FEATURE *Lessons Learned in Modal Testing*
by D. Hunt and R. Brillhart

Part 2: SMART SENSORS, DUMB ENGINEERS—HOW TO AVOID CROSSED SIGNALS IN INSTRUMENTATION

Instrumentation is a critical element of any test. On many modal tests, the instrumentation setup phase requires more effort and time than the actual testing portion. When there are problems with malfunctioning or incorrectly located transducers, data processing time increases and some of the tests may need to be repeated. As the number of measurement locations grows, the opportunities for mistakes and the probability of errors can grow even faster. In recent years, there have been advances in so-called smart sensors that have the ability to electronically store and transmit serial number, calibration value, and location in a standardized format defined within the IEEE-P1451.4 standard. These sensors, using what is now commonly called transducer electronic data sheet (TEDS), can reduce the errors associated with entering this information by hand, where mistakes can be easily made during data entry. However, there remain many other opportunities for problems associated with instrumentation. In this paper, the authors offer their experience, insights, and recommendations associated with the topic of test instrumentation.

THE BASICS OF MODAL TEST INSTRUMENTATION

There are many elements to modal test instrumentation, only one of which is the sensor/transducer. As shown in Figure 1, other physical components include the cable, the power supply/signal conditioning, the analog-to-digital converter (commonly known as the "front end"), and even the mounting block and adhesive (often used for attaching accelerometers). There are also a number of nonphysical elements such as the calibration or transducer sensitivity, useful frequency range, measurement range, units of measurement, and amplifier gain. There are other less obvious elements such as the attenuation of the adhesive and impedance of the cable. Although the data acquisition system can also be considered a part of the instrumentation, where factors such as dynamic range, filtering, and coupling will affect the measurement, we will not address it in this paper. While there are a number of types of transducers that are used in modal testing, we will focus on only accelerometers.

Accelerometer Selection

The choice of accelerometers is critical to making good measurements. This selection must be based on the requirements of the test to be conducted. There are a wide variety of models and manufacturers to choose from, and this choice will often dictate the type of cable and power supply/signal conditioning that will be employed. Perhaps the most common accelerometers in use today for modal testing are of the piezoelectric "voltage" mode type, meaning they require only a DC constant current power supply. These accelerometers contain internal circuitry (PCB Piezotronics, http://www.pct.com/techsupport/tech-gen.aspx) that produces a low-impedance voltage signal compatible with most equipment (oscilloscopes, front ends, etc.). Thirty years ago, most piezoelectric accelerometers were "charge" mode type, requiring an external charge mode amplifier to both power the transducer and convert its signal to voltage. Of course, every transducer type has certain advantages as well as disadvantages. While still used today in certain applications, charge mode accelerometers have several drawbacks for use in modal testing that have made them less desirable than voltage mode accelerometers. They require more tedious setup handling to prevent damage; they typically require more complex and expensive signal conditioning; they can be more expensive; they should be used with low-noise cables (which are also more expensive); their high-impedance signals are more susceptible to environmental influences such as cable movement (triboelectric effect), electromagnetic signals, and radio frequency interference; and they can have problems when transmitting the signal over large distances.

Piezoelectric accelerometers rely on the piezoelectric effect of quartz or ceramic crystals to generate an electrical charge output that is proportional to applied acceleration. This charge signal is converted to a voltage either through a separate charge converter or using electronics embedded in the transducer casing. (Sensors containing built-in signal conditioners are classified as integrated electronics piezoelectric [IEPE] or voltage mode.) Piezoelectric sensors typically have a dynamic amplitude range (i.e., maximum measurement range to noise ratio) on the order of 120 dB. This means that a single accelerometer can measure acceleration levels as low as 0.0001 g to as high as 100 g, assuming one is using the proper type of signal conditioning. Other factors that affect the choice of accelerometer include size and weight, cabling, TEDS capability, and mounting method. The weight of an individual accelerometer, and sometimes the total weight of all accelerometers, mounting blocks, cables, tape, and so forth, should be considered with respect to the potential to influence the modal parameters of the test article.

