Video Article

Data Acquisition Protocol for Determining Embedded Sensitivity Functions

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Abstract

The effectiveness of many structural health monitoring techniques depends on the placement of sensors and the location of input forces. Algorithms for determining optimal sensor and forcing locations typically require data, either simulated or measured, from the damaged structure. Embedded sensitivity functions provide an approach for determining the best available sensor location to detect damage with only data from the healthy structure. In this video and manuscript, the data acquisition procedure and best practices for determining the embedded sensitivity functions of a structure is presented. The frequency response functions used in the calculation of the embedded sensitivity functions are acquired using modal impact testing. Data is acquired and representative results are shown for a residential scale wind turbine blade. Strategies for evaluating the quality of the data being acquired are provided during the demonstration of the data acquisition process.

Video Link

The video component of this article can be found at <http://www.jove.com/video/53690/>

Introduction

Many structural health monitoring techniques rely on changes in measured frequency response functions (FRFs) to detect damage within a structure. However, few of these methods address how to determine sensor placements and/or input force locations that will maximize the effectiveness of the method to detect damage. Embedded sensitivity functions (ESFs) can be used to determine the sensitivity of an FRF to a local change in a structure's material properties. Therefore, because damage typically results in a local change in stiffness, damping, or mass of the structure, ESFs provide a method for determining the best sensor and force locations for FRF-based health monitoring techniques.

The purpose of this video and manuscript is to detail the data acquisition process and best practices for determining ESFs for a structure. The process includes determining various FRFs from modal impact testing, which is performed by exciting a structure with a modal impact hammer and measuring its response with accelerometers. In this work, the structure being tested is a 1.2 m residential-scale wind turbine blade. The goal of the testing and analysis is to identify sensor locations which are most sensitive to damage to the blade. These sensor locations could then be used in a structural health monitoring scheme to monitor the blade for damage.

Besides the use of ESFs to determine the most effective sensor locations to use in a structural health monitoring scheme, several optimal sensor placement algorithms can also be found demonstrated in the literature. In [Kramer], Kramer iteratively evaluates the ability of a set of sensors to observe the modes of a system. More recently, genetic algorithms¹⁻³ and neural networks⁴ have been developed to identify optimal sensor locations. In⁵, a Bayesian approach is used that takes into account the risk of different types of errors and the distribution of damage rates. In⁶, a finite element model was leveraged to identify the sensor locations most likely to detect damage. In most of the sensor placement algorithms presented in the literature, data from the damaged structure, whether simulated or measured, is required. One advantage of the embedded sensitivity approach is that the sensor locations can be determined from the healthy structure.

Another advantage of ESFs is that material properties need not be explicitly known. Instead, the material properties are "embedded" in the expressions for the system's FRFs. Therefore, all that is needed to calculate ESFs are a set of measured FRFs at particular input/output locations. Specifically, the sensitivity of the FRF (H_{jk}) calculated from a response measured at point j to an input at point k , to a change in stiffness (K_{mn}) between points m and n is

$$\frac{\partial H_{jk}}{\partial K_{mn}}(\omega) = -[H_{jm}(\omega) - H_{jn}(\omega)][H_{km}(\omega) - H_{kn}(\omega)] \quad (1)$$

where $\left(\frac{\partial H_{jk}}{\partial K_{mn}}\right)$ is the ESF as a function of frequency, ω^{7-9} . The procedure for measuring the FRFs required to calculate the right-hand side of equation (1) is detailed in the next section and demonstrated in the video.

