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Introduction

1.1 Background and Motivation

Flexible systems refer to those structures that can be bent or folded without breaking [286]. Flexible systems have attracted considerable research and OpenDocument efforts due to their multi-faceted advantages such as lightweight and low energy consumption [300]. The significant advances in material science, computing, and artificial intelligence technologies, particularly during the last two decades, have further inspired the society's expectation and passion for commercially viable flexible systems [368]. However, flexible systems might generate unexpected deformation and vibration during the execution of the task. The vibration will degrade the system performance, even shorten the lifespan of the flexible systems. In addition, the complex environment and sudden failures also bring challenges to the research and application of flexible systems. Therefore, designing an effective control method for suppressing the vibration of the flexible systems is significant in practice.

In recent years, with the increasing maturity of intelligent manufacturing technology and the continuous breakthrough of scientific and technological research results, flexible systems have been widely used and developed in various fields such as aerospace, advanced manufacturing, medical health, and social services. Basically, most mechanical structures in practical engineering can be regarded as flexible systems, in other words, large-span mechanical structures can be regarded as having non-negligible deformation and vibration. The flexible systems mainly have three types of applications, which are briefly described below:

- **Flexible robotic manipulators**: Flexible robotic manipulators are the most typical representative flexible systems, which have the properties of light structure, low energy consumption, and high load/self-weight ratio. Compared with the traditional rigid manipulators, the flexible manipulators have a larger operating space, higher work efficiency, and faster response. Flexible manipulators have many potential advantages and play a very important role in industrial, national defense, and other application fields [113]. Their applications have gradually penetrated into aerospace, medical, and military fields [188], as shown in Figure 1.1. With the rapid development of the aerospace industry and the robotics industry, the traditional rigid system dynamic analysis methods and control strategies cannot meet the requirements of practical engineering [283]. In recent years, the application research of flexible robotic manipulators has received extensive attention, attracting the interest of many scholars and experts.

  The main control goal of the flexible robotic manipulators is to achieve accurate trajectory tracking, and damping vibration (also known as vibration suppression) due to low stiffness is an urgent problem to be solved. The traditional rigid manipulator has a thick base, short arm, limited operating space, and poor flexibility, which cannot meet the requirements of modern

Dynamic Modeling and Neural Network-Based Intelligent Control of Flexible Systems,
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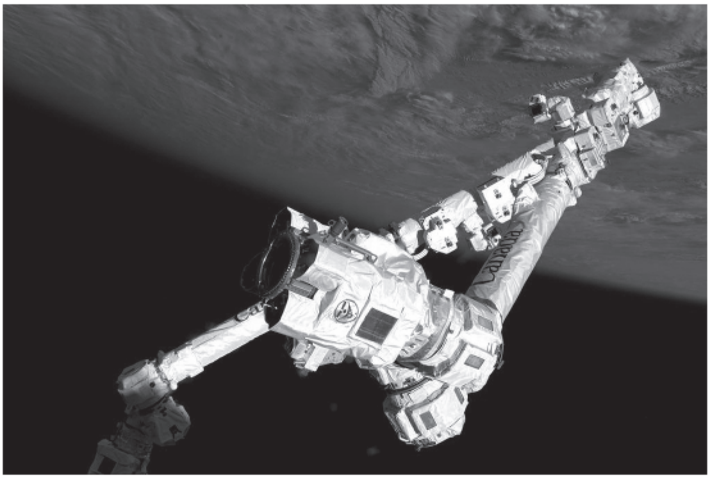

Figure 1.1 Canadarm 2, the Canadian robotic arm on the space station. Source: NASA/Public domain.

industrial automation and high-precision industries. The flexible robotic manipulator has gradually occupied an increasingly important position in the manufacturing, aerospace, and other industries due to its advantages of low energy consumption, flexible operation, and fast response. The flexible robotic manipulator is composed of flexible unit components, mainly including flexible joints and flexible links. These flexible components will produce twisting deformation, elastic deformation, and shear deformation during the movement of the manipulator. The flexible robotic manipulator is thus a rigid–flexible coupled, nonlinear infinite-dimensional distributed parameter system, and its dynamic model is more complex than that of the rigid manipulator. Moreover, the traditional dynamic modeling is too complicated and not suitable for the control design of the high-performance flexible robotic manipulator. Therefore, how to explore efficient dynamic modeling theory for flexible manipulators with dynamic uncertainties is a hot and difficult issue in current research [5].

