Wireless Sensors Applied to Modal Analysis

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In traditional modal analysis test setups, much effort is expended dealing with the limitations of interconnecting wires. This article examines the potential for wireless sensor and data acquisition methods to mitigate some of the inherent problems associated with experimental modal analysis as it is currently performed with "hard wire" technology. Approaches to wireless hardware and software are suggested that could parallel calculations and thus reduce calculation time and improve data quality by elimination of wires.

Modal analysis has become a widely applied tool for understanding complex energy concentrations and dispersions in materials and structures. The engineering purposes of modal analysis include solution designs for noise suppression, diagnosis of dynamic vehicle performance, measurement of structural responses to potentially destructive excitations (impulses), stress analysis for system components, and structural health and prognostic measurements.

The wide variety of applications of modal analysis has engendered an equally wide variety of mathematical methods for computation of modal parameters. However, for purposes of discussion, applications of modal analysis can be subdivided into two categories:

1. The analysis performed by the test and evaluation community for purposes of characterizing system performance.
2. The analysis performed within system designs for purposes of improving performance in an operating environment.

In the first case, modal test setups are installed, tests are performed, and the system is dismantled to be used for other testing. In the second case, the modal analysis hardware and software are an integral part of a working environment.

In either case, certain physical limitations exist. Generally, these limitations include requirements for a large number of sensors, limits on the mass of the sensors so as not to 'load' the test article, and support and security of the interconnecting wires which, if not secured, will add 'noise' modes to the test article.

These difficulties exist because each of the sensors in a conventional modal test setup must be connected to both a power source and a wire or optical signal path. The exact nature and configuration of the power and data connections may vary somewhat with the characteristics of the sensor; however, in some form, an interconnect path must be provided from the sensor to a central location. At this location, the analog information can be utilized to provide the modal characteristics. In many cases, the output from the transducer (sensor) may be a signal that is inherently susceptible to additive noise. Thus, the interconnect must also contain shielding that adequately protects the signal level produced by the source transducer from contamination to outside noise sources.

The experimental contingent of the modal community has historically labored diligently to overcome the data contamination inherent in the mechanical, electrostatic and electromagnetic effects associated with wire. In some cases, the design of these solutions and their implementation far exceed the time needed to perform the testing.

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Analytical Modal Analysis

Analytical modal analysis starts with the measurement of the geometry of a structure, its boundary conditions, and the characteristics of its materials. The mass, stiffness and damping of the structure are expressed in terms of the matrices for these three parameters (M, K and C, respectively). Depending on the complexity of the structure, these matrices can contain thousands, tens of thousands, or even more elements. Individual equations of motion are first formed for each discrete element of the structure. The coordinates for these individual elements are then aligned in system space through a linear transformation, after which the elements are combined, resulting in the matrix formulation of the structure. Generalized displacement and force matrices can be combined into specified and unspecified segments, and this structure matrix formulation transforms so that its left side is expressed only in terms of unspecified coordinates. Once this final formulation is achieved, sufficient information is available to extract the system modal parameters (natural frequencies, damping factors and vibratory mode shapes). Subsequently, the system frequency response matrix can be determined in terms of these modal parameters.

Experimental Modal Analysis

Experimental modal analysis typically starts by determining a frequency response function matrix. Measurements of concurrent dynamic input forces to and responses of the structure, when they are transformed and have their ratio taken, ideally result in the same frequency response functions as determined through the above analytical process. However, this does not always occur in practice. Assuming that quality experimental data are acquired, an update of the analytical finite element model is performed. Disagreement between models can occur due to one or more of the following factors: the measured degrees of freedom do not coincide with the number of degrees of freedom in the finite element model, the set of experimental modal data is incomplete due to limited bandwidth, or damping cannot be accurately included in the finite element model. In some instances, the acquired measurements are directly analyzed in the time domain. However, comparison concerns between models remain the same. Successful updating of the results of finite element modeling enables accurate and reliable predictions of the dynamic behavior of the structural system, greatly enhancing the design process.

Experimental modal analysis can further be subdivided into processes that use various excitation modes, single or multiple excitation sources, and mathematical methods based on time domain or frequency domain manipulations. Experimental constraints frequently dictate the specific excitation plan and the processing approach because each unique plan offers advantages and disadvantages when attempting to design a test, the results of which will fully describe the dynamic behavior of a design.

