Instrumentation for Making High-Precision Dynamic Vibrating-Wire Measurements Using Standard Single-Coil Gages

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An Introduction to Dynamic Vibrating-Wire Measurements

Vibrating-wire gages have been an important and trusted measurement technology in the structural industry for many years. They have been used for a variety of measurements including stress, strain, force, pressure, and displacement. These gages are distinguished from competing technologies by their reliability and long-term stability. Traditionally, vibrating-wire gages have been limited to static measurement applications by the methods used to excite and then precisely measure them. When faster measurements were required, other technologies were employed such as resistive-foil gages. These offered dynamic measurements but had difficulty matching the long-term performance found in vibrating-wire gages. Indeed, in some instances, structures have been instrumented with both types of gages, and the resulting data merged in an effort to extract the benefits of each gage type. The idea of making a dynamic vibrating-wire measurement is attractive because it allows a single set of instrumentation to provide dynamic data that is also long-term stable and robust. This reduces the expense of the equipment and the installation, it eliminates the difficulty of working with two sets of sensors, and it can provide higher quality data.

Campbell Scientific, Inc. (CSI) has a long history of developing vibrating-wire instrumentation including both the vibrating-wire interface as well as full back-end support with dataloggers, communication interfaces, and PC software products. CSI datalogger equipment is used to make dynamic resistive-foil measurements as well. In recent years, CSI developed the AVW200 vibrating-wire interface as a fundamental advancement in how vibrating-wire measurements are made. The patented[1] spectral analysis algorithms that lie at the heart of this technology improved the precision of measured values by orders of magnitude over previous methods and simultaneously improved noise immunity by discriminating signal from noise based on frequency content.

As the next development in its vibrating-wire technology, CSI has introduced a new instrument, the CDM-VW300 Dynamic Vibrating-Wire Interface. This vibrating-wire interface can measure standard single-coil vibrating-wire gages at rates well suited for dynamic measurements. This opens up the opportunity to use existing vibrating-wire gages for measurements that have previously been the domain of other technologies such as resistive-foil gages. The CDM-VW300 offers sample rates ranging from 20 to 333 Hz. The device uses spectral analysis methods to provide very high measurement precision and a unique excitation system that maintains the gage in a continuously vibrating state. The excitation and measurement system is highly agile so it can capture the dynamic motion in the structure. Certain aspects of the dynamic vibrating-wire measurement approach are patent pending[2].

How to Make a Dynamic Vibrating-Wire Measurement

The key components of a standard single-coil vibrating-wire sensor are a taut wire suspended between two anchor points and an electromagnetic coil positioned at the center of the wire. The coil serves two functions: first as an actuator to put energy into the wire and second as a pickup to detect the motion of the wire. Static vibrating-wire measurements are typically performed in a two-step process of exciting the wire and then measuring the wire response for a period of time to determine its resonant frequency. The excitation waveform must be spectrally broad, such as a swept-frequency sine wave, so as to provide sufficient energy at the unknown resonant frequency of the wire. After the excitation, the resonant motion of the wire is sampled, the frequency is determined, and then the resonant energy dissipates prior to making the next measurement. The time required for these steps typically limits this approach to measurement rates slower than 1 Hz.

[1]U.S. Patent No. 7,779,690.

[2]U.S. Patent Pending – Docket No. C1408.10001US01

In order to achieve much higher sample rates, the dynamic approach compresses the measurement cycle by eliminating the broadband excitation and not allowing the wire oscillation to decay. Figure 1 illustrates the timing of this process. If energy can be injected into the oscillation at precisely the right frequency and with the correct phase, then a very short excitation waveform with a small amplitude can maintain the resonance of the wire. If the excitation is not phase-aligned to the wire motion then the resonance will be dampened rather than reinforced. In between these excitation windows, the wire motion can be sampled and the resonant frequency determined. Using the newly calculated frequency, the excitation is adjusted slightly as needed to track the changes in the resonant frequency of the wire. The excitation mechanism has very fine frequency resolution to precisely track even very subtle changes in the resonant frequency. As can be seen in Figure 1, there are usually only a few oscillation cycles of the wire available for determining the wire's resonant frequency. This difficulty is overcome by the spectral analysis algorithm, which can determine the frequency of the wire precisely, even with this short data sample.