- **Flexible building structures**: With the continuous increase of building height, high-rise, and ultra-high-rise buildings can be regarded as flexible building structures. Under external excitations such as earthquakes and strong winds, the vibration of high-rise building structures cannot be ignored. Due to the unpredictability of natural disasters such as earthquakes and strong winds, the seismic and wind-resistant design of structures faces severe challenges. Vibration and displacement control are of critical importance for both high-rise and ultra-high-rise building systems, as shown in Figure 1.2. Since the concept of structural control was first proposed in 1972, the research and application of structural vibration control have received more and more attention. At present, it has become the most cutting-edge development directions in the field of structural engineering and structural mechanics. The high-rise structure system can not only provide residents with a comfortable working and living environment can also relieve the huge pressure caused by population growth and shortage of land resources in large cities. Due to the large number of residents and the huge construction cost of the high-rise structure, when it is subjected to natural disasters such as earthquakes and strong winds, once the structure is damaged or collapsed, its influence and destructive power will be huge. Therefore, it is particularly important to effectively suppress or reduce these vibrations caused by earthquakes and winds, so that the safety, usability, and comfort of high-rise structures can be guaranteed.

  The main control goal of flexible building structures is to achieve vibration suppression under unexpected disturbances. The existing vibration control methods of flexible building

Figure 1.2 The Shanghai Tower. Source: Baycrest/Wikimedia Commons/CC BY SA 2.5.

structures mostly employed traditional passive control strategies. However, the installation and maintenance as well as the replacement of the dampers are time-consuming and non-trivial work. Compared with passive control, active control can select control objectives, such as structural response (displacement, velocity, and acceleration response) and structural displacement, improving the control effectiveness. Actually, the complex flexible building structures, whose degrees of freedom are close to infinity, are distributed parameter systems with many dynamic uncertainties [137]. Most importantly, the dynamic response cannot be predicted accurately. Therefore, how to study the vibration control method of flexible building structures under natural disasters is an urgent problem to be solved.

- **Flexible bionic flapping-wing systems**: The flexible bionic flapping-wing robotic aircraft is inspired by the flight of birds or insects, which has great advantages, such as being lightweight, having high flexibility, and offering low energy consumption. The bionic flapping-wing robotic aircraft has attracted the special attention of many researchers in recent years [316]. The aircraft can stabilize the fuselage in the horizontal position or glide in the sky through flapping wings. The bionic flapping-wing aircraft can generate lift force with high efficiency. In addition, with the advantage of low energy consumption, the bionic flapping-wing aircraft is suitable for flight missions without energy replenishment under long-distance conditions. The bionic flapping-wing aircraft is therefore widely used in both the military tasks (low-altitude surveillance, urban combat, accurate delivery, etc.) and civilian applications (disaster monitoring and relief, field exploration, etc.) [244], as shown in Figure 1.3. Compared with fixed wings and rotary wings, flapping wings have the advantage in flight efficiency [227, 363], which shows the vital importance of the study of the bionic flexible flapping wings. However, flexible wings might generate unexpected deformation and vibration during the flying process. The vibration will degrade the flight performance, even shorten the lifespan of the aircraft. Therefore, designing an effective control method for suppressing vibrations of the flexible wings is significant in practice.

The vast majority of the previous studies have shown that an accurate mathematical model of flexible systems always necessitates complex derivations and heavy computational load. Even if a few studies have employed the software modeling methods, the distinct disadvantages, such as high complexity, poor scalability, and slow response, are followed. Another finding of the comprehensive literature review is that the control theory research of the bionic flapping-wing aircraft is at its initial stage. The previous control research has mostly neglected the vibrations [116, 143], dynamic uncertainties [292], and actuator failures that are extremely unfavorable in view of the practical application. Even among the few vibration studies, most control inputs can only be applied to the wing tip, which is impractical in real flight situations. It is thus desirable to obtain a high-efficiency modeling method and design a feasible intelligent vibration control strategy while solving the system uncertainties and actuator failures.

