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MODAL PARAMETER EXTRACTION FROM LARGE OPERATING STRUCTURES USING AMBIENT EXCITATION

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ABSTRACT

Large Structures (such as wind turbines, trucks, bridges, and offshore structures) are subjected to highly uncertain operating environments in the field. A technique called the Natural Excitation Technique or NExT has been developed to extract response parameters from large operational structures when subjected to random and unmeasured forces such as wind, road noise, aerodynamics, or waves. Six applications of NExT to ambient excitation testing and NExT analysis are surveyed in this paper with a minimum of technical detail. In the first application, NExT was applied to a controlled-yaw Horizontal-Axis Wind Turbine (HAWT). By controlling the yaw degree of freedom an important class of rotating coordinate system effects are reduced. A new shape extraction procedure was applied to this data set with good results. The second application was to a free-yaw HAWT. The complexity of the response has prompted further analytical studies and the development of a specialized visualization package. The third application of NExT was to a parked three-bladed Vertical-Axis Wind Turbine (VAWT) in which traditional modal testing could not excite all modes of interest. The shape extraction process used cross-correlation functions directly in a time-domain shape-fitting routine.

The fourth application was to ground transportation systems. Ongoing work to improve driver and passenger comfort in tractor-trailer vehicles and to refine automobile body and tire models will use NExT. NExT has been used to process ambient vibration data for Finite Element Model correlation and is being used to study Structural Health Monitoring with ambient excitation. Shape fitting was performed using amplitude and phase information taken directly from the cross-spectra. The final application is to an offshore structure. This work is on-going, however initial studies have found a high-modal density, high noise content, and sparse data set. The ability to process ambient vibration data using NExT makes Structural Health Monitoring, model correlation, and diagnostic test much more feasible for large operational structures.

INTRODUCTION

Large Structures (such as wind turbines, trucks, bridges, and offshore structures) are subjected to highly uncertain operating environments in the field. Typically, these structures have been analytically modeled and subjected to laboratory tests (at least on the component level) to estimate their response in operation. Likewise, the health of the structure may be tracked via changes in the response parameters. Unfortunately, traditional techniques which measure the input forces and the output forces to the structure are not applicable since the ambient excitation forces cannot be measured. A technique called the Natural Excitation Technique or NExT has been developed to extract response parameters from large operational structures when subjected to random and unmeasured forces such as wind, road noise, aerodynamics, or waves.

The basis for extracting modal parameters from structures undergoing ambient excitation has a long history dating to the 1960's. There have been several different approaches to the analysis of such data: peak-picking from Power Spectral Density (PSD) functions, Auto Regressive - Moving Average (ARMA) models, the Maximum Entropy Method (MEM), random decrement processing coupled with time-domain parameter extraction, direct use of raw data with time-domain

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parameter extraction, and the use of cross-correlation functions with time-domain parameter extraction. Akaike was among the first to study the use of Auto Regressive - Moving Average (ARMA) type models to analyze systems with ambient excitation [1]. This procedure was applied to a variety of systems including machine tools [2]. The closely associated Maximum Entropy Method (MEM) has been applied to the analysis of offshore structures undergoing wave excitation [3]. Another procedure called random decrement [4] was developed to process ambient-excitation data. This processing allowed the first use a time-domain parameter extraction scheme, specifically the Ibrahim Time Domain (ITD) technique [5], to be applied ambient-excitation data [6]. Later work proved that the random decrement technique was an alternative method for estimating the auto-correlation function [7]. Pappa and Juang later utilized naturally-excited data directly in the Eigensystem Realization Algorithm (ERA) [8] which is also a time-domain parameter extraction scheme [9]. It has also been proposed that the use of data directly in the ERA with Data Correlations (ERA/DC) algorithm [10] is equivalent to using cross-correlation functions in the original ERA algorithm.[11].

Clarkson and Mercer presented a procedure in 1965 to estimate the frequency response characteristics of a structure excited by white noise using cross-correlation functions [12]. Although their work assumed a measured input, the conceptual framework was laid to utilize correlation functions instead of impulse response functions when the excitation was not known. When coupled with a time-domain modal extraction scheme [5, 8, 13, 14], this concept became a very powerful tool for the analysis of naturally-excited structures. This concept was applied by James et. al. [15] to wind turbines and Kim et. al. [11] to a launch vehicle.