Whatever the experimental modal analysis approach, realization of meaningful results can be an arduous task due to the installation difficulty associated with the hardware, communications and data processing functions required. Practical installation problems, enumerated below, result in limitations in the quality of the acquired experimental data and may increase the cost of the testing beyond practical limits.

- Large numbers of sensors and sensor ranges are required.

Figure 1. MicroTAU: Micro Triaxial Accelerometer Unit.

- The addition of mass and/or local stiffening of the structure due to the presence of the sensors changes the behavior of the test article.
- Cable bundles (power and signal) restrict the free movement of the test article.
- Signal and power cable noise are generated due to triboelectric effects associated with high impedance transducers.
- Cable noise may be induced due to electrostatic and/or electromagnetic effects associated with both high and low impedance transducers.
- Other additive or multiplicative noise generation effects.

Purpose

First, an overview is provided of what is now being done with wireless technology applied to modal applications. Next, a concept will be introduced for expanding the capabilities of wireless modal techniques by distributing the modal processing tasks among an array of 'smart' sensors, where many of the calculations can be done in parallel. Performing parallel calculations can reduce the quantity of raw data movement from transducer to central processor. This reduction removes the current radio frequency bandwidth bottleneck that exists in wireless modal systems. The resulting increases in calculation speeds could move modal analysis techniques into "real time" applications where the analysis becomes part of a control/feedback loop for active vibration control, flutter suppression, noise suppression and machinery health monitoring.

Wireless Collection of Modal Data

Within the past five years, NASA and the Department of Defense have announced the need for precision data on which modal processing can be performed to extract critical vibration environments on the International Space Station (ISS), Shuttle and high performance aircraft. These applications are located in challenging environments that preclude the use of hard wire or fiber connections (for power and data paths).

The following wireless systems have been designed, fabricated and qualified as GFE (Government Furnished Equipment) and are currently installed or scheduled for installation on the ISS, Shuttle and other high performance government systems. These designs focus on eliminating wire and replacing it with reliable wireless communications.

In each of the cases listed above, the wireless characteristics of the system design made data acquisition feasible in an environment that normally would have precluded the gathering and use of such information. The following is a brief description of each system and how the wireless capability contributes to the solution (see Table 1 for an overview).

MicroTAU and NASA Shuttle. Invocon, Inc. designed and developed the MicroTAU (Micro Triaxial Accelerometer Unit, shown in Figure 1) as a communications network made up of wireless sensor nodes (measuring 5.5cm × 4cm × 2.8cm) that would measure the vibration environment on the Shuttle airframe and associated payloads. This analysis was required to verify the vibration isolation techniques used to separate the payloads from the excitation of the launch loads. To capture the required data on which modal analysis would be performed, several triaxial sensor packages were required. These units were mounted on both the Shuttle airframe and the payloads so comparisons of the vibration data and comparative modes could easily be computed.

Figure 2. NASA Tech Briefs' cover featuring MicroTAU.

Working with Endevco (a worldwide sensor manufacturer and distributor), Invocon was able to capitalize on the low power, minimum size, versatile orientation packaging and precision performance of Endevco transducers in order to build the wireless triaxial units and successfully qualify them to space standards. The wireless capability of the MicroTAU package not only provides post-mission remote data collection to a central point, but also serves as an automated network to synchronize all the sensors in the network to within ±10µs. Thus all data recorded for specific tests are ready for modal analysis without the inaccuracies of manual post processing synchronization.

Figure 2 shows a copy of the *NASA Tech Briefs* cover that featured the MicroTAU device. The exploded view provides visual access to the Endevco transducers on the bottom, the data acquisition circuitry, the radio networking circuitry, the battery and the antenna. All components are secured internally via a preloaded snap-together case. The case is designed with an inherent stress level produced by the assembly loads that preclude any resonant behavior of the components that would contaminate the test article performance.

MicroTAU can be configured for multiple modes of operation:

- Waiting for a predefined trigger event in the vibration environment on any one of the three channels.
- Waiting for a predefined time period (real-time alarm) when data acquisition should occur.
- Waking or sleeping in three different power conservation modes.
- Downloading data via radio frequency as directed by pre-

Table 1. Wireless systems overview.