These figures shows that the flexible system covers many different objects such as flexible robotic manipulators, flexible bionic flapping-wing aircraft, and flexible buildings. With a large number of applications of flexible systems, its control theory and method issues have become

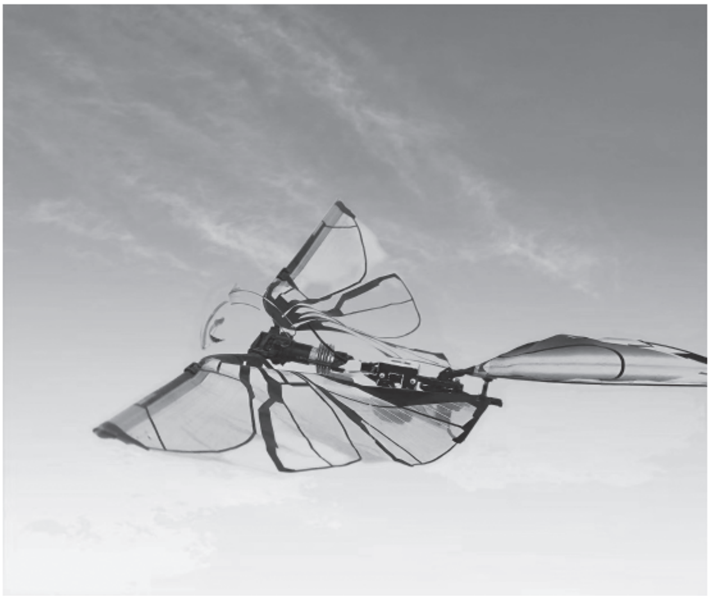

Figure 1.3 The bionic flapping wing aircraft.

a prospective high-tech research direction, which attracts concerns from both academic and industrial fields. It is worth mentioning that only tracking control and vibration control are not sufficient to enable flexible systems moving to its desired position due to potential variations in the environment-related factors. The following issues are essential for designing effective control strategies:

- **Dynamic uncertainties**: Flexible systems are distributed parameter systems with complicated dynamics. The mass matrix, damping matrix, and stiffness matrix are usually not sufficiently accurate enough to obtain.
- **Immeasurable states**: Due to the sensor's limitations or environmental impacts, some states of the flexible systems cannot be measured in practice.
- **External disturbances**: Flexible systems can replace people to do all kinds of dangerous works, and the factors determine that the working environment of the flexible systems is unknown, complicated, and variable.
- **Actuator failures**: Due to the harsh working environment, the failures of the components related to the actuator (such as efficiency loss and actuator bias fault) will inevitably occur.
- **Composite constraints**: Due to the limitation of workspace, the output constraints need to be considered to ensure the safety of the flexible systems during the course of movement.

The issues of dynamic uncertainties, immeasurable states, unknown external disturbances, sudden failures, and composite constraints are thus also required to be addressed.

In order to solve the above technical problems of modeling and intelligent control of flexible systems, the book makes a systematic and detailed study on dynamic modeling and intelligent control of flexible systems.

1.2 Modeling and Control Strategies of Flexible Robotic Manipulators

Flexible robotic manipulators are a type of robots that have flexible links or joints, which can deform under external forces or internal actuation. Flexible robotic arms are widely used in various fields such as aerospace, manufacturing, and medical applications. They have many advantages over rigid robots, such as higher dexterity, lower weight, lower energy consumption, and better adaptability to complex environments. However, they also pose significant challenges in modeling and control, due to their nonlinear dynamics, distributed parameters, and coupling effects. Therefore, developing effective modeling and control strategies for flexible robotic manipulators is an important and active research topic in robotics.

The control of lightweight manipulators is complex based on the nature of flexibility in the system, i.e., flexible joints, flexible links, or flexible joints and links. Among them, the most difficult task is to control the flexible link manipulators because of link flexibility, underactuation, and non-minimal phase nature. Underactuation is due to a finite number of actuators to control infinite degrees of freedom that arise due to link flexibility [21]. Figure 1.4 shows a single-link flexible manipulator, and Figure 1.5 shows a two-link flexible manipulator.