The concept of using natural excitation for modal testing of parked Vertical-Axis Wind Turbines (VAWTs) was first suggested by Lauffer et al. [16]. The technique was developed further and used for the modal tests of other VAWTs [15, 17]. Upon the development of a theoretical basis for utilizing cross-correlation functions in time-domain parameter extraction algorithms and several validation exercises [18], the term Natural Excitation Technique (NExT) was used to refer to this. formalized approach. NExT is a method of modal testing that allows structures to be tested in their ambient environments. Initially, this procedure was developed to allow VAWTs to be tested during parked and operating conditions. Since, these structures are much different in the operating condition as compared to the parked condition, the modal frequencies and damping ratios must be extracted from measured response data. More specifically, knowledge of the total modal damping (structural and aeroelastic) is important for predicting fatigue life and reducing resonant responses. NExT has also been applied to the verification of aeroelastic damping models for rotating VAWT's [18-20], a Horizontal-Axis Wind Turbine (HAWT) [21], a rocket during launch [22], a ground transportation vehicle [18], and a bridge [23]. The work presented herein discusses new applications to a free-yaw HAWT, a three-bladed composite VAWT, an offshore structure, an experimental bridge simulation, and further applications ground transportation vehicles. These new applications are in various stages of completion, but each provides unique insights into the utilization of ambient excitation testing in general and the specific application of NExT. This paper is a survey of recent and on-going work at Sandia National Laboratories and collaborating institutions. Therefore, the technical details are reserved for the references or future reports.

OVERVIEW

Conventional modal analysis utilizes frequency response functions (FRFs) or impulse response functions which require measurements of both the input force and the resulting response. However, ambient excitation (such as wind, wave, road noise, and traffic excitation) does not lend itself to FRF calculations because the input force cannot be measured. NExT is a four-step process designed to estimate modal parameters of structures excited in their operating environment. The first step is to acquire response data from the operating structure. Sensors that can measure strain, displacement, velocity, or acceleration response are required. Long time histories of continuous data are desired to allow significant averaging of the data, provided the operating conditions are relatively stationary.

The second step is to calculate auto- and cross-correlation functions from these time histories using standard techniques [24,25]. Correlation functions are commonly used to analyze randomly excited systems [25]. As the following section will show, the correlation functions can be expressed as summations of decaying sinusoids. Each decaying sinusoid has a damped natural frequency and damping ratio that is identical to that of a corresponding structural mode. The cross-correlation of each output channel will be calculated with respect to a subset of the output channels which function as references. These output-references are chosen to contain all of the relevant modal information and/or to target specific structural responses. In this manner, selection of these output-reference channels is similar to choosing the input-reference locations in a traditional modal test. An appropriate choice can aid in the separation of closely spaced modes and the proper extraction of low-amplitude modes.

The third step of NExT uses a time-domain modal identification scheme to estimate the modal parameters by treating the correlation functions as though they were free vibration responses—that is, sums of decaying sinusoids. The Polyreference technique [14] and the Eigensystem Realization Algorithm (ERA) [8] have been used as the time-domain modal identification schemes in this work to extract modal frequencies and damping ratios. However, for single-input systems, Ibrahim Time Domain (ITD) [5] or Least Squares Complex Exponential [13] could be used.

The final step of NExT extracts mode shape information using the identified modal frequencies and modal damping ratios. References [17,21] detail previous work on shape extraction. It should be noted that it will not be possible to calculate the mass-scaling for the mode shapes. This calculation requires a measurement of the input force which is not possible with natural excitation. An activity closely related to shape extraction uses the identified modal parameters to synthesize the spectra and/or correlation functions of the output sensors. This provides a means of visually verifying the accuracy of the estimated modal frequencies and damping ratios.

APPLICATION TO CONTROLLED-YAW HAWT

NExT has been applied to the ambient vibration data acquired from an operating Horizontal Axis Wind Turbine (HAWT) [21] with two fiberglass blades offset from the hub and a rotor diameter of 17.8 meters. This 100-kW machine, which was produced by Northern Power Systems, was an upwind turbine with a teetering rotor. This means that the rotor was free to pitch, however yaw was actively controlled to point the turbine into the wind. Three strain gauge sensors were applied to the turbine blades and sampled at 36 samples per second. The turbine was operating at 72 rpm in 10, 15, 20, 25, and 30 miles per hour (mph) winds during the data collection.

It is critical to understand the resonance and damping effects of a wind turbine under operation. Therefore, ambient excitation provides the most effective means of acquiring this data. NExT was used to extract the frequency, damping, and shape information from the data. The shape information was extracted using a new procedure whereby auto-spectra and cross-spectra were used to populate a matrix at each frequency of interest. The three closest frequency lines to each modal frequency were chosen for this calculation. A Singular Value Decomposition (SVD) was used to obtain the largest singular value and associated singular vector (or operating shape) of this cross-spectrum matrix. A least squares problem was then solved to obtain the mode shapes. Reconstructions of the auto-spectra and cross-spectra were used to verify the parameter extraction. It should be noted that the harmonics of the rotation frequency were treated as lightly damped modes in this exercise. The controlled-yaw configuration of this device produced a response which was conducive to the quasi-modal response previously used for rotating systems [18]. The next application to a free-yaw HAWT has a much more complicated response during operation and the purpose of ambient testing is to understand the rotating structural dynamics.

