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Hae Young Noh
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P. Scott Harvey *Editors*

Dynamics of Civil Structures, Volume 2

Proceedings of the 40th IMAC, A Conference and Exposition on Structural Dynamics 2022

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Editors
Hae Young Noh
Stanford University
Stanford, CA, USA

Matthew Whelan
University of North Carolina at Charlotte
Charlotte, NC, USA

P. Scott Harvey
University of Oklahoma
Norman, OK, USA

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Preface

Dynamics of Civil Structures represents one of nine volumes of technical papers presented at the 40th IMAC, a conference and exposition on structural dynamics, organized by the Society for Experimental Mechanics, and held February 7–10, 2022. The full proceedings also include volumes on nonlinear structures and Systems; model validation and uncertainty quantification; dynamic substructures; special topics in structural dynamics and experimental techniques; rotating machinery, optical methods and scanning LDV methods; sensors and instrumentation, aircraft/aerospace, and dynamic environments testing; topics in modal analysis and parameter identification; and data science in engineering.

Each collection presents early findings from analytical, experimental, and computational investigations on an important area within structural dynamics. Dynamics of civil structures is one of these areas which cover topics of interest of several disciplines in engineering and science.

The dynamics of civil structures technical division serves as a primary focal point within the SEM umbrella for technical activities devoted to civil structures analysis, testing, monitoring, and assessment. This volume covers a variety of topics including structural vibrations, damage identification, human-structure interaction, vibration control, model updating, modal analysis of in-service structures, innovative measurement techniques and mobile sensing, and bridge dynamics among many other topics.

Papers cover testing and analysis of different kinds of civil engineering structures such as buildings, bridges, stadiums, dams, and others.

The organizers would like to thank the authors, presenters, session organizers, and session chairs for their participation in this track.

Stanford, CA, USA — Hae Young Noh
Charlotte, NC, USA — Matthew Whelan
Norman, OK, USA — P. Scott Harvey

Contents

Chapter 1
Smart Active Vibration Control System of a Wind Turbine Blade Using Piezoelectric Material

Ali Hashemi and Jinwoo Jang

Abstract Vibration suppression has become one of the major issues in sensitive structures. The active vibration control (AVC) has been widely used in the field of vibration damping in rotary structures. In this article, deriving analytical solution of lateral vibration and active vibration control of a wind turbine (WT) blade are investigated. First, a new semi-analytical solution is developed to obtain the lateral deflection of a wind turbine blade under external loadings. We propose a method to map a wind turbine blade to an Euler-Bernoulli beam with the same conditions, in order to find vibration and dynamic responses of the blade by solving analytical vibration solutions of the Euler-Bernoulli beam. Piezoelectric (PZT) material is used in this research as an actuator-sensor to excite the structures and sense the responses. The governing equations of the beam with piezoelectric patches are derived based on the integration of the piezoelectric transducer vibration equations into the vibration equations of the Euler-Bernoulli beam structure. Finite element model of the wind turbine blade with piezoelectric patches is developed. A unique transfer function matrix is derived. The beam structure is projected to the blade by using a unique transfer function matrix which is derived by exciting the structures and achieving responses. The results obtained from the mapping method are compared with the results achieved from the FE model of the blade. A satisfying agreement has been observed between the results. Next, in order to suppress the transverse vibration of the wind turbine blade, piezoelectric ceramic patches are used as an actuator in combination with linear quadratic regulator (LQR) control system. The obtained results show that the proposed smart control system contains PZT patches and LQR control system is able to efficiently suppress lateral vibration.

