CS 238/AA 228 Decision Making Under Uncertainty
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Final Project Proposal – Group 35
October 1st, 2021

Semi-active Vibration Damping Control of Wind Turbines using Reinforcement Learning

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ABSTRACT

Research and development of structural control devices have gained great attention in recent years as a method to protect structures against natural hazards. Efforts by structural engineers in an attempt to quantify structural dynamics and viscous damping have achieved success by enacting proxies such as transmissibility, equivalent viscous damping, and damping ratios to deduce maximum forces transferrable to the foundation of a structure. Although existing methods are sufficient to aid in the design of structures via the derivation of steady-state solutions, they are insufficient to capture the cyclical fatigue stemming from the total response of induced vibrations. This study aims to develop an autonomous control framework to attenuate such vibrations applicable to a simplified wind turbine model by using reinforcement learning to deduce optimal damping ratios under uncertain vorticity and structural conditions. Establishing the optimal damping ratio under uncertainty may then provide a trivial target for control systems such as semi-active tuned-mass dampers and electromagnetic shock absorbers to tune towards.

Introduction

Three large barriers to wind energy are high upfront cost, questionable reliability, and immature technology. This project proposal outlines a framework to efficiently control turbine structural frequencies to minimize vortex induced vibrations and thus reduce fatigue and improve longevity of the structure. The motivation behind this project stems from efforts by industry, such as the European start-up Vortex Bladeless, and academia [1, 2] to harness energy from structural vibrations.

A case study for Taipei 101 estimated that the average power stored and dissipated in the motion of the building subjected to a light breeze can be as high as 108 kW [2]. With the advent of regenerative damping devices, it is now possible to harness some of this energy instead of letting it go to waste while simultaneously providing damping for the building as demonstrated by Shen and collaborators with semi-active devices capable of recapturing the energy at an efficiency of 27.4% [1]. Although Shen et al. had found some success, their study had determined the need for the development of a control system and highlighted high costs associated with their novel approach.

This proposal aims to address some of the concerns raised by Shen et al. applied to wind turbines. Most buildings demonstrate unique characteristics which render the hefty computational power and monetary cost needed to develop and maintain a one-and-done dedicated vibration control system unjustifiable outside of locations subjectable to extreme winds. The mass production potential of wind turbines would allow for a specified vibration control system to be reused. Wind turbine components are concentrated towards the top of a slender tower. This geometry effectively allows for the adoption of a simplified lumped-mass model in subsequent simulations. The infrastructure required to support semi-active damping devices would be readily available on wind farms both for actuating the devices as well as storing and transferring energy harnessed in the regeneration process. Finally, a thorough understanding of the wind profile at the location of wind farms would be readily available to accurately describe site specific vortex shedding behavior.

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Models of Vorticity and Equation of Motion

A simplified single degree of freedom (SDOF) mass-spring-damper system will be used to model the wind turbine behavior under forced and free vibration. To complement a sequential decision-making process, an implicit time integration scheme – via the Newmark β method [3] – based on interpolation of assumed acceleration function $\ddot{u}(t)$ is used to describe the motion of the structure at each time step:

$$\left(\frac{4m}{\Delta t^2} + \frac{2c_i}{\Delta t} + k\right) u_{i+1} = p_{i+1} + \frac{m}{\Delta t^2}\left(4u_i + 4\dot{u}_i \Delta t + \ddot{u}_i (\Delta t)^2\right) + \frac{c_i}{\Delta t}\left(2u_i + \dot{u}_i \Delta t\right) \quad (1)$$

where m, k are the mass and stiffness of the system respectively, c_i is the viscous damping of the system at time step i, and $u, \dot{u}, \ddot{u}$ are displacement, velocity, and acceleration of the system for each time step $i = 0$ to $n - 1$. The p term is force, and in this case, normalized and derived from a sinusoidal function stemming from the effects of vortex shedding. The frequency of vortex shedding, f_s, on a fixed cylinder has a linear relationship with incoming flow velocity, U [4]. This frequency can be thus described by Eq. 2 as follows:

$$f_s = \frac{St \cdot U}{D} \quad (2)$$

where St is the proportionality constant and D is the diameter of the cylinder.

Application of Reinforcement Learning

Dynamics of SDOF mass-spring-damper systems are relatively well understood, providing a means of validating results generated from a novel reinforcement learning approach. Resonance behavior may occur when a structure's natural frequency aligns with that of harmonic loading. In this case, a structure to harmonic loading frequency ratio of one would suggest that increasing the damping ratio of the system would decrease transmissibility of forces. Contrarily, if the ratio is greater than $\sqrt{2}$, increasing the damping ratio of the system would counterintuitively increase transmissibility [3].

In accordance with this nonlinear transmissibility behavior, the state of the problem can be defined as the ratio between the structure's natural frequency to the loading frequency from the vortex shedding phenomenon. The state will be constantly changing at each timestep, prompting actions of increasing, reducing, or maintaining the system's damping ratio to be taken to minimize motions described by Eq. 1. This paves the way for a sequential Markov decision process while the structure is subjected to various wind profiles.

Goals of Proposed Study

Course Project

- Develop policy $\pi(U_i) \rightarrow c_i$ to minimize vibrations for a simplified SDOF system, constraints TBD.

Future

- Sim-to-real validation by collecting accelerometer sensor data and applying Fourier transforms to deduce real structural frequencies as opposed to theoretical model frequencies used in this study.
- Apply framework to multiple degree of freedom problems with non-trivial transmissibility behavior under higher fidelity vorticity models exhibiting turbulent behavior.

References

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