Modeling of flexible robotic arms involves deriving the equations of motion that describe the coupled rigid–flexible dynamics of the system. The widely used modeling approaches are the Hamilton's principle [200], Newton–Euler equation [361], Lagrangian equation [167], Kane equation [50], Gaussian equation [88], etc. The Newton–Euler equation is based on vector mechanics, and the rest of the methods refer to analytical mechanics. The resulting models

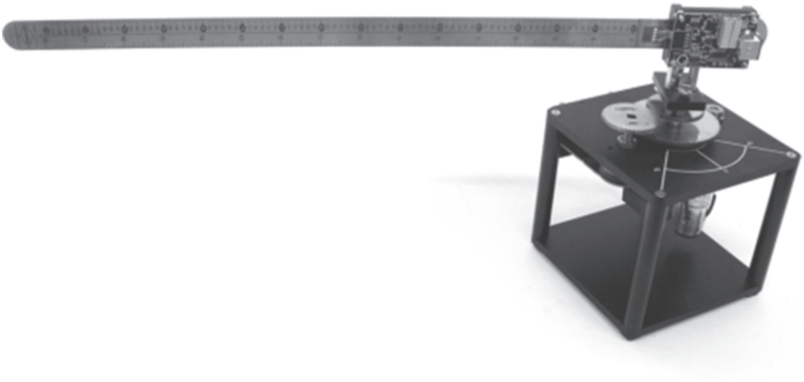

Figure 1.4 A single-link flexible manipulator system.

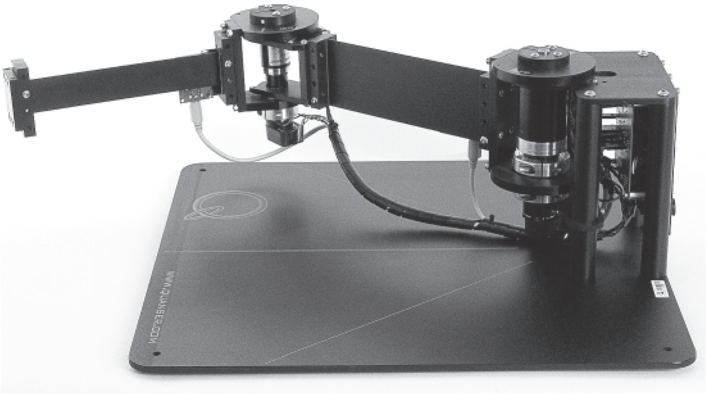

Figure 1.5 A two-link flexible manipulator system.

are usually partial differential equations (PDEs) or ordinary differential equations (ODEs) with boundary conditions.

Control of flexible robotic arms aims at achieving desired performance objectives such as tracking, stabilization, vibration suppression, and disturbance rejection. Various control strategies have been developed for this purpose, such as sliding mode control 1, adaptive robust boundary control 2, and fuzzy adaptive control 3. These strategies can be classified into two categories: boundary control and distributed control. Boundary control only uses actuators and sensors at the base or tip of the arm, while distributed control uses distributed actuators and sensors along the arm. Boundary control has the advantages of simplicity, robustness, and low cost. However, it may suffer from spillover effects, which occur when the unmodeled high-frequency modes are excited by the controller. Distributed control can overcome this problem by taking into account the full PDE model of the system. However, it may require more complex hardware and software implementation. In conclusion, modeling and control design of flexible robotic arms are active research topics that have attracted much attention in recent years. There are still many open problems and challenges that need to be addressed, such as model reduction, parameter estimation, sensor fusion, fault detection and isolation, and cooperative control of multiple flexible arms.

From these studies, it can be concluded that there is no single best modeling or control strategy for flexible robots, and the choice should be based on the specific application scenario and the characteristics of the robot. Future research can explore more efficient and accurate modeling methods and more intelligent and adaptive control methods to solve some of the challenges in modeling and control of flexible robots.

