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Real Time Modal Property Identification of Full-Scale Large Buildings using LabVIEW

The Requirements

Two recent clients required ANCO Engineers, Inc. to build two comprehensive systems using sinusoidal vibrators driven by NI-LabVIEW and to experimentally identify modal properties (mode shapes, resonant frequencies, and damping). These systems are applied to buildings, high-speed rail road bridges, powerplants, dams, and similar full-size civil structures. Resonance searches for these projects needed to be performed by introducing a stepped sinusoidal force using a controlled logarithmic sweep typically in a frequency range from 0.1Hz to 30Hz. 80 or more accelerometers and other transducers need to be monitored with field portable systems. These data are Fourier analyzed to produce frequency response plots and streamed to a solid-state hard drive in real time. Typical stream rates are up to ~5KHz.

Background

Sinusoidal forces are traditionally introduced using eccentric mass vibrators (EMV's) or hydraulic actuators with reaction masses (HAR's) allowing the application of variable forces. For EMV's the frequency stability and measurement of the vibrator rotation speed is required to be highly stable and accurately read within 0.05% of the target drive frequency. The HAR requirements are a 0.5% repeatability of the target force and frequency. Additionally, the LabVIEW API developed needed to control both force excitation devices and modes (EMV & HAR), monitor different sets of safety features, and enforce different types of shut down protocols.

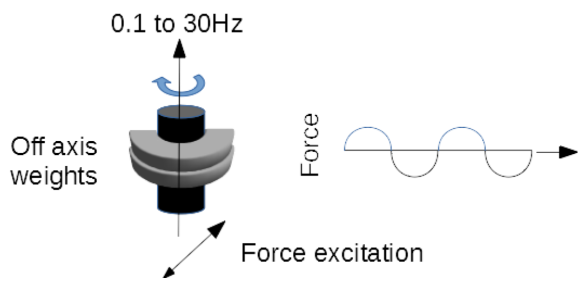

Figure 1) Principle operation of a single axis EMV system

The Solutions

For the EMV; the system used two counter rotating shafts with eccentric masses to create a uniaxial sinusoidal force. Both shaft rotations were controlled and driven using timing belts and pulleys that are connected to a VFD controlled electric motor which is interfaced to NI hardware. The main drive shaft was indexed with a Hall effect sensor to create a once per revolution synchronization pulse. The HAR system functions somewhat differently in that it uses a hydraulic actuator connected to a free moving reaction mass. The actuator was driven in displacement control using a PID servo controller for the two or three stage servo valves. The servo controller is interfaced to the NI hardware from which it receives its displacement command signal. A load cell provides signals for active feedback control. A unified LabVIEW program was written and is configurable using an 'ini' file to manage either system (EMV or& HAR) using a NI-6255 DAQ card (or equivalent). In both cases the program introduced a sinusoidal frequency sweep at specified frequency steps within a user selectable frequency range. In addition, the

HAR mode manages the sinusoidal drive function force amplitude. All sensor data were analyzed using a 2nd order Fourier series:

$$f(t) \sim \frac{1}{2}a_0 + \sum_{n=1}^{\infty}[a_n \cos(nt) + b_n \sin(nt)]$$

Using custom developed LabVIEW vi's, the magnitude and phase derived from each sensor's time history can be correlated to the frequency of the drive function. This approach provided a very accurate representation of a sensors signal at a given sinusoidal frequency of excitation, resulting in frequency response plots indicating both frequency and phase. Furthermore, the correlation and averaging allow accurate measurement of small signals contaminated with DC offset and high frequency noise. This process allowed for monitoring key locations on buildings and identifying estimates of modal properties. These estimates allowed verification and improvement of structural FEA models, and determine properties that cannot be analytically derived such as structural damping.

The Challenges

Running EMV's and HAR's in the field can be challenging on multiple levels with safety being the ultimate concern. Such devices are capability of introducing very large forces (typically 10-100 tons) on critical structures. Only well developed and checked programs run by experienced engineers can operate such equipment safely. Full scale building responses are on the order of 0.01-0.1g. Usually this testing is performed after business hours to avoid annoying the building occupant. The LabVIEW program written for these applications needed to have a large portion of its code dedicated to automatically detecting system parameter violations and immediately react accordingly with specifically designed emergency shutdown processes.

