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Wei Huang
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Optimized Engineering Vibration Isolation, Absorption and Control

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Preface

Nowadays, the engineering vibration control technology has been applied widely with the rapid development of China's industry and great progress in science and technology. This technology has played an important role in the vibration control of large power equipment, ultra-precision equipment, and building structures. Moreover, this is a key support technology in the fields of machinery, electronics, electricity, metallurgy, weapons, and aviation.

Improper vibration control will negatively affect the normal operation and service life of the equipment, the normal measurement of instruments and meters, the health of staff and residents nearby, and even the service life and safety of nearby industrial buildings.

With the continuous improvement of equipment, the vibration load, the frequency range, and the demand for low-frequency micro-vibration control of the equipment increased. However, traditional passive vibration isolation cannot fully adapt to the increased working frequency band. This is due to the fact that the damping and stiffness characteristics are not adjustable once the vibration isolation parameters are determined.

Active vibration control has the advantages of large output, good control effect, and the ability to continuously adjust the control output according to the change of excitation. Notably, the design and parameter optimization of the control system has an important impact on the control effect. The emergence of smart materials and smart dampers has promoted the rapid development of semi-active control technology, such as magnetorheological (MR) and electrorheological (ER). The control algorithm and the target design based on active control effect are important research concerns.

This book focuses on the system and parameter optimization of vibration isolation, absorption, active and semi-active control of engineering vibration, as well as the optimal arrangement of sensors. The research in this book is an attempt to develop the advanced technology of engineering vibration control and, hopefully, plays a certain guiding role for practical engineering.

We expect that the researchers and practitioners can explore engineering vibration control technology and discipline development from different perspectives and viewpoints.

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Chapter 1
Introduction

Abstract In this chapter, the background, purpose, and significance of the studies presented in this book are carried out, and the importance of vibration control for two types of industrial equipment, i.e., power equipment and sensitive equipment is indicated. Besides, single-stage and double-stage isolation system with passive, active and semi-active control strategies are studied by reviewing lots of literature, and some advanced vibration control techniques and artificial intelligence methods are studied, such as magnetorheological damper, dynamic vibration absorber, particle swarm optimization etc.

1.1 Background, Purpose, and Significance

With the rapid development of modern industrial engineering, vibration control technology plays a crucial role in engineering construction. For instance, if the vibration risks are not adequately eliminated, they will affect the equipment's regular operation and service life, the standard measurement of instruments and meters, the physical health of workers and nearby residents, and even the safety of the nearby industrial buildings.

The equipment commonly used in industrial engineering can be divided into power equipment and vibration-sensitive equipment. The power equipment includes large-scale slewing, reciprocating, impact, and random vibration devices. These equipment have played an essential role in the national economy and defense construction. However, the vibration generated during their use causes damage to the equipment itself and harms the operators, industrial buildings, and the surrounding environment (Fig. 1.1).

On the other hand, vibration-sensitive equipment includes high-precision microscopy, optical interference detection, biochemical analyzers, precision grinding, and processing machine tools. These equipment are distributed in astronomical optics, military engineering, rapid detection, nanotechnology, laser devices, ultra-thin metals, grating scribing, and other fields. During their use, deviations and incorrect results are caused by minimal environmental disturbances (Fig. 1.2).

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(a) Steam turbine (b) Rotary compressor (c) Water pump

(d) Reciprocating compressor (e) Forging hammer (f) Textile machinery

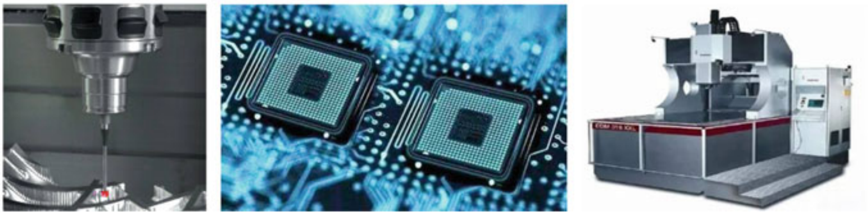
(g) Shaking table (h) Centrifuge

Fig. 1.1 Typical modern power equipment

There is still a particular gap between China’s vibration control technology and the advanced international level, which restricts the rapid and high-quality development of China’s industry to a certain extent. The painful lesson of the ‘ZTE incident’ is still remembered. The media has made sharp judgments about this event, ‘Powerful nations still need to be hard on their own, and wars without smoke will eventually require scientific and technological researchers to develop high-end core technologies… today’s core technology has been blocked by foreign swords … ZTE’s tragedy will be staged if we still do not recognize the support of advanced technology …’. In fact, high-quality chips are closely related to micro-vibration control technologies, which are crucial links made from the cultivation of crystals. If the environmental vibration exceeds the standard, crystal damage is typically caused, significantly reducing the chip’s quality. This is the epitome of the critical role of vibration protection technologies in modern industrial engineering.