Protocol

1. Pre-test Preparation

1. Design and fabricate the test fixture. Design the fixture to replicate realistic boundary conditions by choosing bolt locations to match the mounting locations of the blade. Choose steel for the fixture to minimize the contribution from the fixture to the dynamic response of the test specimen.
 1. Bolt the blade to the custom t-bracket.
 2. Clamp the fixture to a steel table.
2. Identify and mark grid of impact locations.
 1. Choose 30 points that span the entire blade.
 2. Mark points with a marker or wax pen and number for reference. Measure point spacing using a tape measure for later use in visual representation of results.
3. Select and calibrate accelerometers.
 1. Choose single axis, 10 mV/g accelerometers. Be sure to choose accelerometers with the appropriate sensitivity in order to avoid overloading the sensor and to achieve good signal-to-noise ratios. Also, be sure the frequency range of the sensors is sufficient to capture the frequency range of interest for the test specimen.
 2. Calibrate each sensor.
 1. Attach the sensor to a hand-held shaker whose output is a single-frequency force with a magnitude of 9.81 m/sec² rms (i.e., 1 g).
 2. Measure the response for 2 sec.
 3. Determine the rms amplitude of the response from the software readout.
 4. Multiply the rms amplitude by 1,000 to determine the calibration factor for the accelerometer in units of mV/g.
4. Select hammer and hammer tip.
 1. Choose an impact hammer with a sensitivity of 11.2 mV/N. Be sure to select a hammer that sufficiently excites the test specimen in both amplitude and frequency range.
 2. Choose a nylon tip. Be sure to select a hammer tip that sufficiently excites the test specimen in both amplitude and frequency range.
 3. Connect the hammer to the data acquisition system with a BNC cable.
5. Identify sensor locations and attach sensors (**Figure 4**).
 1. Choose locations at points *m* and *n* on either side of the damage location.
 2. Mount a third accelerometer at location *k*. Data from this sensor will be used to validate the results of the embedded sensitivity function analysis.
 3. Attach accelerometers using super glue. Allow the super glue to set completely before conducting the impact testing.
6. Select test parameters in the data acquisition GUI.
 1. Enable double hit detection.
 2. Set the sampling frequency to 25,600 Hz. The usable frequency range is, therefore, 12,800 Hz.
 3. Set the sample time to 1 sec.
 4. Select the hammer channel as the trigger channel. Set the trigger level to 10 EU.
 5. Set the pre-trigger length to 5% of the total sample time. The pre-trigger data is data collected before the data acquisition is started that has been stored in a buffer. It is important to retrieve and save this data so that the entire impact event is captured.
 6. Select the H1 FRF estimator. This estimator assumes that there is noise on the response channels and no noise on the force channel. Note: Do not window data during acquisition. Windows can be applied in post-processing, if necessary.
 7. Enter accelerometer and hammer information, including calibration factors and identification notes.
 8. Save settings for record keeping and for use in future tests.

2. Impact Testing on the Healthy Blade

1. Impact point 1 with the hammer. When the amplitude of the impact force exceeds the chosen trigger level, the data acquisition system will be triggered and data, including the selected amount of pre-trigger data, will begin recording.
 1. During data acquisition, monitor channels to avoid channel clipping and double impacts by observing the time histories displayed in the data acquisition software.
 2. During data acquisition, monitor the coherence for each accelerometer channel to evaluate the quality of the acquired data by observing the coherence plot in the data acquisition software.
2. Repeat step 2.1 four more times at point 1.
 1. Use consistent impact amplitudes for all impacts.

3. Repeat steps 2.1 and 2.2 for all points.

3. Impact Testing on the Damaged Blade

1. Repeat section 2 on the damaged blade in order to collect data for validating the embedded sensitivity function results. Except for the change in the test specimen, all test parameters are kept the same.

Representative Results

Figure 1 shows a typical embedded sensitivity function. Similar to an FRF, the ESF has peaks near the natural frequencies of the structure. The higher the value of the ESF, the more sensitive the location is to damage between points m and n . Each of the thirty points tested on the wind turbine blade has a unique ESF. These ESFs can be compared to determine which sensor location would be most sensitive to damage. For example, **Figure 2** shows the amplitudes of the ESFs near 142 Hz. From this plot, it is clear that sensor locations corresponding to the squares in the first and third columns are most sensitive to the damage. Note that these locations are determined from data acquired from the healthy blade.

Figure 3 shows the measured difference in FRFs between the FRFs determined from data from the healthy blade and those determined from data from the damaged blade. The similarities between the difference in FRFs and the ESFs show the effectiveness of the ESFs to predict the locations at which the largest changes in FRFs due to damage will be exhibited.