Additional challenges are due to signal strength and picked up noise from any number of sources that arise from several hundred feet of cable runs between the computer and transducers. Besides using proper cable shielding techniques, ANCO has found that the use of Fourier analysis allows for proper processing of low signal values. The large dynamic voltage range of the NI data acquisition boards and the use of analog anti-aliasing filters also contributes to the ability to monitor small signals. The result is data suitable for structural analysts to validate FEA models

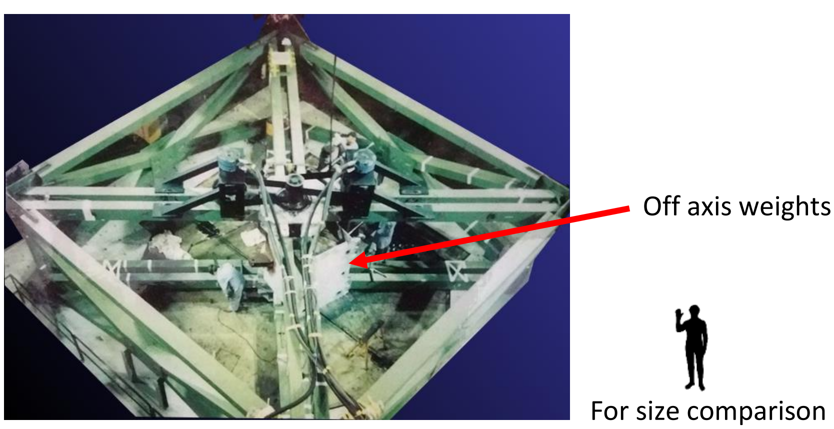

Figure 2) Example of a large eccentric mass vibrator. The single center shaft contains the off-axis weight at the 5 o'clock position. This system was designed to study the high level (1g) response integrity of nuclear power station containment.

A smaller but not less intimidating system is shown in the video below:

Video 1) Example of smaller 2-axis eccentric mass vibrator used for exciting buildings and ships. Force generation is in the up and down position.

Using LabVIEW API and National Instruments PXI Hardware

A simple but sophisticated API was developed to provide fast and clear access to real time data. The API allows configuration of drive control parameters and safety parameters. All control parameters are live which allows real time modification during operations by the operator.