System	Customer	Customer
MicroTAU (Micro Triaxial Accelerometer Unit)	NASA	Shuttle
IWIS (Internal Wireless Instrumentation System)	NASA	ISS
WAIS (Wireless Airborne Instrumentation System)	Navy	Atmospheric
WATS (Wireless Autonomous Telemetry System)	Air Force	Atmospheric

Figure 3. IWIS: Internal Wireless Integration System.

Figure 4. WAIS: Wireless Airborne Instrumentation System.

defined instructions or user control from a laptop computer.

MicroTAU Modal Advantages. The operational advantages achieved by the MicroTAU due to the wireless capability of the system are the following:

1. Automatic synchronization of multiple axes and multiple sensor data inputs without interconnection cables with precision of at least 10μs.
2. Transfer of multiple sensor data from the measurement point to a central computer where analysis can be accomplished without interconnection cables.
3. Improved data quality due to quantization of the analog signals at the sensor and the resulting elimination of the interconnection cables.

IWIS and NASA ISS. The IWIS (Internal Wireless Instrumentation System, shown in Figure 3) currently operates on the International Space Station to measure extremely small microgravity conditions. The system has a resolution of 0.5μg and an absolute accuracy of ±100μg for one year after calibration.

The system provides structural engineers the ability to measure the response of the ISS structure as it is exposed to excitations caused by docking, assembly maneuvers and orbital reboost. Engineers use the data to validate predicted modal characteristics of the Station as those characteristics are changed by the additions of new station modules.

IWIS is deployed by the astronauts inside the partially completed ISS to collect data on the impulse response of the structure. Data collected on the impulse response will help to verify the structural integrity of the ISS on orbit and update models predicting the modal response of the ISS. Complete understanding of the resonant modes of the structure will allow effective planning of the re-boost and Reaction Control System (RCS) firing sequences when the Shuttle is docked with the Station. Since these characteristics will change as the Station is assembled, it is important to keep these data current with each addition to the Station. The wireless nature of the data acquisition network minimizes the time necessary for deployment and recovery of the system. Further, some of the RCS test firings must occur when all airlocks between modules are closed. A wired system would not have the flexibility needed to accommodate mission changes and data acquisition windows of opportunity.

In the event the IWIS data gathering modules on the ISS loads are blocked from a direct line-of-sight to the central data gathering location, units located elsewhere will act as relays for the data thereby ensuring that the data always have a transmission path. The IWIS system deliveries commenced in fall 1998. IWIS was initially launched in September of 2000, and the system is currently installed on the ISS.

IWIS Modal Advantages. The operational advantages achieved by IWIS due to the wireless capability of the system are the following:

1. Automatic synchronization of multiple axes and multiple sensor data without interconnection cables with a precision minimum accuracy of ±300ns.
2. Transfer of multiple sensor data from the measurement point to a central computer where analysis can be accomplished without interconnection cables.
3. Improved data quality due to quantization of the analog signals at the sensor and the resulting elimination of the interconnection cables.

WAIS and Navy Atmospheric Platforms. A Wireless Airborne Instrumentation System (WAIS, Figure 4) was originally designed for the Naval Air Warfare Center (NAWCAD) for aircraft testing. Prototype Hardware successfully flew aboard a CH-53 helicopter in 2001 and was scheduled for another platform test in early 2003. The purpose of this system was to replace the wires between various test sensors and existing analog telemetry equipment. Benefits of this system included reduced test installation time, increased signal quality and extended analog sensor placements on rotor hubs or other extreme locations.

Use of Direct Sequence Spread Spectrum (DSSS) technology in the radio avoids interference with any of the on-board systems (navigation or communications). Automated network message routing through the airframe to the central data recorder precludes interference problems. The routing of the data through the airframe must occur with minimum delay or "data latency" because of the critical nature of the system.

The hardware meets full military specifications. WAIS consists of data gathering units that are located in remote sections of the aircraft. These units service up to 16 transducers. They power the transducers, gather the data, and control the 2 Mbps data flow to the central point in the airframe. The central data receiving point in the airframe buffers the incoming data and outputs either analog signals or a pseudo-PCM data stream to a data recorder or a PCM encoder. A third piece of hardware is used for system setup and initialization. It communicates with the system installed on the aircraft and takes complete control of the on-board system during the initialization process. This includes set up of the data sample rates, filter settings and real-time message routing. When the setup is completed, the ground unit exits the network, leaving the network to perform the data acquisition job under control of the on-board central data collection unit.

