Case Studies of Tools Used in Teaching Structural Dynamics

Kurt Veggeberg
National Instruments
11500 N. Mopac, Austin, TX 78759 USA

ABSTRACT

This is an overview of case studies of the tools used in teaching structural dynamics and their development. A key feature was the requirement for hardware and software to be comprehensive for the application, but easy to use and affordable. One example includes the hardware and software used in ambient vibration monitoring and forced impact testing on the International Bridge Study. The other includes the use of ModalVIEW for a full modal analysis of a modified unmanned aerial vehicle (UAV) to better understand its flight characteristics and to help determine appropriate flight conditions for operation by the Unmanned Aircraft Systems Engineering (UASE) laboratory team at the University of North Dakota.

Keywords : Modal Analysis, Experimental Modal Analysis, ModalVIEW, LabVIEW, National Instruments

1. Introduction

A desirable feature in teaching structural dynamics is for hardware and software tools to be comprehensive for the application, but easy to use and affordable. This is an overview of case studies where such tools were used. One example includes the hardware and software used in ambient vibration monitoring and forced impact testing on the International Bridge Study. The International Bridge Study was designed to demonstrate and document the best-practices in bridge technology integration and educate bridge inspectors, consultant, technology providers, and others. Drexel University conducted live load testing, forced impact testing and ambient vibration monitoring over the length of the study as well as completing the modeling both before and after testing. The other example includes the use of ModalVIEW to conduct a full modal analysis of a modified unmanned aerial vehicle (UAV) to better understand its flight characteristics and to help determine appropriate flight conditions for operation by the Unmanned Aircraft Systems Engineering (UASE) laboratory team at the University of North Dakota. ModalVIEW has an easy to understand interface for every step of the vibration testing process, from connecting the sensors to animating the structure with the mode shapes.

2. International Bridge Study hardware and software

National Instruments cRIO data acquisition system were used in testing the structural behavior of a bridge in the International Bridge Study (IBS) through ambient and forced excitation to calibrate and improve the accuracy of the bridge model to diagnose, perform prognosis, and design treatments to mitigate performance deficiencies of bridges. [1]

The Intelligent Infrastructure Alliance (IIA), hosted by the Civil, Architectural & Environmental Engineering Department at Drexel University, is a university - government - industry partnership. The IIA was invited to participate in the International Bridge Study (IBS) with the goal of establishing the worldwide ***"best practices"*** for the integration and application of technology to diagnose, perform prognosis, and design treatments to mitigate performance deficiencies for a given bridge. As part of this program, a steel stringer bridge was selected in northern New Jersey for a round robin study conducted by teams from the United States, Europe and Asia. The primary objectives of the program included developing more accurate estimates of bridge structural health improve and disseminate knowledge of bridge performance, and to promote the safety, longevity and reliability of the United States highway transportation system. (Figure 1)

IIA conducted live load testing, forced impact testing and ambient vibration monitoring over the length of the study as well as completing the modeling both before and after testing. The selected bridge was considered to be representative of a large portion of bridges in form, material, age and span length. In this research, an integrated analytical/experimental strategy and an associated experimental tool was used for an objective evaluation of bridge condition to supplement visual inspection. Termed as rapid modal analysis**,** this test technique aims at reducing both the time and personnel required to produce estimates of bridge flexibility at strategic coordinates using spatially truncated measurement grids.

Given the concerns surrounding the vibration of the spans, a preliminary ambient vibration monitoring of the bridge was conducted during one of the site visits. This study consisted of recording ten minutes of data from four accelerometers installed on the sidewalk of each span (so no traffic control was required). During a ten minute time window, ambient traffic was able to provide sufficient input and signal to noise ratios for all sensors, including those located at the boundaries, resulting in reliable modal parameter estimation.

Figure 1. US 202/NJ 23 Bridge used in International Bridge Study

For the US 202/NJ 23 Bridge, the primary objective of the impact test was reliable estimation of modal parameters to allow for an effective model calibration. Using the modes (and their variations) estimated by the a priori model, a series of fixed sensor locations for both Span 2 NB and Span 2 SB were selected. The instrumentation plan aimed to provide regular and spatially well-distributed sensor number of sensors near nodal points of critical modes, and to select impact locations at maximum modal displacements of principal modes.