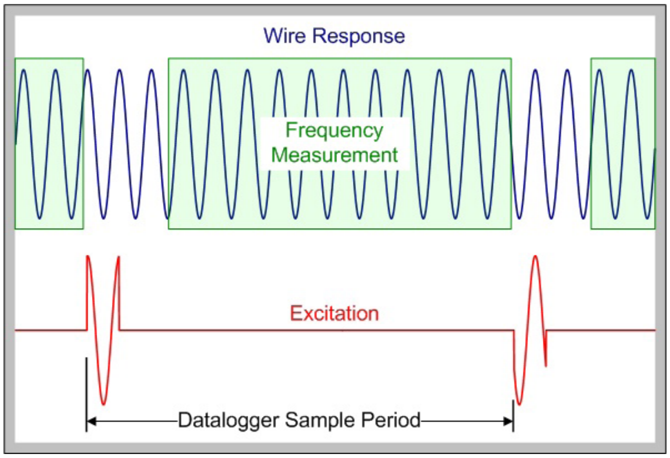

Figure 1. Timing Diagram for Dynamic Measurement

An important aspect of the dynamic measurement timing is synchronizing the process to an external timing source that is independent of the wire oscillation. Synchronization has intrinsic benefits to the measurement quality and also allows simultaneous sampling of multiple channels. Figure 1 shows that the datalogger sample period dictates when the excitations are introduced and when the frequency measurement is made. Since this sample period is independent of the wire motion, the excitation may begin at any point in the phase of the oscillation. When measuring single-coil gages, it is important to avoid including the excitation in the measurement since this can skew the measured frequency and result in increased measurement noise and a diminished dynamic response. Synchronization guarantees that the frequency measurement never overlaps the excitation window. The multi-channel simultaneity enabled by time-synchronization is another important benefit when correlating measurements from multiple sensors. Time-synchronized excitation control is a key differentiator between this approach and other autoresonant coil excitation methods.

Dynamic Vibrating-Wire Performance

The dynamic vibrating-wire interface has been tested with a wide variety of sensors from different manufacturers to establish its interoperability. The sensors include strain gages, crack meters, pressure transducers, and load cells. These experiments have been conducted in the lab and also in field deployments.

In one experiment, shown in Figure 2, a tracking solar array was instrumented with vibrating-wire and bonded-foil strain gages at the indicated locations. The panel of the array measures 45 x 26 feet and pivots atop a 20 foot tall concrete and steel pedestal. When the array tilts and rotates, significant dynamic stresses are generated in the structure.

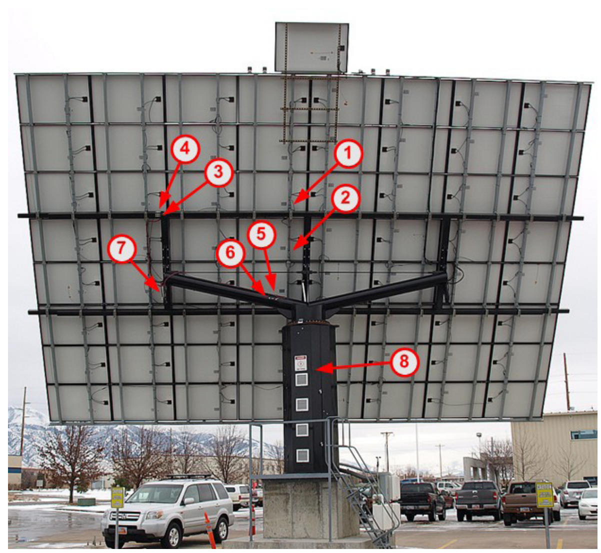

Figure 2. Solar Array Test Structure

Figure 3 shows a representative 10-second time series of strain data measured by a vibrating-wire gage (blue) and a bonded-foil gage (red) while the solar array was in motion. For visibility, an artificial offset was applied to the data in the figure. As shown by the figure, the vibrating-wire gage was able to capture the same structural motion as the bonded-foil gage even with fast slew rates on the signal. The vibrating-wire gage, a Geokon VK-4150, was measured at 100 Hz with the CDM-VW300. The bonded-foil gage, a Hitec Products Inc. HBWF-35-250-6, was also measured at 100 Hz using a CR3000 datalogger. Comparing the spectra of these two signals shows that the frequency responses of both gages were able to fully capture the spectral content of the motion of the structure.