WAIS Modal Advantages. The operational advantages achieved by WAIS due to the wireless capability of the system are the following:

1. Automatic precision synchronization of multiple axes and multiple sensor data without interconnection cables with timing accurate to within ±300ns.
2. Transfer of multiple sensor data measurements from the measurement point to a central computer where analysis can be accomplished without interconnection cables.
3. Improved data quality due to quantization of the analog signals at the sensor and the resulting elimination of the interconnection cables.

WATS and Air Force Atmospheric Platforms. Invocon developed a synchronous, real-time, wireless data acquisition system for the flight-testing of aircraft for the U.S. Air Force. The system consisted of a five-node, low power, data acquisition and communications network capable of monitoring in-flight aircraft performance. The Wireless Airborne Test System (WATS, Figure 5) operates by transmitting data from remote

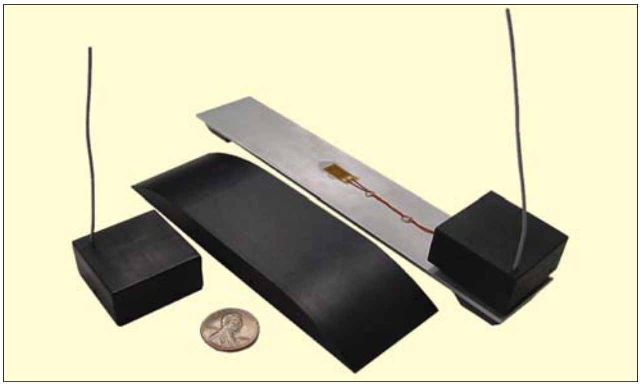

Figure 5. WATS: Wireless Airborne Test System.

sensor units (RSUs) installed throughout the aircraft to the System Interface Unit (SIU) with minimum latency. Digital data are transmitted over an RS-232 port to an on-board data bus or a laptop computer for immediate display, storage and processing. The system operates in a real-time mode in which data are synchronized to ±10μs. The system consists of wireless accelerometers, wireless aerodynamic pressure sensors and wireless strain gage sensors.

All wireless sensors in the network also measure and transmit temperature at the sensor. These data are used to correct temperature effects on the miniature sensors.

Installation of the units on the test article can be done with appropriate bonding materials due to the low mass of the devices. Data from all sensors can be displayed and recorded in real-time. The sample rate for the units is 20Hz and matched to the dynamic range expected from airframe vibration and/or flutter. The operating time from the internal batteries is 24 hours of continuous data. A user can set the units in an idle mode to conserve power. The operating temperature range is –35°C to +75°C, and the radios can transmit 100 ft.

WATS Modal Advantages. The operational advantages achieved by WATS due to the wireless capability of the system are the following:

1. Automatic synchronization of multiple sensor data channels without interconnection cables with precision to 10μs.
2. Transfer of multiple sensor data from the measurement point to a central computer where analysis can be accomplished without interconnection cables.
3. Improved data quality due to quantization of the analog signals at the sensor and the resulting elimination of the interconnection cables.

Why Wireless?

Astute readers will have already discovered that the specific advantages of all the aforementioned systems are virtually identical. The repetition stresses the reality of the benefits wireless technology provides. In each application case, end-user requirements (dictated by environment and operational constraints) drove the system design to provide all three advantages for the four systems currently used in dramatically different environments.

Therefore, it is reasonable to conclude that given the 'right' set of features, wireless sensors (organized into 'smart' data acquisition networks) will be the method of choice in modal testing. Further, for some cases, modal data acquisition will simply not be feasible without the use of wireless technology.

The Question. This begs the pivotal question: Would anyone willingly sacrifice synchronization, no wires and higher quality data unless there was a very good reason? This question is applicable to both the 'experimental' community as well as those attempting to use modal analysis in commercial products. Since both user communities are aware of the advantages of wireless, why has modal analysis not moved entirely to wireless systems?