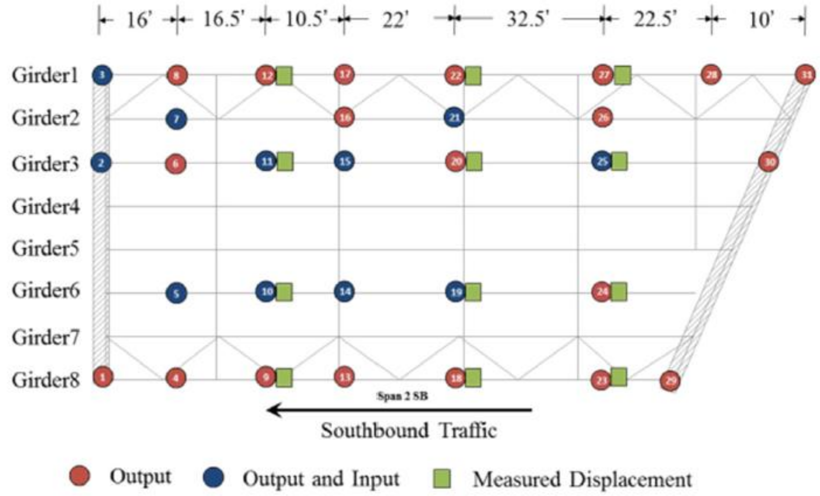


Figure 2. Sensor locations for the span of bridge being tested

Impact excitation was to be applied by drop hammer and sledgehammer. Natural frequencies derived from mode shapes from both types of the excitation tests and those derived from the ambient vibration test varied by less than five percent. This small difference demonstrates that each excitation method can produce consistent estimates of the damped natural frequencies. Each driving point location was impacted five times with the sledgehammer and three times with the drop hammer in order to average out the effects of extraneous inputs. Several clean impact response cycles are needed to obtain adequate FRFs. Since the Drexel drop hammer provided high force levels and a flat frequency spectrum, the results obtained during the drop hammer tests were selected for presentation.

The data acquisition system used for the forced (impact) vibration testing campaigns was provided by National Instruments and combined a CompactRIO chassis with eight NI 9234 dynamic signal acquisition modules used to read piezoelectric accelerometers programmed via LabVIEW. The entire data acquisition system was debugged while collecting time domain data under ambient excitation. The PCB 393A03 accelerometer was used since it has a significantly more robust connection design than common piezoelectric sensors designs that use the 10-32 microdot connection. All calibration factors were input to the test file, and each sensor was checked for proper operation. Prior to conducting the multi-reference impact testing on the top side of the structure, numerous ambient excitation time records were collected during normal operation of the structure. The ambient monitoring program provided valuable information about the natural frequencies and mode shapes of each structure under ambient conditions. The test control during impact testing was conducted from the topside of structure and the control laptop was connected to the data acquisition system on the ground via an Ethernet cable. (Figure 3)

Figure 3. National Instrument cRIO data acquisition system used for impact testing campaigns on bridge

The drop hammer used in this research was designed by the Drexel University team. An adjustable heavy, moving mass drops from an adjustable height and a PCB 200C50 load cell with a medium polyurethane impact tip (Model 084A32) provides an impact on the surface of the deck. Since the impact carriage bounces off the bridge deck, several impacts occur. The rebound control system aims to stop these multiple impacts and consists of a brake system activated by a control system that tracks the position of the impact carriage. The sensing/control system includes a National Instruments (NI) CompactRIO Data Acquisition system (cRIO DAQ) that interfaces with an Acuity AR700 laser distance gauge. The cRIO controller runs a NI LabVIEW Real-Time program that interfaces with the NI 9112 cRIO chassis, and a host PC that runs an interactive user interface. An NI 9205 analog input module reads distance measurement data from the laser, while an NI 9269 analog output module provides control signals to the mechanical control system. (Figure 4)

Figure 4. Automated drop hammer system with rebound control designed by Drexel team

The motivation of this research was to explore the feasibility and reliability of a “rapid modal analysis” concept for bridge condition evaluation. The concept incorporates multi-input-multiple-output (MIMO) modal analysis of a bridge by controlled impact(s) at the critical coordinates of the superstructure while measuring the impact, as well as the transient acceleration responses of the superstructure. Although bridge modal analysis by impact has been demonstrated as a reliable tool for flexibility, its feasibility for widespread applications to bridges was not considered favorable due to the need to close the bridge for an extended period. On the other hand, the challenges of reliable bridge condition evaluation and the opportunity to adapt new tools, such as a falling weight deflectometer (FWD), justified further exploration for transforming MIMO modal analysis into a rapidly applicable method with only a short-duration (~15 min) traffic control. To build on this research and findings, additional work is recommended to develop and evaluate the implementation of the proposed rapid modal analysis tool.