Keywords Active vibration control · Smart structure · Structural dynamic · Analytical vibration analysis · Transfer function matrix · Piezoelectric actuator and sensor

1.1 Introduction

The control of unwanted vibration of wind turbine blades plays a key role in ensuring wind turbines' (WT) high efficiency and cost-effectiveness and also, increasing the structure's lifetime. Blade vibrations cause extreme operation instability of wind turbines and even catastrophic failure of the whole turbine which must be prevented from. Many investigations have been conducted to control vibration of sensitive rotary structures by utilizing passive, active, and semi-active control systems. In order to damp the undesired vibration of structures, proper actuators are needed to apply controlling forces. Due to the changing blade dynamics and excitation conditions, passive control methods have been less utilized for rotating structures. Active control typically provides large vibration reduction which can be tremendously helpful in damping unwanted vibration of sensitive structures. This control process needs to employ smart materials. Among different smart materials, piezoelectrics have three unique advantages, being lightweight, low cost, and convenient usage, as well as provide sensing and actuating features which can make them an appropriate material for vibration control. Piezoelectric (PZT) transducers have been widely used in active vibration control systems owing to their special properties as sensor and actuator. PZT transducers have been utilized in various shapes and forms such as perfect layer along surfaces of structures or patches in different sizes. Piezoelectric-based vibration alleviation can reduce the unwanted vibration levels of rotating structures consequently abating the risk of high cycle fatigue while lowering blade weight and drag. In this research, we propose an active vibration control system with PZT patches as sensor and actuator. To simulate the implementation of active control rules on structures, we

A. Hashemi · J. Jang (✉)
Department of Civil, Environmental and Geomatics, Florida Atlantic University, Boca Raton, FL, USA
e-mail: jangj@fau.edu

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propose an innovative semi-analytical method to project an actual shape of a wind turbine blade to the same scale of an Euler-Bernoulli beam in order to derive an analytical solution for the wind turbine blade's dynamic response and then use the method to apply controlling rules to a wind turbine blade. Implementation of controlling rule on the wind turbine blade is not feasible by using finite element commercial software like ANSYS due to high computational cost. Hence, the proposed transfer function method is used as a surrogate to obtain the controlled deflections of a wind turbine blade in this research. Therefore, in the first step, we focus on developing a new semi-analytical solution to obtain lateral deflection of a wind turbine blade under different external loadings, and next, a suitable control system is designed in order to suppress unwanted transverse deflection of a wind turbine blade.

Derivation of analytical solutions for vibration and elasticity analysis of structures has always been noticed as an important field of research in structure analysis and design. Due to the low computational cost especially for large-scale structures, analytical solutions of dynamic responses have attracted considerable attention. However, deriving analytical solution for many structures could be very challenging due to their complicated geometry. Moreover, during recent years, a considerable increase of global warming caused sustainable energies, such as wind energy, to have absorbed wide attention as great alternative energy resources. Various types of wind turbines, such as off-shore and on-shore wind turbines with different sizes and power outputs, have been investigated in recent years as a result of this fact. Normally, large and complex wind turbines have been more concentrated due to their efficient power generation capacity. Large-scale wind turbines can suffer from significant vibrational deflection, particularly on the edges of their blades. These unwanted vibrations can cause severe structural damage and failure of the power generation systems. Due to their complex shapes and continuous interaction between wind flows and their blades, analyzing dynamical and vibrational responses of wind turbine blades is tremendously complicated. A new understanding of analytical solutions for analyzing dynamic behaviors of these kinds of structures, can contribute to the analytical analyzing of different mechanical and structural systems including twisters and heavy solid structures. In comparison to analytical methods, the vibration of these twister structures has primarily been investigated using finite element (FM) simulation and other numeric methods such as finite difference (FD) and differential quadrate (DQ). To control vibration of structures, three controlling systems including passive, active, and semi-active have been considered. These systems use various controlling rules such as proportional pulse derivative (PD), fuzzy logic control, and sliding mode control. Active control outperforms other methods for wind turbine blades due to various environmental excitation conditions and it provides large vibration reduction.

