will dominate the multi-channel test systems of the future. Imagine a system with distributed acquisition clusters in patches of 16 transducers, all connected along a single Ethernet backbone, with only a single cable run across the 150 foot bridge span rather than hundreds of coaxial cables or dozens of multi-conductor ribbon cables. Consider also an airframe test, which requires only this communication backbone to penetrate the fuselage during flight testing. Bigger still, consider a system of digital transducer clusters, each with their own IP address, located not just throughout a given facility, but across the country and world, with

data accessible over the internet anytime you'd like.

In conclusion, the dynamic test and measurement community will see the rapid evolution of smarter sensors, effectively lowering measurement channel prices and simplifying the user interface for a much broader deployment across new industries.

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⁴ **Forrest**, *Up-To-Date Structural Dynamic Test Capability Speeds Modal Analysis*, TEST Engineering & Management, April/May 1991

⁵ **Crystal Semiconductor Corporation**, *Application Note: Delta Sigma A/D Conversion Technique Overview*, AN10 Rev. 1, January 1989

⁶ **Hewlett Packard Corporation**, *Feeling Comfortable with VXI*, 1997

⁷ **Robinson**, et al, *Using Accelerometers To Measure Complex Machinery Vibration*, SENSORS Magazine, June 1997

⁸ **Stillmaker**, et al, *Repeatability Study of Three Dimensional Sonic Digitization*, Proceeding of the 15th International Modal Analysis Conference, Volume II, Pages 1224-1228, 1997

⁹ **Bono**, et al, *Automated 3D Coordinate Digitizing for Modal / NVH Testing*, Sound and Vibration, Volume 30, Issue 1, January, 1996

¹⁰ **Chen**, et al, *Recent "Smart Piezoelectric Transducer" Developments With 2-Wire Systems*, Proceeding of the 12th International Modal Analysis Conference Proceedings, Volume I, Pages 143-145, 1994

¹¹ **Chen**, et al, *A Mixed Mode Smart Transducer Interface for Sensors and Actuators*, Sound and Vibration, April 1998