Available hardware (sensors, excitation devices and data acquisition hardware) as well as software including LabVIEW and ModalVIEW were used. There was no budget for additional equipment purchase which is typical in many academic applications.

Processing data on site was used as a data quality check and as a tool to provide useful insight to inform the design and execution of the impact test. Plot mode shapes help determine whether the shapes make sense physically. Seven possible modes were identified from 2-15 Hz. The conclusion was that rapid modal analysis methods complement full scale comprehensive testing techniques and are not intended to replace any of the validated and mature structural testing techniques presented in the literature.

3. ModalVIEW

ModalVIEW is a turn-key software solution offered by AB Signal required that has been used by a number of universities for education. These include Drexel University, the University of North Dakota, Penn State College of Engineering and others. After obtaining a set of time histories, it can animate the response of a structure’s vibration behavior. ModalVIEW software was designed in LabVIEW by a former National Instruments (NI) software developer. ModalVIEW software supports direct acquisition from NI dynamic signal acquisition (DSA) hardware including PXI, PCI and USB to speed up the time needed to perform experimental measurements. ModalVIEW incorporates the steps required for modal testing and analysis. It supports frequency-based and order-based operational deflection shapes (ODS), experimental modal analysis (EMA) and operational modal analysis (OMA).

The software was an outgrowth of Modal Analysis Parameter Extraction LabVIEW VIs developed as a part of a toolkit. This consists of a set of algorithms used to identify the modal parameters of a structure (natural frequency, damping ratio, mode shapes). These algorithms are either used for experimental research or for operational on-line monitoring. These algorithms include Peak Picking, Least Square Complex Exponential Fit, Frequency Domain Polynomial Fit, Stochastic Subspace Identification, and FRF Synthesis. Each of these algorithms perform the same function of identifying the modal parameters, however, each are optimized for a specific test scenario. [2]

4. Structural Analysis of a Small Unmanned Aircraft Using ModalVIEW and NI CompactDAQ

The Unmanned Aircraft Systems Engineering Laboratory at the University of North Dakota was interested in analyzing how adding wing pods changes the flight characteristics of a small unmanned aerial vehicle (UAV) used for flight testing multiple payloads. They chose ModalVIEW and an NI CompactDAQ system that can measure up to 32 channels to extract and visualize the modal parameters of the aircraft with and without the added weight of wing pods to determine if they adversely affect flight performance. They chose this software because of its ease of use and perfect fit for the type of testing they are doing. A paper on this application, "Structural Analysis of the Effects of Wing Payload Pods on Small UAS," was presented at SEM IMAC XXX in 2012. [3]

The Unmanned Aircraft Systems Engineering (UASE) laboratory team operates a Bruce Tharpe Engineering (BTE) Super Hauler UAV. They develop aircraft payloads up to 30 lb (14 kg) for intelligence, surveillance, and reconnaissance (ISR) missions, as well as airborne sense and avoid (ABSAA) systems. The Super Hauler is 10 ft long (3 m) and has a 12 ft (3.6 m) wingspan and a dry weight of 48 pounds (22 kg). The aircraft's behavior in its original configuration is well understood, but adding wing payload pods for future missions will change the aircraft's structural and flight behavior.

The Super Hauler is custom designed to provide a large, unobstructed payload bay to mount multiple payloads for flight testing. This capability meets the needs of the previous payloads tested, but adding wing payload pods is necessary to conduct new missions and evaluate payloads for radar-related work. The wing payload pods will most often be used in pairs to equalize the wing loading and provide a symmetric load on the airframe. They will run the electrical and power connectors and wiring inside of the wing so they are out of the airflow. In this manner, the antenna systems inside the wing pods have an uninterrupted front-facing field of view.

The goal was to obtain a full modal analysis of the UAV to better understand its flight characteristics and the effect of the wing pods, and to help determine appropriate flight conditions for operation. This sort of testing has been done before on many different kinds of aircrafts, but it was hoped that their work will assist others that are testing small UAVs in a similar manner.

ModalVIEW and NI CompactDAQ hardware were used to create a plug-and-play system. ModalVIEW has an easy to understand interface for every step of the vibration testing process, from connecting the sensors to animating the structure with the mode shapes that were found.