In general, over the years, IEPE voltage mode piezoelectric accelerometers have gained favor and become the transducer of choice due to their robust design, high sensitivity, and ease of installation. Manufacturers of these accelerometers have optimized their performance and configurations to make instrumentation even easier. Further, data acquisition manufacturers have incorporated the constant current supplies needed to power the sensors making the overall test configuration simpler. Since most modal tests are performed under

---

***Editor's Note:** ET has launched a new Feature series titled* Lessons Learned in Modal Testing. *There are many useful practical concepts that will be presented in this series of papers that are written by some well-known people, with a vast number of years of experience in modal testing. The five-part series began with a focus on the practical applications of fixturing, followed by an article on avoiding crossed signals in instrumentation. The next three articles describe how to manage impact and transient excitation and effectively use modal shakers. The final article will define 101 ways to extract modal parameters. This new Feature series clearly illustrates the complement of the relationship between SEM's IMAC and the Annual Spring Conference membership and their expertise. The papers in this series are adapted from a session organized at IMAC-XXIII by Dave Hunt of ATA Engineering. Series editor: Dr. Peter Avitabile, director, Modal Analysis and Controls Laboratory, University of Massachusetts, Lowell, MA.*

D. Hunt and R. Brillhart (SEM member) are affiliated with ATA Engineering, San Diego, CA.

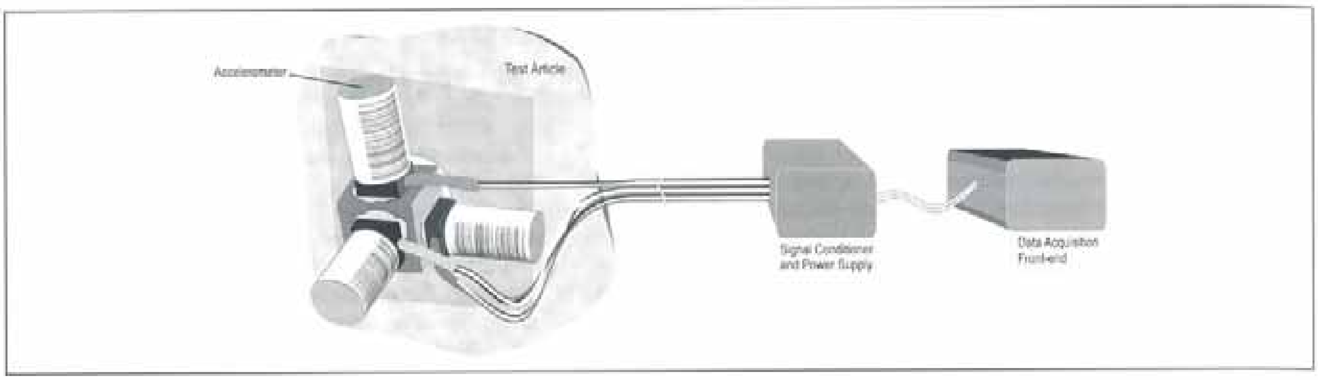

Fig. 1: Primary components of the accelerometer instrumentation and data collection

modest temperature ranges, the voltage mode piezoelectric accelerometer tends to be selected more often than the charge piezoelectric accelerometer, which does provide better performance over a wider temperature range. This makes the selection of the modal accelerometer simpler and can often be based on the test article size and the frequency range of interest.

Accelerometer Attachment

The attachment of the accelerometer can have an effect on the measurement for a number of reasons. The adhesive will attenuate the signal, most notably at higher frequencies. Double-back tape, wax or putty, hot glue, epoxy, and other bonding materials all have an upper frequency limit beyond which they act as a mechanical low-pass filter. With more complex test article geometries, the chance for misalignment of the accelerometer increases. Figure 2 shows a typical accelerometer attachment, which includes a nonresidue tape, hot glue attachment of a mounting block, and three accelerometers with associated cables. Identifying bar codes for both the accelerometers and node location are also shown.

Selection of the proper attachment method is again a function of the test being conducted. The size of the transducers being used affects the appropriate technique. Also, where the sensor is to be placed should be considered. It is a real disadvantage to have a sensor signal be lost in a test due to debonding when there is no way to access the transducer. Of course, the frequency range of interest should guide the method of sensor attachment just as it does the original selection of the sensor.