At the first step, this research aims to propose a unique semi-analytical solution for a wind turbine blade, which can describe lateral blade movements under specific external forces. In general, a semi-analytical solution technique is proposed to solve linear partial differential equations. The semi-analytical method depends on analytically solving the equations derived by discretizing the spatial coordinates of partial differential equations. Semi-analytical approaches have a substantial advantage over numerical methods in terms of solution time. This study demonstrates how to project the real form of a wind turbine blade to the same size as an Euler-Bernoulli beam to derive an analytical solution for the wind turbine blade's dynamic and vibration response. The blade of the GE 1.5 megawatt model, which has 45 meter blades on a 9 meter tower, is considered in this work. The blade's material is assumed steel in order to simplify deriving equations. Plumbum-titania-zirconia is considered as piezoelectric sensor-actuator patches to sense and actuate structures. At the second step, for the purpose of alleviation of vibrations and transverse deflection of the wind turbine blade with piezoelectric patches, a linear quadratic regulator (LQR) control method is designed in this research. Due to decreasing computational cost, the proposed semi-analytical method is used to project controlled transverse vibration of the actual shape of the wind turbine blade to the Euler-Bernoulli beam instead of utilizing finite element model of the blade in order to implement control rules.

1.1.1 Background

Rotating structures, which have significance in many practical applications such as turbine blade, airplane propellers, and robot manipulators, have been investigated for a long time. The vibrations of twister beams have been widely studied with different types of beam models, e.g., Euler-Bernoulli and Timoshenko, using analytical or semi-analytical solutions and numerical or finite element methods (FEMs). The majority of previous research considered Euler-Bernoulli and Timoshenko models to describe twister and under-loading beams without considering shear deformations. The normal frequencies, mode shapes, and maximum vertical displacements of rotary beams have all been studied in order to better understand their dynamic behaviors. However, it is challenging to obtain dynamic behaviors of rotary beams due to various environmental elements including different wind flows and gravity loads. Huang et al. [1] obtained the natural frequencies of an Euler-Bernoulli beam during high-speed rotation using an exponential series solution. Arvin [2] investigates the nonlinear free vibrations of a rotating beam. He utilizes the von Kármán-strain displacement relations and derived nonlinear motion equations by