1.3 Vibration Control Technologies of Flexible Building-like Structures

Flexible building-like structures are civil engineering systems that have high flexibility and low damping, such as high-rise and ultra-high-rise buildings. They are susceptible to vibrations caused by natural disasters such as earthquakes and strong winds, which may endanger the safety of the structures and the occupants. Therefore, designing effective vibration control technologies for flexible building-like structures is a significant and challenging task.

Vibration control technologies can be classified into two categories: passive and active. Passive control technologies use devices that do not require external power or feedback signals, such as tuned mass dampers, base isolators, and viscoelastic dampers. Active control technologies use devices that require external power and feedback signals, such as active mass dampers (AMD), active tendon systems, and piezoelectric actuators. Figure 1.6 shows a one-floor AMD system, which consists of one flexible floor, two flexible walls, and a linear cart system. The linear cart system includes a DC motor that provides the driven force, an accelerometer that

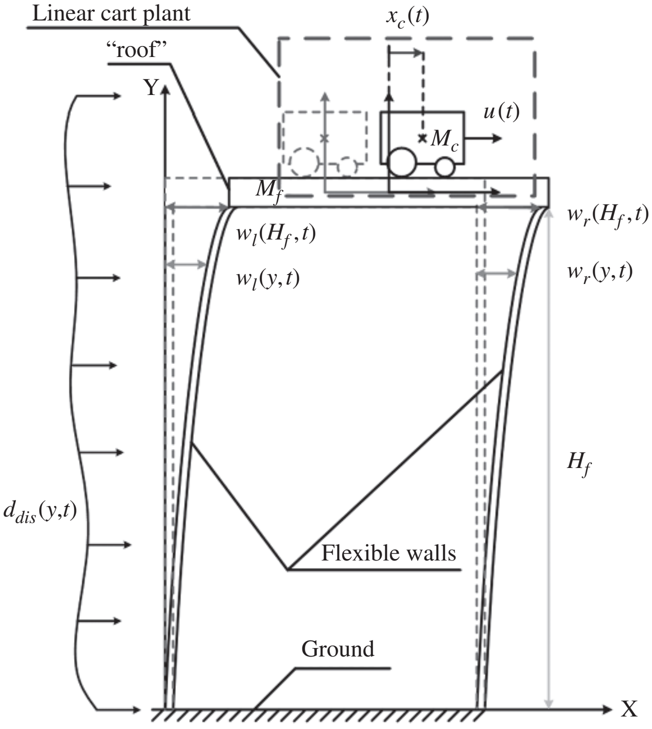

Figure 1.6 One-floor active mass damper system.

measures the acceleration of the flexible floor relative to the ground, and an encoder that measures the cart position.

Passive control technologies have the advantages of simplicity, reliability, and low maintenance cost. However, they also have some limitations, such as fixed parameters, limited performance, and possible resonance problems. Active control technologies can overcome these limitations by adjusting the control parameters according to the feedback signals and the desired performance objectives. However, they also have some drawbacks, such as complexity, high cost, and stability issues.

The main challenges in vibration control of flexible building-like structures are: (1) modeling the complex dynamics of the coupled rigid–flexible system; (2) designing robust and adaptive control strategies that can deal with system uncertainties, nonlinearities, and external disturbances; (3) implementing the control devices and sensors at appropriate locations; and (4) ensuring the stability and performance of the closed-loop system.

Various methods have been proposed to address these challenges in the literature. In a study [83], Gao et al. used Euler–Lagrange approach to model a single-floor building-like structure with an AMD and proposed a sliding mode control strategy based on reinforcement learning. In another study [120], He et al. used Hamilton’s principle to model a flexible structure with a tip payload and designed an adaptive robust boundary control strategy based on Lyapunov stability theory.

In future works, the control design of the multi-floor building-like structure will be considered. Multiple constraint problems such as constraints, saturation, and backlash will be studied. In addition, excitations caused by wind and earthquake, which may have a wider range of frequency, are further included so as to more practically simulate real-world engineering problems.