APPLICATION TO FREE-YAW HAWT

The AWT-26 HAWT produced by Advanced Wind Turbines differs from the Northern Power Systems HAWT discussed above in that it is a downwind machine which is free to yaw to point the 26-meter rotor away from the prevailing wind. This machine was also a two-bladed teetering machine which meant the pitch degree of freedom was still free. This configuration enhances the rotating coordinate system effects [26]. This turbine was instrumented with four strain gauges (two on the blades and two on the low speed generator shaft), two accelerometers on the non-rotating tower, a yaw sensor, a teeter sensor, an azimuth sensor, and a low speed shaft torque sensor. Since this data set contained sensors in both the rotating and the stationary coordinate system, a conversion was needed to place the data in the inertial frame. The rotating coordinate system instrumentation included measurements in both in-plane directions as well as the azimuth position which allowed the necessary rotation into the inertial frame. NExT was used to extract several resonances the associated damping parameter. However the structural modes of the system appear as families of resonance phenomena separated by multiples of the rotation rate. The extremely high density of these resonance phenomena has prompted an analytical study to further understand this class of machines [27]. Visualization of the modes in such a mixed-coordinate system data set is a problem. Therefore, a visualization procedure has been developed and integrated with the modal analysis capability [28]. The next application to a parked three-bladed VAWT does not have rotating coordinate system effects, but obtains shape information via a simplified approach.

APPLICATION TO THREE-BLADED VAWT

A modal test was performed on a three-bladed Vertical Axis Wind Turbine (VAWT) in Tehachipi Pass, California which was produced by Flowind, Inc. The purpose of the test was to correlate a finite element model for design purposes. The structure was 45 meter tall with three pull-truded fiberglass blades with constant cross-section and cord length of 68 centimeters. The blades were attached to a one meter diameter tower to complete the rotor substructure of the VAWT. The rotor was designed to rotate at 50 rpm and produce 300 kilowatts of power. Since the modal response of the structure can destructively interact with the rotational forcing functions, a correlated model is essential to the design of a reliable wind turbine.

The VAWT was instrumented with 63 Endevco model 7751 accelerometers at 31 locations on the blades, tower, and guy cables. A 64-channel Precision analog filter and HP 3565 data acquisition system completed the signal processing and data collection system. SDRC's IDEAS software was used for data reduction. Two types of excitation were used during the test: step-relaxation during the day and NExT during the higher night-time winds. Eleven modes, with .2 to 1.4 percent of critical damping, were extracted between one and five Hz. A significant number of pairs (tower modes) or triplets (blade modes) were expected but, only one member of the family was typically extracted from this data set. During high wind loading, the structural response amplitude was seen to be quite significant, therefore a NExT analysis was possible.

During the data analysis, NExT was used to extract modal frequencies, modal damping, and mode shapes. These parameters were critical in the successful completion of this test, since not all important modes could be extracted from the step relaxation inputs. Hence, the ability to analyze natural excitation was critical to producing a complete modal description of the structure. This is the first time these authors have used a data set with some parameters extracted from traditional excitation and some by natural excitation. Also, the shapes were estimated by application of a time domain shape-fitting routine to the cross-correlation functions between the measured outputs. This procedure is a simple process that appears to work in some applications. One area of further study will be to compare theoretically, analytically, and experimentally the various shape estimation routines to determine relative advantages and disadvantages. Other applications involving fixed and rotating coordinate systems are ground transportation systems.

APPLICATION TO GROUND TRANSPORTATION VEHICLES

Vehicles, including passenger cars and tractor-trailers, are randomly excited by road noise and harmonics of the tire rotation rates. Previously, work has been performed to use ambient excitation and NExT to characterize the structural response for a tractor-trailer system [18]. More recent work has utilized ambient excitation testing to characterize the vibration response seen by the driver and passengers in a tractor-trailer system. The initial work utilized auto-spectra and cross-spectra to monitor the ride quality of two different tractor-trailer systems and using different tire pressures. Follow-on work will utilize more extensive analysis and testing (including NExT) to understand the various vibration isolation systems. This work will be used to redesign the isolation systems to obtain a more comfortable environment. NExT will also be applied to a passenger vehicle in the future to verify mathematical models for the automotive and tire structures. The next section discusses some initial work on the application of ambient testing to Structural Health Monitoring of operational civil structures.