Hamilton's principle. Da Silva [3] presents a systematic and versatile research of a helicopter rotor blade's responses. At the first step, he developed full nonlinear partial differential equations governing the motion of the blade, which take into account geometric nonlinearities caused by deformation, and then the system's equilibrium solution was described by the system. Yigit et al. [4] studied the flexural movement of a radially rotating beam connected to a rigid body. Fully connected nonlinear motion equations were derived utilizing the extended Hamilton's principle. Hanagud [5], Baruh [6], and Choura et al. [7] studied dynamical models of rotating Euler-Bernoulli beams without considering centripetal forces on beams. Most of previous studies about dynamical models of structures did not investigate the interaction between fluids and structures [8]. Song et al. [8] established an elaborate model in understanding the fluid-structure interaction between a structure and air flow. The arbitrary mesh interface (AMI) framework was used in conjunction with the open-source OpenFOAM tools. Wang et al. [9] provided numerical simulations of wind turbine blade-tower interaction. The vibration analysis of wind turbine blades or other rotating beam form structures may be broken down into two sections. The first is edge-wise vibration that occurs outside of the rotating circle of the beam, and the second is flap-wise vibration that occurs in the rotation plate. Lee et al. [10] studied flap-wise vibration of a composite rotational Euler-Bernoulli beam and the relationship between rotational speed and natural frequencies. Asr et al. [11] suggested prestressing in the blade structure of the H-Darrieus wind turbine in the context of axial compression stress that their research presented a structural comparison in terms of their dynamic vibrational response among reference and prestressed turbine rotor configurations. Jokar et al. [12] obtained the dynamic modeling and free vibration analysis of horizontal axis wind turbine blades in the flap-wise direction by evaluating blade kinetic and potential energies and using Hamilton's principle. Farsadi et al. [13] perform a semi-analytical solution for the free vibration analysis of uniform and symmetric pre-twisted rotating TW which adopts the Green-Lagrange strain tensor to derive the strain field of the system and Hamilton's principle to derive the governing equations of the dynamic system. Afzali et al. [14] derive a vibration model for a H-rotor/Giromill blade that the authors assume the blade under transverse bending and twisting deformation was treated as a uniform straight elastic Euler-Bernoulli beam. Derivation of the energy equations and simplified aerodynamic models for bending and twisting blades have been distributed, and the equations of Lagrange have been extended to assumed modal coordinates to derive nonlinear motion equations for bending and twisting blades [15–19]. Meksi et al. [20] derived the equations of motion of functionally graded sandwich plates from Hamilton's principle based on a new shear deformation plate theory. Alsabagh et al. [21] implemented the Rayleigh-Ritz method for a typical 5-MW wind turbine blade and developed MATLAB codes and then obtained natural frequencies for both flap-wise and edge-wise vibrational behavior. Chen et al. [22] derive a dynamic model of curved beams by using the absolute nodal coordinate formulation based on the radial point interpolation method (RPIM). Chen et al. [23] examined the free vibration of rotating tapered Timoshenko beams by using the technique of variational iteration. Mokhtar et al. [24] investigate the rotor-stator interaction phenomenon in the finite element (FE) framework by using Lagrange multiplier based on contact mechanics. Tang et al. [25] present a developed approach that is used to identify the operational blade vibration modes by measuring the vibrational displacements with a non-contact single point laser sensor during the wear process. Liu et al. [26] study structural vibrations by establishing a dynamic equilibrium equation of a coupled system. They develop a blade's excitation force model consisting of transverse and vertical excitation forces using a quasi-steady method. Hamilton's principle and the finite element (FE) method with a rotating pre-twisted and leaned cantilever beam model (RPICBM) with the flap-wise-chordwise-axial-torsional coupling are set up by Zheng et al. [27] who validate the efficacy of the model through comparisons with the literature and the FE models in ANSYS. Warminski et al. [28] study dynamics of a rotor composed of a flexible beam linked to a slewing rigid hub based on extended Euler-Bernoulli theory for a slender beam model, which considers a nonlinear curvature, synchronized transverse and longitudinal oscillations, and the hub's non-constant angular velocity. In different engineering structures, rotating composite beams and blades have a wide variety of applications [29]. Rafiee et al. [29] present a comprehensive analysis of scientific papers on rotating composite beams as presented in the past decades that for the flexural study of a sandwich beam combined with a piezoelectric layer. Wang [30] proposes a fundamental mechanics model uses the Maxwell equation in the formulation in order to extract the distribution of the piezoelectric potential. Chen et al. [31] develop a semi-analytical solution of the dynamic features of the AG-WEC by the frequency and time domain analysis based on the potential flow principle. Huang et al. [32] present a high-order finite element model and sliding model control method for a rotating flexible structure with the piezoelectric layers in order to effectively reduce the vibration. Lin [33] uses proportional and derivative controls to damp the vibration of a rotating beam by using a pair of PZT sensor and actuator layers. Bendine et al. [34] investigate on the active vibration control of a composite plate using discrete piezoelectric patches. A finite element model with PZT patches was derived based on first-order shear deformation theory, and a damping effect on composite plate was provided by using PZT actuators and applying linear quadratic regulator (LQR) control algorithm. Larbi and Deu [35] presented an efficient electromechanical finite element formulation to analyze the dynamic analysis of a cantilever beam with piezoelectric patches. Ma et al. [36] investigated on an active vibration control of a moving cantilever beam with piezoelectric ceramics as actuator by using pulse derivative closed-loop feedback system. Sivrioglu et al. [37] successfully tried to attenuate the vibration of a blade with a piezoelectric actuator patch implementing robust multi-objective control. The controlled response of a fuzzy logic controller was measured for various piezoelectric materials in active vibration control by Sharma et al. [37] and then compared them with each other. A smart active vibration control system was proposed with a new robust controlled by Cui et al. [38]. In their investigation, the system comprised PZT materials, signal conditioning, and the embedded sensor system. Pu et al. [39] applied an adaptive vibration control system contains a filtered-U least mean square algorithm and a surface bonded piezoelectric actuator to a smart structure. An active control system was designed by Brahem et al. [40] based on a full-state linear quadratic regulator controller which was applied to a rotary beam in order to alleviate the vibration. Shakir and Saber [41] developed a linear coupled finite element model by ANSYS for the piezoelectric actuation of a cantilever beam to study smart beam behavior in open- and closed-loop cases. Qiu et al. [42] developed a sliding mode control strategy to damp the vibration of a piezoelectric flexible cantilever plate. The finite element modeling was utilized to simulate the controller on bending and torsional vibration in their research. Ghaderi and Ghatei [43] presented an integrated virtual synchronization/linear quadratic regulator method to identify the system's unknown physical parameter and vibration control of structures based on estimated parameters.