1.4 Modeling and Control Approaches of Bionic Flexible Flapping-wing Aircraft

The modeling and control of bionic flexible flapping-wing aircraft is a challenging and promising research topic in the field of micro aerial vehicles (MAV). Inspired by the flight of birds or insects, bionic flapping-wing aircraft can achieve high maneuverability, low noise, and low energy consumption. However, the flexible wings of such aircraft also introduce complex aerodynamics, nonlinear dynamics, and uncertainties, which pose difficulties for the design, analysis, and control of the system. Therefore, it is important to develop effective modeling and control approaches for bionic flexible flapping-wing aircraft to improve their performance and reliability.

The modeling and control of bionic flexible flapping-wing aircraft is still an active and open research area with many challenges and opportunities. Some of the current challenges include improving the accuracy and efficiency of the modeling methods; developing more robust and adaptive control methods; incorporating sensor feedback and vision-based navigation; enhancing the flight performance and autonomy; integrating multiple flapping-wing aircraft into a swarm system; exploring new applications and scenarios for flapping-wing aircraft. Some of the future directions include using machine learning and artificial intelligence techniques to improve the modeling and control methods; exploiting bio-inspired mechanisms and materials to enhance the wing design; incorporating energy harvesting and storage devices to extend the flight endurance; developing new test beds and platforms for experimental validation; and collaborating with other disciplines such as biology, physics, chemistry, etc., to gain more insights into flapping-wing flight.

The flexible flapping wing is essentially an infinite-dimensional distributed parameter system with complex dynamic characteristics, which causes enormous challenges to system dynamic analysis and modeling [27, 176, 206]. The existing modeling methods for flexible structures include modal superposition method (MSM), finite element method (FEM), lumped mass method (LMM), finite segment method (FSM), and absolute coordinate method (ACM). In a study [71], Ferhatoglu et al. proposed a new MSM utilizing novel hybrid mode shapes for the dynamic analysis of nonlinear systems. The accuracy and computational efficiency of the proposed MSM are verified by several cases. However, obtaining the mode shape functions always requires complex derivations. FEM and assumed mode method (AMM) were compared to investigate the coupled vibrations of a flexible-disk rotor system with lacing wires [366]. Although the precision of both methods can be improved with the increasing number of elements, the issue of the heavy computational demand will be followed.

Several studies have applied different modeling and control methods to bionic flexible flapping-wing aircraft and compared their performance and effectiveness. For example, Biswal et al. [16] developed three nonlinear dynamic models with increasing complexity and designed a family of LQR controllers for each model. They tested the robustness of the controllers on different models and examined the trade-offs between performance and complexity. Shao et al. [250] designed a bionic flapping-wing aircraft model with an unfolding-bending effect and used ADAMS and XFlow co-simulation to analyze its aerodynamic characteristics. They investigated the effects of flutter frequency, airflow velocity, fuselage angle of attack, and aileron torsion angle on its aerodynamic characteristics. Gao et al. [84] proposed an adaptive finite-time fault-tolerant controller for uncertain flexible flapping-wing aircraft with actuator faults. They proved the stability of the controller using the Lyapunov theory and demonstrated its effectiveness through simulations.

1.5 Outline of the Book

Chapter 1 provides an overview of dynamic modeling and intelligent control of flexible systems, introducing several important issues in the study of flexible systems. The modeling and control methods of three typical flexible systems are discussed separately.

Chapter 2 provides the corresponding mathematical preliminaries of subsequent chapters, including the Hamilton's principle, model discretization methods, Lagrange's equation method, neural networks (NNs), and Lyapunov stability theorem.

Chapter 3 develops the dynamic model of the single-link flexible robotic manipulator, which overcomes the challenge of the system dynamics being infinite-dimensional. The fuzzy NN control with uniform approximation performance is designed to solve the system uncertainties. Numerical simulations and extensive experiments have been investigated to verify the effectiveness of the proposed methods.

Chapter 4 establishes a finite-dimensional dynamic model of the two-link flexible robotic manipulator. A high-gain observer-based NN control strategy is proposed to estimate the immeasurable states in practice. The semi-globally uniformly ultimate boundedness (SGUUB) of the closed-loop system is guaranteed via Lyapunov stability theory. The simulation and experimental results demonstrate the effectiveness of the proposed control strategy.