The Answer. In spite of all the desirable benefits enumerated above, wireless sensors and their associated communications networks also manifest severe drawbacks. Specifically, in the modal analysis systems described above, some of the limitations were apparent because the wireless capabilities of the systems were entirely dedicated to moving only raw data from the sensors to a central recording/processing location. The plan for each of the system applications described above was to simply substitute wireless radio links for (what had always been) shielded cables. Actual modal analysis takes place entirely post-mission in a single computer.

The Proposed "Next Level" for Modal Wireless

The remainder of this article introduces the concept of redistribution of the modal calculations into 'smart' sensor networks. These networks have computing and communications architectures designed for signal processing that can broaden the applicability of wireless modal analysis and lay the groundwork for real-time modal solutions that can support on-line applications for government and industry.

To take modal wireless to the "next level," Invocon initiated the Internal Research and Development program to assess the feasibility of a single modal 'system' paradigm change that could dramatically affect the applicability of wireless modal analysis across the entire market.

The key to success lies in addressing the problems associated with limited communications bandwidth.

Conventional modal data transfer from sensors to processing computers is accomplished using wire to transmit analog signals. Thus, there are no severe limits to the maximum frequencies that can be collected for analysis. Digital communications from the sensor to the processing point require significant bandwidth. Furthermore, each sensor is gathering data simultaneously and must acquire and store it without losing synchronization between the sensors. Wires can transmit signal concurrently without interference. Radio frequency devices must send data simultaneously on a noninterference basis. This communications bottleneck limits the sample rates and dynamic ranges that wireless systems can provide.

The solution introduced herein is to distribute the processing throughout the modal sensor network so as to perform data reduction at the source and in parallel. This reduction can lessen the volume of data needed to be passed through the network but will not diminish the information content of those data.

Practical, technical, and market forces will help the distribution of the processing needed for modal analysis down to the lowest level possible in the data acquisition network:

- U.S. industry produces circuitry for complex data processing that is the most compact and powerful in the world. Portable computing and personal electronic logistical support are huge competitive markets that ultimately drive electronics to the price and performance limits. Therefore, the free market forces will ultimately reduce the cost of data processing to an absolute minimum with respect to size and power. One good example is evolution of Digital Signal Processor (DSP) architecture chips that are designed to perform complex time-to-frequency domain calculations. In five years, these devices have seen size reductions of 300% and power reductions of an order of magnitude. The needs of consumer cell phone market precipitated this rapid evolution. DSPs were incorporated into cell phones to perform control and digital filtering for echo suppression. Thus, the market produced dramatic improvements in circuitry, the advantages of which can be enjoyed by the modal analysis market.
- Using processing power at the sensor node level, lossless data compression can be done to reduce the data flow in the network, thus reducing operational power and bandwidth requirements.
- Time-to-frequency calculations at individual nodes can further reduce the baseband data communications load while alleviating computational load of the main processing node.
- Calculations designed to measure signals in relation to a predetermined 'model' can further reduce the amount of data