Figure 1. The amplitude of the embedded sensitivity function for point 1. The value of the ESF corresponds to the sensitivity of the FRF at point 1 to damage in the structure at the chosen location. The values change as a function of frequency. Peaks in the ESF tend to correspond to natural frequencies of the structure. [Please click here to view a larger version of this figure.](#)

Embedded Sensitivity Function at 142 Hz

Figure 2. The amplitudes of the ESFs for all thirty points at 142 Hz. Each colored square corresponds to the value of the ESF at 142 Hz for each spatial location tested. Hot colors correspond to points at which the ESFs predict the largest change in FRF due to damage. Cooler colors indicate that the change in FRF at that point will be relatively small. [Please click here to view a larger version of this figure.](#)

Difference in FRF at 142 Hz

Figure 3. The difference in the FRFs, H_{jk} , for all thirty points at 142 Hz. The differences were calculated by subtracting the FRFs determined from the healthy and damaged blades. Hot colors indicate large differences in FRFs. Cool colors indicate small changes in FRFs. [Please click here to view a larger version of this figure.](#)

Figure 4. Impact points used during testing. Points were chosen to span the blade. [Please click here to view a larger version of this figure.](#)

Discussion

Test fixtures should be designed to replicate realistic boundary conditions so that results will be applicable under operating conditions. The selection of the number of impact points used for testing is a trade-off between having sufficient spatial resolution and the testing time. Select the hammer based on the size of the test specimen and the frequency range of interest. In general, the smaller the hammer, the broader the frequency range excited. However, smaller hammers typically produce lower amplitude forces. Impact hammers are instrumented with a force gauge to measure the time history of the impact. The type of hammer tip also affects the frequency range of excitation. The harder the tip,

the broader the frequency band of excitation. Super glue is chosen over wax, for example, to minimize the attenuation of the response by the mounting material.

In the data acquisition software, enable double hit detection in order to automatically indicate when a double impact has occurred. Single impacts are desired because they produce a broader, more repeatable force spectrum. When the amplitude of the force rises above the selected trigger level, the data acquisition is started. Time data is acquired by the data acquisition software. During acquisition data should be monitored to ensure data quality. Channel clipping, which occurs when the response measured by the sensor exceeds the allowable voltage range, should be avoided. Coherence is an excellent metric to use to judge data quality. In general, coherence should be near one for all frequencies within the frequency range excited by the impact. Dips in coherence are expected near anti-resonance frequencies of the test specimen because the signal to noise ratio is low and the noise is uncorrelated with the input. Once quality data is acquired, the time histories are converted into the frequency domain via the Fast Fourier Transform (FFT), and the average FRF is estimated using the H1 estimator¹⁰.

To determine the ESF from the FRFs measured during testing, equation 1 can be used in one of two ways. First, the direct approach can be used, which requires measurements for H_{jm} , H_{jn} , H_{km} , and H_{kn} . These FRFs would be determined by placing a sensor at location k and moving a sensor to each potential sensor location j . Impacts would be applied at the two locations that span the damage location. To make data collection more efficient, the principal of reciprocity can be used to reverse the input and measurement locations. Using this approach, H_{mj} , H_{nj} , H_{mk} , and H_{nk} are determined. Now, instead of having to move the sensors for each different measurement, the sensors stay stationary and the impact location is moved. Once the ESFs are calculated for each location, their amplitudes are compared to determine which location j is most sensitive to damage between locations m and n . Note that a single damage location is assumed in this work.

The results of the ESF analysis can now be used in an FRF-based structural health monitoring scheme. In¹¹, it was demonstrated that the sensor locations identified by ESFs as being most sensitive to damage were more effective in identifying the presence of damage to a wind turbine blade.

Other methods to predict locations at which a structure's FRF will be sensitive to damage typically rely on analytical modeling of the structure^{6,12}. FRF data is simulated using different combinations of input and measurement locations. However, the results of these methods rely on the development of a reliable and accurate model, which requires detailed knowledge of material properties and the geometry of the structure. Because ESFs can be calculated from experimentally measured data on the healthy structure, the identification of material properties is not required and the geometry of the structure does not need to be determined.

One potential limitation of the technique is that it requires *a priori* knowledge of where the damage is going to occur. In many applications, this requirement is not limiting because due to stress analyses and prior experience, the damage location can be foreseen. In applications where the damage location is unknown, multiple data sets can be acquired, each time assuming a different damage location. Within the data acquisition protocol, many best practices were identified that not only apply to data acquisition for ESFs, but also apply generally to modal impact testing. Being able to judge the quality of the data being acquired improves with experience, but knowing fundamentals including determining force roll-off and evaluating coherence will enable even those new to modal impact testing to acquire high-quality data.

Disclosures

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