Chapter 5 presents the vibration control design for a string with the boundary time-varying output constraint. The dynamics of the string is a distributed parameter system described by a PDE and two ODEs. A barrier Lyapunov function with a logarithmic function is adopted to prevent the time-varying constraint violations. Adaptive control is designed to handle the system's parametric uncertainties. Stability analysis and the solvability of the inequality equations are provided. Numerical simulations are provided to illustrate the effectiveness of the proposed control design.

Chapter 6 focuses on a stand-alone tall building-like structure with an eccentric load. An NN control approach is proposed to suppress vibrations caused by unknown time-varying disturbances (earthquake, strong wind, etc.). The output constraint on the angle of the eccentric load is also considered, and such an angle can be ensured within the safety limit by incorporating a barrier Lyapunov function. Simulations and experiments based on MATLAB and Quanser are carried out to verify the feasibility and effectiveness of the proposed control.

Chapter 7 discusses an adaptive vibration control method for a single-floor building-like structure equipped with an AMD. The method uses a hybrid learning control strategy to suppress vibrations caused by unknown time-varying disturbances such as earthquakes or strong winds. The effectiveness of the proposed control approach is demonstrated through experimental investigation on a Quanser Active Mass Damper. The research results aim to bring new ideas and methods to the field of disaster reduction for engineering development.

Chapter 8 investigates a single-floor building-like structure equipped with an AMD. Optimal vibration control, while dealing with system uncertainties, is realized by the reinforcement learning technique. When the unexpected natural disasters occur, the proposed controller applying to the AMD can compensate for the increase in the system vibration caused by external disturbances. The experimental results in the form of graphics and tables have shown the effectiveness of the proposed control algorithm.

Chapter 9 develops the visualization model of the rigid–flexible coupled bionic flapping wing by the advanced system-level modeling software MapleSim. A novel NN controller based on disturbance observer technology is proposed to compensate the system uncertainties. The proposed method can successfully suppress the vibration of the flapping wing while accurately tracking the desired trajectory. Co-simulation results from MapleSim and MATLAB/Simulink validate the effectiveness of the proposed method.

Chapter 10 focuses on the flexible wings of the aircraft, which have great advantages, such as being lightweight, having high flexibility, and offering low energy consumption. A novel adaptive finite-time controller based on the fuzzy NN and nonsingular fast terminal sliding-mode scheme is proposed for tracking control and vibration suppression of the flexible wings, while successfully addressing the issues of system uncertainties and actuator failures. Co-simulations through MapleSim and MATLAB/Simulink are carried out to verify the performance of the proposed controller.

Chapter 11 discusses the importance of vibration control for bionic flapping-wing robotic aircraft and autonomous ornithopter applications. A visualization model of the rigid–flexible coupled bionic flapping wing is established using MapleSim software. A novel adaptive vibration controller based on NN algorithm is proposed to compensate for system uncertainties. The proposed method can successfully suppress the vibration of the flapping wing while accurately tracking the desired trajectory. The effectiveness of the proposed method is validated through cosimulation results from MapleSim and MATLAB/Simulink.

Chapter 12 investigates dynamic modeling, active boundary control design, and stability analysis for a coupled floating wind turbine (FWT) system, which is connected with two flexible mooring lines. It is a coupled beam-strings structure, and we design two boundary controllers to restrain the vibrations of this flexible system caused by external disturbances based on the coupled PDEs-ODEs model. Meanwhile, significant performance of designed boundary controllers and system's stability are theoretically analyzed, and a set of simulation results are provided to show the efficacy of the proposed approach.

Chapter 13 summarizes the practical significance of the application of NN-based intelligent control and proposes some future research directions in this field.

In summary, this book proposes high-efficiency modeling methods and novel intelligent control strategies for several representative flexible systems developed by means of NNs. The book discusses the tracking control of multilink flexible manipulators, the vibration control of flexible buildings under natural disasters, and the fault-tolerant control of bionic flexible flapping-wing aircraft. Expanding on its theoretical deliberations, the book includes many case studies demonstrating how the proposed approaches work in practice.