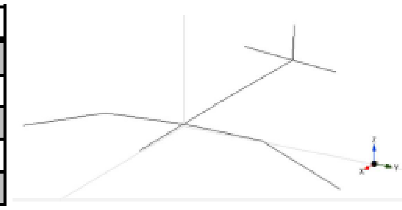
They used experimental modal analysis to obtain structure modal parameters by measuring and analyzing the dynamic response of the structure when excited by a stimulus. ModalVIEW supports a variety of multiple-degree-of-freedom (MDOF) global fitting analysis methods and multiple-input, multiple-output (MIMO) polyreference experimental methods using impact hammers or shakers. It also has an animation tool that was used to visualize the aircraft’s mode shape.

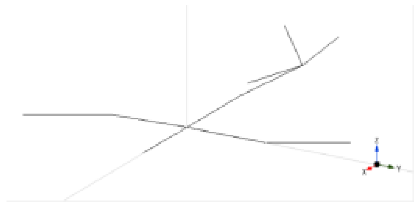
The Super Hauler was isolated for analysis by placing it on bungee cords in a test rig so all the wheels were 1.25 in. off the ground, which simulates a free-free boundary condition for modal testing. A 5 lb weight was mounted on each wing to simulate the wing pods. To perform the analysis, the BTE Super Hauler was first instrumented with accelerometers in key locations. A mixture of PCB Piezotronics triaxial and uniaxial accelerometers were mounted directly on the aircraft’s outer skin. The accelerometers were connected to an NI cDAQ-9178 chassis containing eight NI 9234 dynamic signal acquisition (DSA) modules. The Super Hauler was excited with a PCB Piezotronics 086C03 impact hammer.

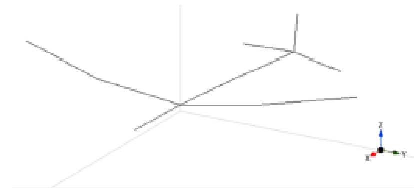
The NI CompactDAQ front end interfaced seamlessly with the ModalVIEW software for the analysis. Six impact tests were performed both with and without the simulated wing pods attached. Each of the tests consisted of impacting the Super Hauler at one of the nodes, measuring the frequency response, then obtaining the natural frequencies from the frequency response function (FRF) and animating the line model with the corresponding mode shapes. It was speculated that the first natural frequency without the pods doesn't have a match in the set with the pods because there isn't as much structural coupling between the wings and the fuselage.

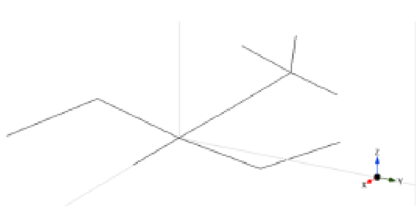
In the mode shapes observed, the natural frequencies all shifted dramatically down with the addition of the wing pods. This was expected since a substantial amount of weight was added. The wing pods account for 20 percent of the total weight, and they have a fairly dramatic influence on the structural response. Although significant changes in frequencies were observed, none of the fundamental modes shifted out of the operational frequency range of the aircraft without the pods installed. Therefore, it is expected that changes in flight dynamics will not be a significant factor in flight performance.

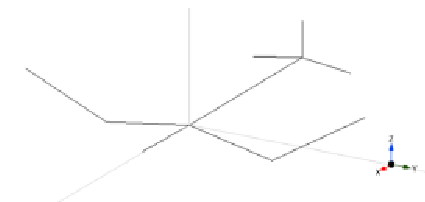
Without Pods	With Pods	Description
12.4 Hz	-	Wing-tip bending only
27.0 Hz	10.8 Hz	Tail twisting only
27.6 Hz	12.54 Hz	Wing bending opposite tail bending
72.8 Hz	19.9 Hz	Wing bending and tail twisting
90.8 Hz	27.9 Hz	Mode 2 wing bending











Conclusions

A key feature in teaching is the requirement for hardware and software to be comprehensive for the application, but easy to use and affordable. The case studies here illustrate examples that can be useful for teaching experimental and analytical structural dynamics.

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References

[1] Prader, J., Rapid Impact Modal Testing for Bridge Flexibility: Towards Objective Evaluation of Structures, PhD Thesis, Drexel University May 2012. http://www.di3.drexel.edu/w2/files/Prader_Thesis_2012.pdf

[2] Modal Parameter Extraction LabVIEW VIs. National Instruments. http://zone.ni.com/devzone/cda/epd/p/id/6121

[3] Lemler, K., Semke, W., "Structural Analysis of the Effects of Wing Payload Pods on Small UAS" Topics in Modal Analysis II, Volume 6 Conference Proceedings of the Society for Experimental Mechanics Series Volume 31, 2012, pp 515-523.