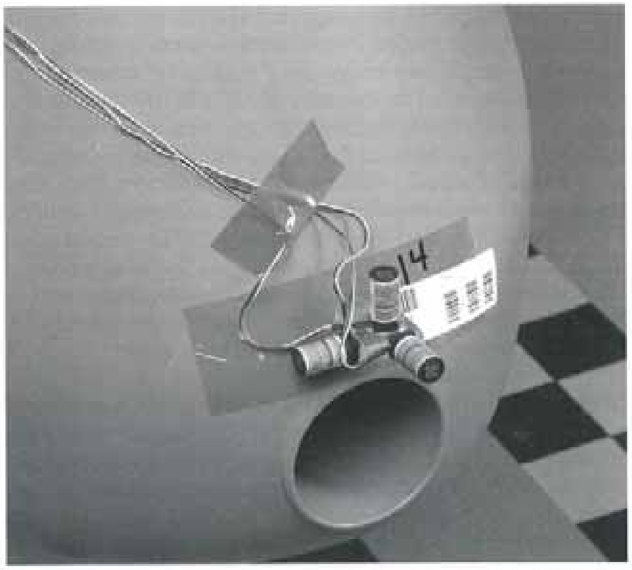

Fig. 2: Typical accelerometer attachment using hot glue and a mounting block

Accelerometer Cables

In the authors' experience, the accelerometer cables are often the weakest link in the entire modal test setup, especially when cables are used in one test after another. There are a number of cable types that can be used in modal tests, as shown in Figure 3. Coaxial cables with microdot connectors have historically been a traditional cable used in test instrumentation with charge type accelerometers and older style voltage type accelerometers. These may be low-noise (if used with charge transducers) or standard cables. These are the most expensive of cable types and may be easily broken if they are bent into sharp angles nearing 90°. They also have small connectors that must be turned several times to tighten

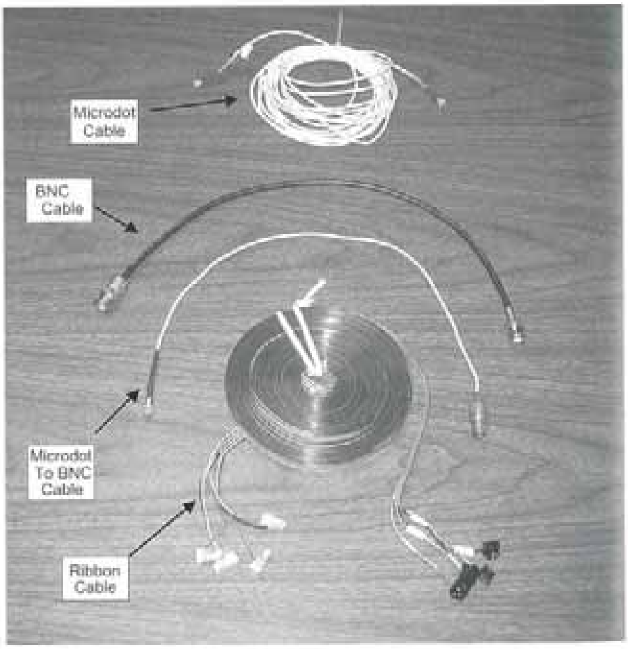

Fig. 3: Four types of accelerometer cables

properly. Dirt and other foreign materials can often find their way into these connectors when they are installed and lead to problematic electrical connections to the transducers.

Coaxial cables with bayonet nut coupling (BNC) connectors have also been commonly used in modal tests. These are a more rugged type of cable, less expensive than microdots, and with connectors that are easier to attach and less fragile than microdot connectors. However, there are few if any accelerometers that have BNC connectors so this requires yet another cable that goes between the BNC cable and the microdot. This cable is often a microdot-to-BNC cable (also shown in Fig. 3), which has the same fragility and connector issue as a regular microdot cable. Additionally, the larger coaxial cable used is much heavier than other cabling and leads to substantial weight if there are numerous transducers.

In more recent years, ribbon cables have been developed, some of which have one end that is hardwired into the accelerometer socket. These cables can accommodate three or four accelerometers (see Fig. 2) and have a connector at the other end, which connects to a "gather box" (see Fig. 4). This gather box can accommodate 16 accelerometer channels and be located close to the accelerometers. A multipin cable then carries the 16 channels back to the signal conditioning/power supply. At this end of the instrumentation, we have 15 fewer cables than with the other types of cables. For applications where there are hundreds of accelerometers, we end up with a manageable number of cables instead of what sometimes looks like a rat's nest! The ribbon cables provide a substantial improvement in weight savings and ease of installation over previous cable types.