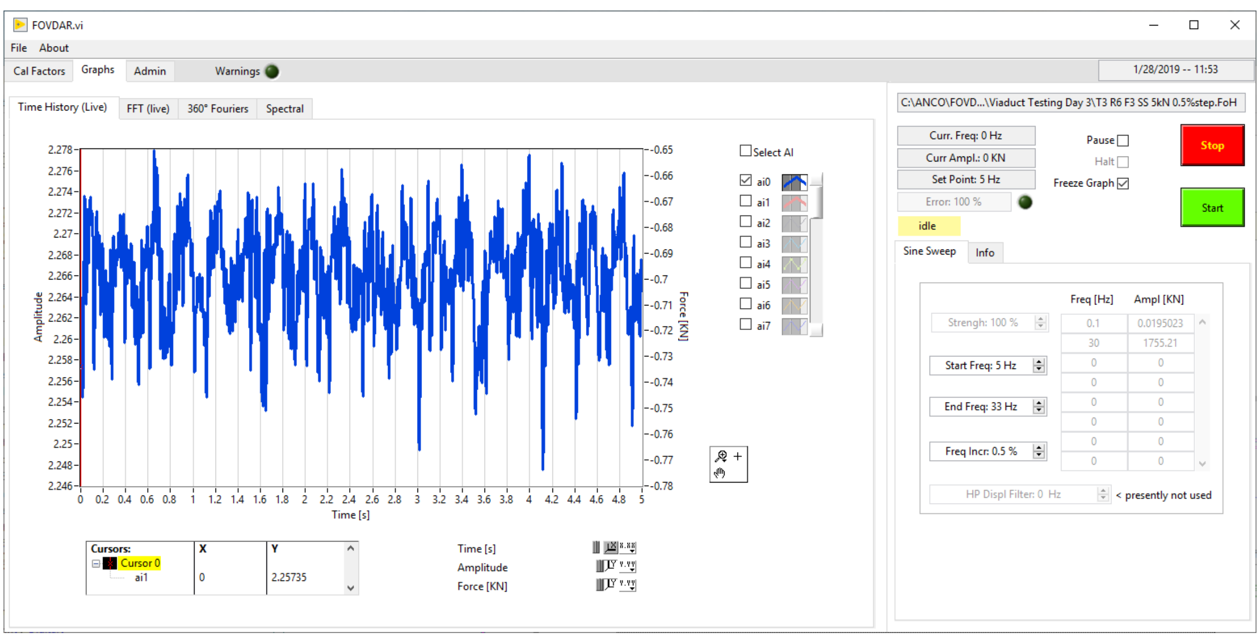

Figure 3) Example of raw unprocessed time history data taken at a constant force excitation near 4Hz. The data chart is configured as a real time oscilloscope providing immediate feedback on all sensors.

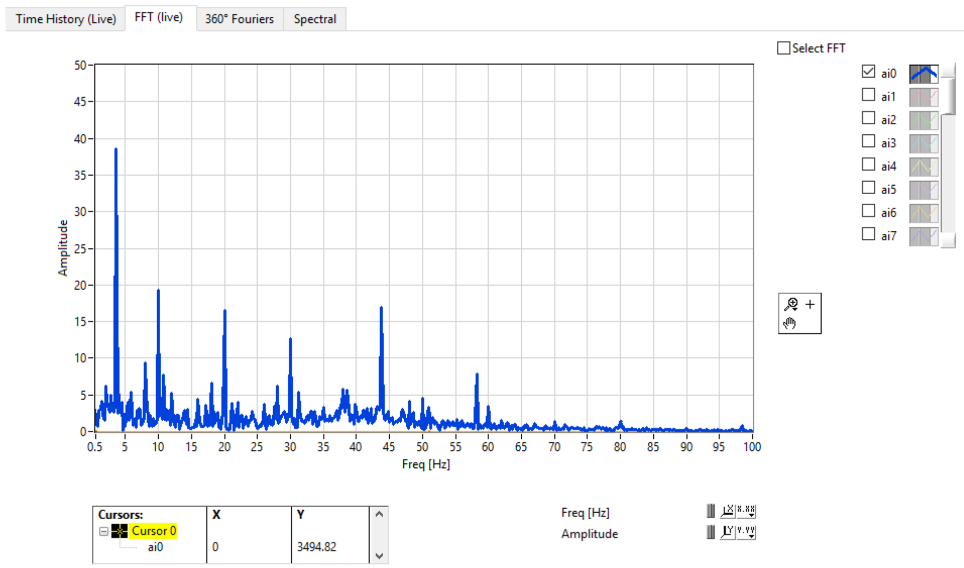

Figure 4) Excerpt of the API showing the corresponding FFT taken at a constant force excitation near 4Hz.

As described above, the isolation of single frequency components is key for spectral analysis to determine frequency response functions. The screenshot below shows a signal referenced to the sinusoidal drive force function near one of the higher frequency building resonant harmonics. Although signal strength is very low (~10mV) compared to signals at resonance, using the NI-DAQ card's high dynamic range made this a useful and meaningful test.