APPLICATION TO A HIGHWAY BRIDGE

Bridges represent another natural application for NExT. These structures see frequent, large amplitude motion due to traffic crossing the bridge or traveling on adjacent roadways/railways [23]. In a recent experimental exercise, Los Alamos National Laboratories (LANL) applied NExT to a traffic excited highway bridge. The Interstate 40 bridge over the Rio Grande river was scheduled to be replaced. Therefore, New Mexico State University (NMSU) acquired funding and permission to use the bridge as a test-bed for research in modeling, testing, and structural health monitoring of bridges. LANL and Sandia National Laboratories supported NMSU in this work. LANL produced a Finite Element Model (FEM) of the bridge and correlated with the data. The 130 meter long structure had 13 accelerometers placed on each of the two support beams for a total of 26 sensors.

One aspect of this study, was to compare techniques for exciting the structure for model-correlation purposes. Ambient excitation data was acquired before traffic was removed from the bridge. A hydraulic shaker system was designed to artificially excite the structure after traffic was removed. NExT was used to analyze the ambient data [23]. The modal frequencies extracted by NExT compared favorably to those extracted using artificial excitation. A third approach to estimating shapes was used in this work. Amplitude and phase information was extracted directly from the cross-spectra matrix at the closest frequency line to each modal frequency. These shapes also compared favorably to both the traditional modal approach and to the FEM results.

The periodic testing of large civil structures using ambient excitation is cost effective and uses the actual excitation levels seen in operation. Therefore, structural health monitoring is a much more feasible approach for these large civil infrastructure projects.

The I40 bridge test provided another data set which may be used to perform initial development work in structural health monitoring. A set of 11 accelerometers were placed on one 50 meter long support girder. Four different levels of damage were induced into the structure [29]. The shaker was used to excite the structure with a random, but unmeasured, input after each of these damage scenarios. Hence, a data set from an actual bridge was produced. Ambient excitation is simulated as are increasing levels of damage. This data set is currently being used to initiate studies in structural health monitoring using ambient excitation at Los Alamos [30] and Sandia.

APPLICATION TO OFFSHORE STRUCTURES

Offshore structures are another application for ambient excitation testing coupled to structural health monitoring. Sandia has recently been provided with data from an offshore structure undergoing wave and wind loading during a hurricane. The deep-water jacketed platform was instrumented with eight strain gauges below water, four above water accelerometers, and four displacement sensors above the water-line. This is a sparse data set for such a large structure, but represents one of the most complete data sets available from an offshore structure. The data set spans a period of 20 hours during the hurricane.

Although a NExT analysis of this data is underway, the Complex Mode Indicator Function (CMIF) [31] has been used to perform an initial analysis of the information content in the data set. The primary resonances are below .3 Hz. The region between DC and .3 Hz is extremely noisy and/or is modally dense. Significant variations in the relative magnitudes of the resonances can be seen over the course of the data set. However, the detailed analysis is needed to answer the question of relevance to the structural monitoring question.

SUMMARY AND CONCLUSIONS

Six applications of NExT to ambient excitation testing and NExT analysis are provided. In the first application, NExT was applied to a controlled-yaw HAWT. By controlling the yaw degree of freedom an important class of rotating coordinate system effects are reduced. A new shape extraction procedure was applied to this data set with good results. The second application was to a free-yaw HAWT. The rotational effects are much more pronounced in this work and a large modal density was found. The complexity of the response has prompted further analytical studies. The availability of outputs in rotational and inertial coordinate systems has prompted the need to develop a specialized visualization package. The third application of NExT was to a parked three-bladed VAWT. The multiplicity of the modes made it very difficult to extract all the modes using traditional modal excitation procedures. NExT was used to complete the set of extracted modes by augmenting the traditional excitation modes. The shape extraction process used cross-correlation functions directly in a time-domain shape-fitting routine.

The fourth application was to ground transportation systems. Ongoing work to improve driver and passenger comfort in tractor-trailer vehicles and to refine automobile body and tire models will use NExT. The application of NExT to a bridge was discussed next. Los Alamos utilized NExT to process ambient vibration data and to correlate an FEM of the bridge. A favorable comparison of NExT results to those from traditional modal testing was performed. Shape fitting was performed using amplitude and phase information taken directly from the cross-spectra. Another data set was acquired with a random, but unmeasured input. This data-set is currently under study to link NExT to Structural Health Monitoring. The final application is to an offshore structure. This work is on-going, however initial studies have found a high-modal density, high noise content, and sparse data set. The analyses discussed herein used three different shape-fitting procedures. A comparison of these procedures should be undertaken as well as a better shape-fit procedure developed for rotating systems. It is obvious that NExT has a wide variety of applications. It has been successful with several data sets from large operational structures. The ability to process ambient vibration data makes Structural Health Monitoring, model correlation, and diagnostic test much more feasible for these operational structures.

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