Instrumentation Management

When making measurements, the test engineer (and by extension, the data collection software) needs to know, for each front-end channel, the node location or number and sensing direction of each transducer and the calibration and gain of the transducer. It may be helpful to have a text label associated with each transducer (e.g., left wing tip leading edge) so that the engineer can better interpret the data when it is displayed together with the text information. For proper record keeping and traceability, it is useful to record the accelerometer serial number. Again, for tests with 100 or more accelerometers, some automated system of recording this information is invaluable. In the remainder of this paper, the authors look at how they have addressed this issue.

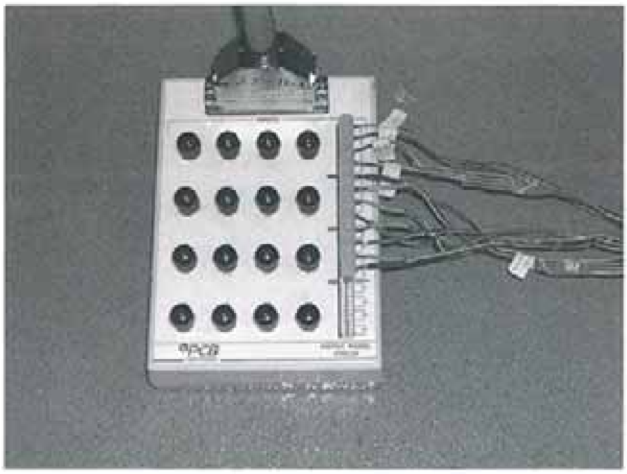

Fig. 4: The "gather box" simplifies the instrumentation cabling system

EXAMPLES OF WHAT TO AVOID

In our experience, there are two types of instrumentation problems to avoid. One is where the chance for erroneous data is high. The other is where problems or certain instrumentation choices will cause delays in the test. Of course, erroneous data, when discovered, often lead to delays in testing due to the time required to correct the error.

Measurement errors related to the instrumentation include erroneous calibration or gain factor, incorrect identification of the measurement location, accelerometers not oriented properly, and improper bonding of the transducer and/or mounting block to the test article. Many of these errors are easily overlooked and never discovered. For example, if the calibration factor is entered by hand, it is very easy to enter a wrong value because these numbers are rarely integers. Small errors may not be detected. An accelerometer that is misaligned by 10–45° will produce a magnitude error of 1.5–29.3%, respectively, which may go unnoticed. When the accelerometer is not well bonded, it may appear that the transducer is working properly; yet, there may be amplitude errors, especially as the frequency range increases.

There are a number of factors that affect the time required to install, troubleshoot, and easily remove the instrumentation. These factors include the bonding method, the type of accelerometer and cable used, and very importantly, how all the setup information is entered into the data acquisition system. Manual data entry, even when mistakes are not made, is very time consuming. Bonding methods such as epoxy and dental cement take a lot of time and are often not needed when the frequency range of interest is below several hundred or even 1000 Hz. Having to use individual cables between the accelerometer and the front end may result in long cable runs and the conglomeration of cables referred to previously.

In the following section, we look at approaches we developed to mitigate these potential problems.

EXAMPLES OF INSTRUMENTATION SUCCESS

In the early 1980s, the authors were involved in several modal tests involving hundreds of accelerometers for each test. In most of those tests, the instrumentation was provided and installed by the organization responsible for the test article, while our company (then SDRC) had responsibility for data collection and analysis. The instrumentation method included a single, long microdot cable for each accelerometer and the instrumentation phase took a very long time. Since we were performing more and more tests for customers where they wanted us to supply the instrumentation, we decided to develop our own system that simplified the cabling and reduce the time required for the setup phase.