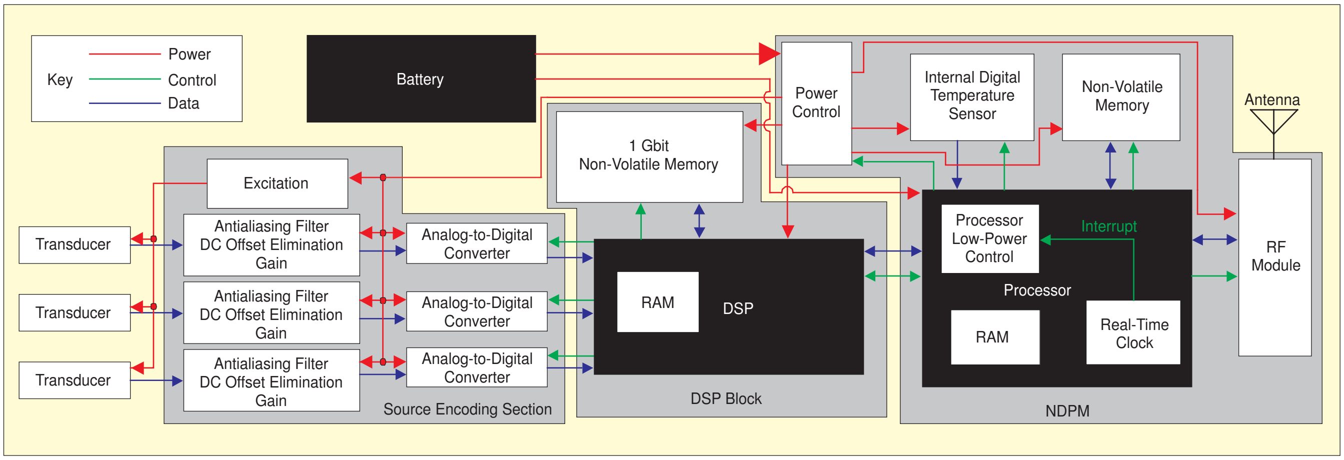

Figure 6. Wide-Band MicroTAU block diagram.

to be transferred through the hardware.

- By using the existing network communications protocol to synchronize and exchange data between the nodes in an active-analysis modal scheme, the wireless network does "double duty."
- 'Smart' network control protocol provides capability to relay data when direct communication between the remote and master nodes is not possible (because of excessive distance or an obstruction) and minimizes the size, weight and power of the wireless sensor.
- 'Smart' network protocol also implements functions to constantly review the optimum forwarding path through the network (based on radio frequency signal quality) and ensures those data are moved with maximum efficiency.

Nodal Parallel Processing

Currently most modal analysis systems and software assume that all data from all the sensors in an array will be made available to a single processor on which the modal computations will be performed. It is possible to achieve distributed parallel processing in the sensor network. Redistribution of the processing tasks to lower levels in the network can provide parallel operations that save time and reduce data handling.

This solution requires two design thrusts: hardware and software. Invocon is currently designing the Wide-Band MicroTAU for modal analysis of the NASA Shuttle fuel flow lines. MicroTAU technology defines the wide band vibration environment and its possible contribution to the fuel flow liner cracks. Invocon has used the requirements for mathematical redistribution of modal solutions to evaluate the performance of the Wideband MicroTAU for use as a 'baseline' demonstrator of distributed processing modal solutions. Figure 6 shows the guts of the system and its three major parts:

1. The sensor signal conditioning block.
2. The DSP (Digital Signal Processing) block.
3. The NDPM (Network Data Processing Module).

The device can store a gigabit of data and can directly address a significant amount of the memory from either of the two processors.

The network processor deals with the communications and supervisory tasks within the system. The DSP controls the high-speed data acquisition processes and analysis. The sensor source encoding block performs filtering and Analog-to-Digital Conversion (ADC) before storing or processing the data. Location of the ADC adjacent to the transducer shortens the path the analog signal has to travel. The vulnerabilities of noise induction during this stage have been almost eliminated as well as potential for signal deterioration due to attenuation, cable damage, cross talk and inductive pickup at higher frequencies.

The NDPM is the organizational supervisor of the sensor. It is a microcomputer with processor, memories and the operating system. It controls power consumption, implements networking protocols, frames the data messages for transmission and tracks the battery and memory usage. It also controls the networking protocols that can provide relay operation if LOS (Line-of-Sight) communication is not possible with all the remote nodes.

The DSP block is a Harvard architecture DSP. Its architecture is optimized for time-to-frequency domain transformations as well as other computation-intensive operations such as matrix inversion. This block will execute the specialized functions associated with modal analysis such as the Fast Fourier Transform (FFT) and subsequent Frequency Response Function (FRF) calculation and the Auto-Regressive Moving Average (ARMA) modeling of data.

Each sensor will perform processing of its own measurements, which is a part of the general data analysis. Since all the sensors will run in parallel, this approach results in a distribution of the computational load between all sensors, thereby reducing the number of tasks performed by the central computing unit and the overall analysis running time. The processing will also reduce the amount of data exchanged between the nodes and thus circumvent the bandwidth bottleneck that had so far precluded proliferation of wireless modal sensors.

Modal Analysis Identification Methods

We have researched the majority of the analytical approaches used in experimental modal analysis.[2] We have examined the premises of each analytical approach to isolate the part of data processing that can be done at the sensor evaluating the amount of information needed for the computation. We were also looking for a stage of data processing common to all analytical approaches so that the sensor could process the data up to that point without losing general applicability (versatility), which is a hallmark of a universal sensor.

Modal analysis techniques are fundamentally divided into two groups: frequency and time domain methods.