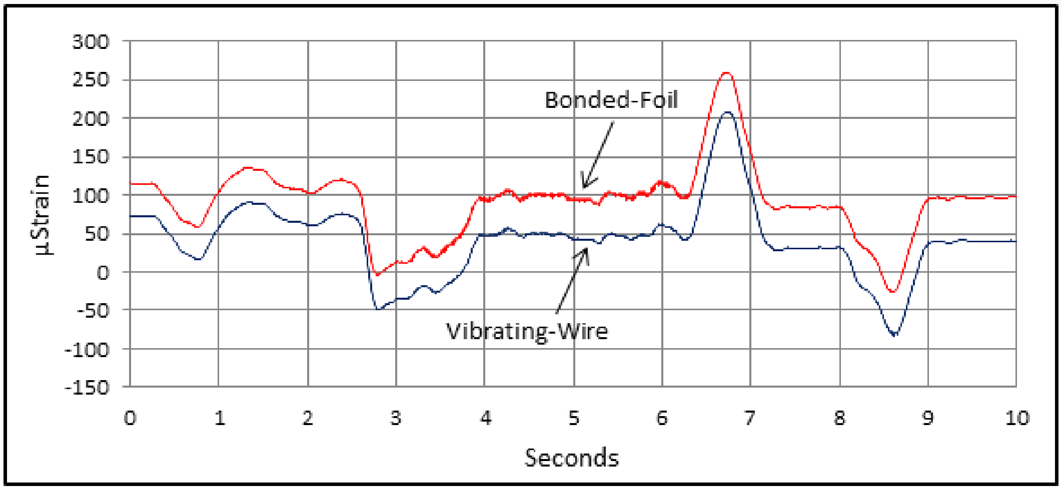

Figure 3. 100 Hz Dynamic Vibrating-Wire Data (Blue) and Bonded-Foil Data (Red)

The dynamic vibrating-wire interface offers excellent noise performance for measuring vibrating-wire gages. This performance typically matches or exceeds the performance of the resistive-foil gages. As an example, the noise performance of the gages used to generate the data in Figure 3 was measured while the structure was at rest with minimal dynamic forces applied. In this state, the measurement noise for the vibrating-wire gage was about 0.075 µε (micro-strain) RMS, giving the sensor a full dynamic range of over 33 000 (90 dB) when measured at 100 Hz. By comparison, the measurement noise for the bonded-foil gage was slightly higher at 0.13 µε RMS. The dynamic vibrating-wire interface allows the user to trade off measurement sample rate and measurement noise performance. As shown in Figure 4, improved noise performance accompanies the slower sample rates. A special function of the CDM-VW300 is the 1 Hz measurement rate listed in Figure 4. The 1 Hz measurement is performed in parallel with any of the higher sample rates as a reference static measurement, and the data is available concurrently with the dynamic data. This concurrent static measurement has the same immunity to external electromagnetic interference as the AVW200 static vibrating wire interface.

Sample Rate (Hz)	Typical Noise (Hz RMS)
1	0.005
20	0.008
50	0.015
100	0.035
200	0.110
333.3	0.450

Figure 4. Typical Noise Performance

A Complete Instrumentation System

The dynamic vibrating-wire interface is one important piece of the larger data acquisition system provided by CSI. The complete system includes the hardware and software required to get data from the point of measurement back to a PC for analysis. The CDM-VW300 makes the dynamic vibrating-wire measurements and then communicates the data to one of CSI's dataloggers, such as a CR3000. The dataloggers are programmable measurement-and-control devices that are adaptable to a wide variety of applications. The loggers interface to both analog and digital sensors and are equipped to make all of the ancillary measurements needed for long-term monitoring applications. These may include meteorological measurements, road surface conditions, and many other parameters. To provide the final communication link between the datalogger and the user's PC or computer network, a variety of CSI communication devices are available, such as Ethernet, radios, cell modems, and removable flash-card storage. A suite of software tools allows configuration and monitoring of the system, as well as collection, viewing, and management of the data. Together, these products provide a full end-to-end data acquisition solution.

Vibrating-wire gages are an important long-term monitoring tool in the structural, transportation, geotechnical, and other industries. With the dynamic vibrating-wire approach, those same trusted gages can be used to collect both static and dynamic data with the same high-precision and long-term stability that was previously limited to static measurements. This provides opportunities for cost savings in the instrumentation system and also opens up new possibilities for future measurements.