Our main objective was to eliminate the need for long microdot cables. These cables were expensive and also tended to have a short life—they could not be reused on test after test without incurring a significant failure rate. Our solution, shown in Figure 5, incorporated the use of a home-made gather box that would allow us to connect 12 microdot cables and then run one long multipin cable back to the signal conditioning amplifier. (This 12-channel gather box became the prototype for the subsequent development by PCB Piezotronics for the gather box described previously.) With this gather box approach, we could use short microdot cables that were less expensive and easier to manage. The long multipin cables were more rugged and lasted longer. By modifying the 12-channel signal conditioner to accept the multipin cable, we now had a system that could be installed more rapidly and at less overall hardware cost.

Our next focus was data management. We had two goals. The first was to simplify the entry of setup information (calibration, channel identification, etc.) into the data collection system while minimizing the chance of errors. Second, we wanted to document the setup so we could have a record of which accelerometer was at every location in case there were questions later where we might need this information. We developed a software program that allowed us to enter the location, channel number, and serial number of every accelerometer. The program also read a database of serial number versus calibration that was created in our lab when the accelerometers were calibrated. Another input file contained an identification text for each node on the structure where we would place an accelerometer. The output of this program was two universal ASCII data set files that were in the proper format for our data acquisition system—one was the calibration file and the other was the channel table file. We were able to print out the setup from either the setup program or our data acquisition software, I-DEAS Test.

In the 1990s, this program was replaced with a more modern Microsoft-Excel-based system that uses bar codes and a laser-scanning Palm Pilot™ Handheld.[1] Implementation of a bar code enhancement to the modal test setup process was first observed by the authors at McDonnell Douglas Aircraft in St. Louis. This method of tracking the transducer and cable installation led to improved ideas for this setup process. This newer system not only further streamlined the bookkeeping process but also further minimized the opportunity for errors since we could now electronically record (scan) the accelerometer serial number and location, as shown in Figure 6.

At the same time, we were working on these two improvements and we were also looking for ways to make accelerometer installation easier. On one airplane modal test, we noticed that technicians were using hot glue to attach accelerometer mounting blocks. The process was very fast because the adhesive dried so quickly and required no preparation (unlike epoxy and other similar bonding materials). In addition, the hot glue resulted in a very strong connection (unlike double-back tape). Over time, we even began to use hot glue for the exciter block attachment and found it would hold for forces of 20 pounds rms or greater using a random input.

We were still faced with one time-consuming step—attachment of the accelerometer. Most of the accelerometers we used in the 1980s had a 10/32 threaded hole that required the accelerometer to be screwed into a mounting block and then the microdot cable screwed into the accelerometer. To complicate matters, where we attached three accelerometers to one block (in order to make a triaxial measurement), we would encounter connectors that interfered with each other, causing us to have to change accelerometers until we found an arrangement that would work. If we had to replace an accelerometer, we might have to disconnect or adjust the adjacent accelerometer(s).

PCB Piezotronics continued to be involved in how we were conducting tests. They also worked closely with the University of Cincinnati, and through these collaborations they had begun developing accelerometers and cabling that both reduced overall cost and made the installation easier. In 1982, they introduced the Structcel® accelerometer system that included a mounting pad and integrated cable and a separate accelerometer that plugged into the mounting pad. The corresponding system included a signal conditioning system with a light for each channel indicating whether it was connected properly. Over time, these features were incorporated into the PCB Model T333B accelerometer (shown previously in Fig. 2), a 100-mV/g transducer with TEDS technology, and the same type of mounting/attachment as the Structcel.

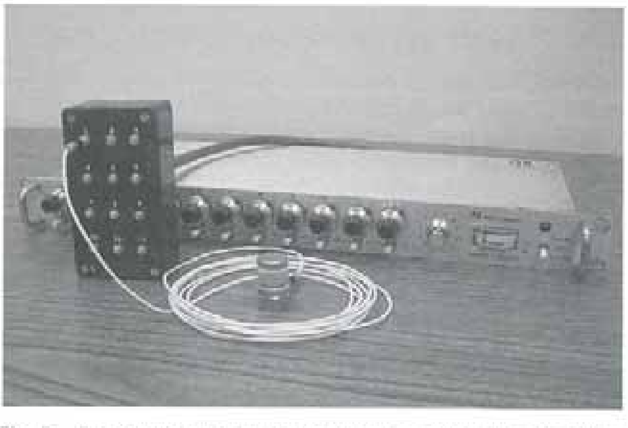

Fig. 5: Prototype system of gather box and integrated cabling system

Fig. 6: Using a Palm Pilot to scan the setup information reduces errors and improves efficiency