Frequency Domain Techniques. Frequency domain techniques either use displacement or a frequency response function (FRF). One widely used is the receptance FRF, defined as a ratio between the displacement and the applied force at each frequency point. Theoretically, a full FFT of the displacement in the range of interest will be sufficient for the methods that use displacement to determine the modes, such as Peak Amplitude, Quadrature Response and Maximum Quadrature methods. Moreover, peak parameters (location, amplitude and width) may be calculated remotely, thereby reducing the amount of information the node has to provide to the central unit.

To accommodate the analysis methods that require FRF, each sensor node will calculate the FFT coefficients of its measured data. This is combined with those from the force transducer unit to calculate the response function. The analysis methods that employ curve-fitting techniques need high granularity as well as a wide range of points to achieve a reliable fit. Storage required for this configuration will be provided on the unit.

Data reduction will be performed whenever the reduction algorithm does not compromise the data quality required by the analysis method. Similar algorithms will be used at the force transducer in a synchronous fashion. At the end of the acquisition, the force transducer will broadcast its measurements (FFT coefficients) to other nodes. These nodes will combine the acceleration (FFT) data they have collected with the force measurement and compute FRF. Certain numerical factors will be imposed on the acceleration DFT to account for the effects of the integration. These factors are contingent upon the order of the frequency point, but do not change with time, therefore they can be applied only once before the FRF computing step.

Time Domain Techniques. Time domain methods operate on the time histories of the excitation and response. The Autoregressive Moving-Average (ARMA) model is fundamental to direct time-domain methods. The ARMA process relies on a finite number of previous measurements of the system output, i.e., displacement referred to as Auto-Regression, and on a finite number of previous measurements of the input (force excitation in our case) referred to as a Moving Average process.

It is envisioned that during data acquisition the sensor node will record the acceleration. At the end of acquisition, the node with the force transducer will broadcast its data to other nodes for processing. The accelerometer nodes will perform integration of their acceleration to obtain the displacement if required by the analysis methods. The nodes will then calculate the ARMA coefficients that will be transmitted to the central node for further processing.

Several algorithms for ARMA modeling researched during this study show promise. Quick, superficial search yielded several algorithms mentioned as performing better that 'traditional' ones. These and other potential candidates will be explored along with "golden standards" such as Levinson-Durbin and Schur algorithms that are used directly for ARMA calculations. In general, modeling of the time series data with white-noise like excitation were extensively studied for the space physics applications. We will evaluate the suitability of each for the chosen DSP architecture as well as to the analysis methods to be employed.

The indirect time-domain methods that use Impulse Response Function (IRF) could be addressed capitalizing on the fact that the IRF is an inverse FFT of the FRF. Therefore, the FRFs obtained in a way described above could be transformed into the IRFs.

Domain-Independent Method. Entirely orthogonal to both domains, this approach would use lossless data compression to avoid complications due to bandwidth limitations. The central node will then reconstruct the data and encode them into a format accepted by a full-analysis software package. While it does not utilize the processing capabilities of the wireless nodes for the direct benefit of the data analysis, this approach still offers all other advantages of the wireless system in situations when neither time nor frequency domain methods are acceptable.

The domain-independent method can also be used in conjunction with the data processing discussed in previous sections, further reducing the bandwidth necessary for data exchange between the nodes.

Conclusion

Wireless technology is currently being applied to data acquisition and collection for modal analysis. Significant advantages of the wireless approach have enabled modal techniques to be extended to applications that would have previously not been possible. Currently available wireless systems simply substitute radio frequency communications links for their wire or fiber predecessors.

The specific technical advances that offered the modal world the ability to use wireless are the core of the its current limitations. These are exampled by bandwidth limitations as well as size, weight and power.

Implementation of a distributed processing overlay to existing wireless sensor data acquisition networks can contribute directly and indirectly to a wider and less problematic use of modal techniques in the wireless world. As the applicability of the technique widens as a result of systemic improvements, more modal applications will enjoy the universal advantages of wireless:

1. Automatic precision synchronization of multiple sensors without interconnection cables.
2. Transfer of multiple sensor data from the measurement point to a central location where modal data can be viewed and manipulated by experimenters.
3. Improved data quality due to quantization of analog data at the sensor and the communication of this data with methods that preclude additive noise.

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