1.2 Theory and Modeling

To obtain analytical solutions for dynamic and vibration responses to any external forces and excitations and applying control rules, unlike complex structures such as wind turbine blades, the Euler-Bernoulli beam has been widely investigated. Since the Euler-Bernoulli beam theory is based on a few key assumptions and the beam has a simple geometric form, analytical study of the Euler-Bernoulli beam is achievable. The Euler-Bernoulli beam theory assumes that "plane sections remain plane" and that deformed beam angles (slopes) are small; thus, shear deformations may be ignored. The novelty of this research work includes the projection of a wind turbine blade's deformations and lateral deflections to the same scale of Euler-Bernoulli beam and then using this mapping system for applying controlling rules on the wind turbine blade and obtained controlled vibration movements of the blade. We proposed a unique transfer function matrix to undertake the projection of a wind turbine blade to an Euler-Bernoulli beam. Lateral deflections of the Euler-Bernoulli beam are transferred to the wind turbine blade by utilizing the proposed transfer function matrix. This projection will permit us to simply obtain the dynamic and vibration responses of a wind turbine using the Euler-Bernoulli beam. Next, to damp the unwanted lateral deflection of the wind turbine blade, linear quadratic regulator (LQR) is considered in this study. An active vibration control is proposed in this study combining piezoelectric material as actuator and a designed linear quadratic regulator control method. The transfer function method is used to implement the control system on the structure in order to decrease computational costs.

To develop the transfer function matrix, both the wind turbine blade and the Euler-Bernoulli beam need to be excited with the same external excitation. At the next step, the lateral movements of selective specific nodes on their surfaces are obtained. Furthermore, in the proposed method, the Euler-Bernoulli beam should have the same length with the wind turbine blade which is 45 meters in this study. We obtain the lateral deflection of the Euler-Bernoulli analytically in this research. FE models are used to calculate the counterpart of the wind turbine blade. Piezoelectric patches are utilized to apply external excitations and sense the dynamic responses of both the wind turbine blade and the Euler-Bernoulli beam. Due to the electromechanical properties, piezoelectric materials are effective sensors and actuators. The piezoelectric sensors/actuators are patched on the surfaces of both structures. The external excitations and the dynamic responses of the structures are measured by the piezoelectric patches. To derive two initial function matrices related to the Euler-Bernoulli beam with PZT patches and the wind turbine blade with PZT patches, same external loadings are applied to the structures, and corresponding responses are obtained. Next, two initial function matrices are used to achieve a total transfer function for the whole system. At the final step, to damp unwanted lateral vibration of the blade, an active vibration control system is designed. To obtain controlled transverse movements of the blade, first, the controlling rules are applied to the to the governing dynamic equations of the beam with PZT patches under an external loading. Then, controlled lateral movements of the blade are obtained using the proposed mapping system. ion of the wind turbine blade.

1.2.1 The Euler-Bernoulli Beam Includes Piezoelectric Patches

An anticipated shape of the beam with patches is depicted in Fig. 1.1.

The beam under discussion here is considered as an Euler-Bernoulli beam with length (L), width (b), and height (h) which are divided into n equal sections. The boundary conditions of the beam are considered to be a cantilever beam, similar to a blade in a wind turbine, attached at one end to a support, in order to achieve the best results. Edgewise vibrations are