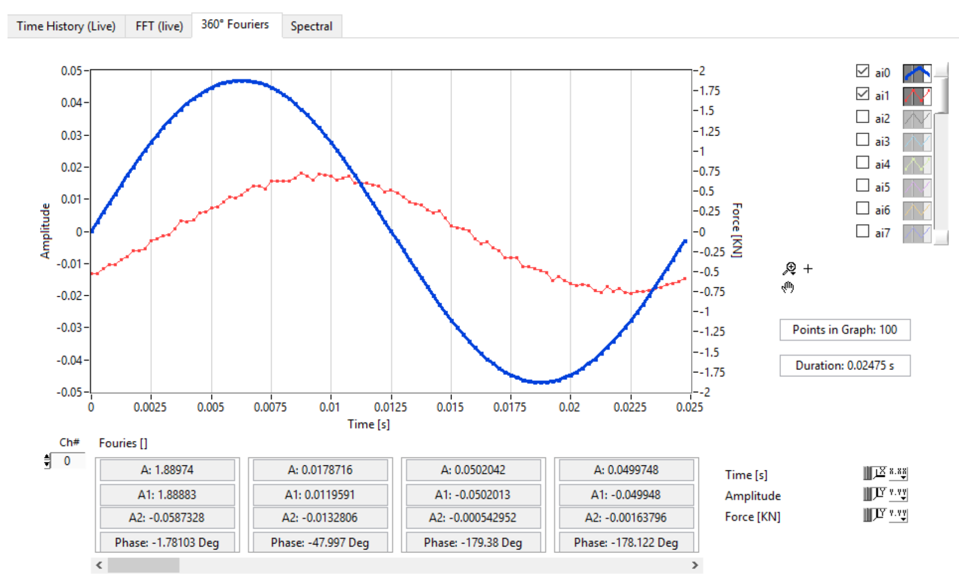

Figure 5) Isolated processed signal referenced in real time to a single frequency excitation. Displayed are the signals Fourier parameters for magnitude (A), real (A1), and imaginary (A2) components (i.e. phase) for multiple channels.

Plotting the result of all Fourier series data segments for each sinusoidal frequency allows the graphical representation of the building spectral response to a variable forcing frequency sweep.

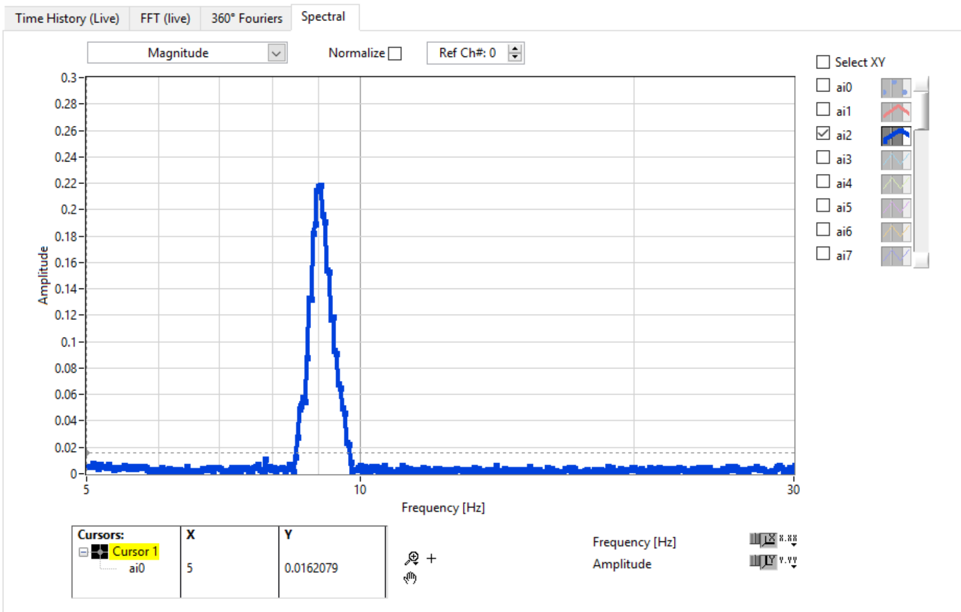

Figure 6) Spectral performance (frequency response plot) of a bridge showing a distinct large resonance

Benefits of using LabVIEW and NI Hardware

ANCO has chosen NI-hardware and the LabVIEW programming environment because both provide a reliable and safe platform to execute complex vibrational tests on critical structures. Using LabVIEW's fast mathematical tool sets for FFT's and other functions allowed the display of data in real time without adding to the CPU processing load. LabVIEW's graphical toolsets allowed to design an effective front panel which displayed complex data in a concise and organized format. This was an important safety feature as it gives qualified engineers and scientists immediate feedback on sensors that are often several hundred feet away from the control computer, other electronic units, allowing necessary intervention.

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