The result of all these developments is an accelerometer instrumentation system[2] that can be installed, connected, verified, and easily integrated with the data acquisition software. Our current experience on modal tests indicates that we can perform all these tasks at a rate of 15 min per accelerometer channel, even for large test articles such as aircraft, where we have to run cables up to 100 feet. This means a crew of three people can complete the installation of 300 accelerometers in just two 12-h days. By devoting a fourth person to the team who sets up the other equipment and works on positioning the exciters, we can be ready to test in 2 days.

RECOMMENDED BEST PRACTICES

By combining these best practices for instrumentation with appropriate commercially available products and providing proper training, any organization should be able to see improvements in their modal testing work. We list here the elements we use in our testing group.

Accelerometer Calibration

Have your calibrations performed by a laboratory that follows National Institute of Standards and Technology (NIST) standards (ISO 10012-1). This ensures that questions about accelerometer response levels can be traced back to the calibration data. We have invested the time and equipment to do these ourselves. The calibration results should be stored in a database or file such as Excel that lists, for every transducer, the make and model, serial number, calibration, calibration date, and date the calibration expires. Set up a regular calibration schedule.

Accelerometer Selection

Have a bar code on every accelerometer corresponding to its serial number. Over time, replace your non-TEDS accelerometers with TEDS type (with integrated cabling) and acquire signal conditioning that will read the TEDS information, which at a minimum should be the channel number and serial number. Some labs may choose to write the calibration into each accelerometer's TEDS memory.

Accelerometer Installation

Before installing anything, mark all measurement locations using nonresidue tape and include a bar code associated with the location that includes the node number and which directions (x, y, z) are to be measured. When the engineer or technician is ready to attach the block and accelerometer, they can quickly see what is called for at each location (Fig. 7). In addition to using hot glue, it can be helpful to use a small bubble level that you can orient on top of the accelerometer block as you attach it to ensure it is properly aligned.

Instrumentation Data Management

The use of a bar-code-based system has been key to reducing the time required to have the instrumentation setup correctly with little chance of having the types of undiscovered errors that were described earlier. The data management system we developed in the 1990s was further improved with the inclusion of TEDS capable sensors and is now available commercially (The Modal Shop Inc., http://www.modalshop.com/resource/pdf/5020A.pdf). By tying the accelerometer serial number to the calibration (using the calibration file), measurement location (using a laser scan as shown in Fig. 6), and to a data acquisition front-end channel using TEDS, we can know everything we need to about what is connected to every data channel. We have avoided entering any of the information manually.

Fig. 7: The use of bar codes, nonresidue tape, and hot glue enhances the accelerometer installation

Training

It is not enough to provide tools to the test team. They must be properly trained in order to realize and appreciate the same benefits that the authors have seen in our organization. A key element of this training is having newer members of the team work with others who are proficient in all elements of a modal test, including the instrumentation phase. This way the test gets performed to the high standards required while everyone gains experience.

SUMMARY

It has become commonplace to conduct modal tests with 100–500 accelerometers. Installation and management of the instrumentation is a critical element of the test, both in terms of data quality and time required. In the past 25 years, there have been many advances in transducers, cabling, installation, and data management. TEDS capable accelerometers (also known as smart sensors) with a mounting block and integrated cable have been one significant advance. By using all the available technology and the best practices described here and an experienced test team, the instrumentation phase of a modal test can be accomplished in as little as 1 or 2 days based upon a rate of 15 minutes per accelerometer. And you can avoid or minimize those crossed signals!

References

1. Brillhart, R., and Dillon, M., "Automated Test Setup in Modal Testing," pp. 578–582, 20th International Modal Analysis Conference, Los Angeles, CA, February 4–7, Society for Experimental Mechanics, Bethel, CT (2002).

2. Brillhart, R., "Improving Test Efficiency and Accuracy with TEDS," pp. 146–157, 20th Aerospace Testing Seminar, Manhattan Beach Marriott, Manhattan Beach, CA, March 26–28, Aerospace Corporation, Manhattan Beach, CA (2002). ■