Effective vibration isolation and control measures for power equipment can reduce its vibrations and decrease their adverse impact on the surrounding environment. For

(a) Electron microscopy (b) Optical scanning (c) Grating Scribing



(d) Probe (e) IC manufacturing (f) Precision machine tools

Fig. 1.2 Typical modern sensitive equipment

vibration-sensitive equipment, vibration suppression can effectively lower the impact of ambient vibration on the equipment and ensure the regular use of the equipment.

Passive isolation is simple, easily implemented, and widely used system in vibration control engineering. However, its parameters are fixed, and it cannot actively adjust to changes in external interference once the system is designed (such as changes in frequency and excitation form). As a result, active control systems are typically considered. In such devices, the response of the controlled object is obtained in real-time and sent to the active controller. Thereafter, the instructions are sent simultaneously to drive the actuator by which active control force is generated to counteract severe vibrations in real-time. Hence, its control effect can be adjusted autonomously according to the changes in external interference.

In recent years, scholars have investigated system improvement, vibration isolation parameters optimization, and advanced algorithms development for hybrid passive isolation and active control systems. However, there is still extra room for theoretical and applied studies focusing on advanced control, especially those aiming to improve the effectiveness of active control technology. Besides, there are still gaps in the implementation and integration of such systems in actual engineering applications. Currently, the finite element method (FEM) is considered as a vital technique in modern engineering vibration control. A key issue herein is to improve the computational accuracy of engineering vibration control and reliably approximate the theoretical calculation as much as possible. If the theoretical analysis and numerical calculation results significantly differ, it is difficult for research and development personnel and engineers to choose reliable results. These problems cause critical issues in using passive and active control systems. The current research shows that most of the problems are based on simplified calculations using

MATLAB/SIMULINK and LABVIEW. Thus, the control object's actual characteristics cannot be considered. As a result, improving the way to perform detailed passive and active control calculations in the finite element environment is an urgent research direction.

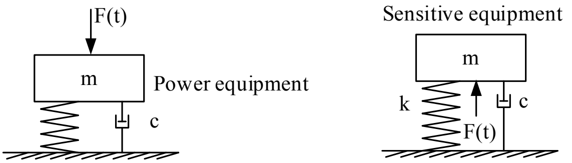
Indeed, passive control system optimization is an effective way to improve the control effect and performance. Among the currently available techniques, system decoupling is a vital link that must be considered in engineering vibration control design. In this system, the response of the control object under coupled and decoupled conditions varies considerably. The most obvious disadvantage of the coupled system is restraining translation and torsion, which significantly causes adverse effects.

For micro-vibration control, the vibration source hazards often have low frequencies. Therefore, designing a vibration isolation system with a low natural frequency is necessary. A low frequency for a steel spring damper with quasi-linear stiffness results in substantial deformation, and the actual engineering application is a challenging issue. In addition, once the system design is completed, the natural frequency changes with the change in the load mass. On the other hand, introducing air springs into the micro-vibration control has gradually overcome the problems involved in low-frequency design and large static deformation. Alternatively, these issues can be overcome by ensuring a constant chamber's effective height. A dual-chamber air spring is typically added with a specific additional air chamber volume for a single chamber. The upper and lower air chambers are usually connected through orifices, which effectively address the load-dependent natural frequency changes. Accordingly, the air spring floating system is suitable for medium and large loads. In contrast, a quasi-zero stiffness system can be considered for low-frequency micro-vibration control of small loads, which is a more forward-looking research direction.

1.2 Literature Research and Review

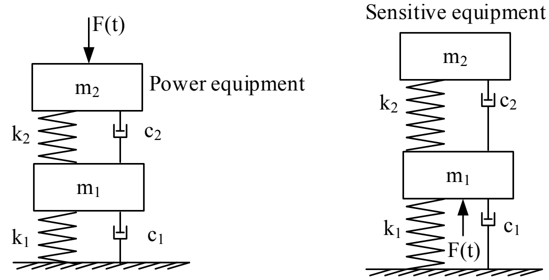
Figure 1.3a and b describe passive vibration isolation for power and sensitive equipment, which are two different single-stage vibration isolation systems. This passive isolation strategy is an early researched and applied method that has a simple structure and convenient design [1–4]. However, single-stage systems are often not ideal in the frequency domain, and two-stage systems are required [5]. Figure 1.4 shows the corresponding model. The dynamic characteristics of the two-stage vibration isolation system based on the minimum mean method have been previously analyzed [6]. Wei et al. [5] proposed a hybrid method for parameter optimization design of a two-stage vibration isolation system based on a genetic algorithm (GA) [7] using the principle of maximum entropy optimization. Farshidianfar et al. [8] concluded that calculating the vibration isolation of equipment using a two-stage vibration isolation system is necessary and effective.

The above passive vibration isolation system does not consider external energy input and does not rely on other automatic control systems. Once the system is designed, its structural parameters and damping and stiffness characteristics are



(a) power equipment (b) sensitive equipment

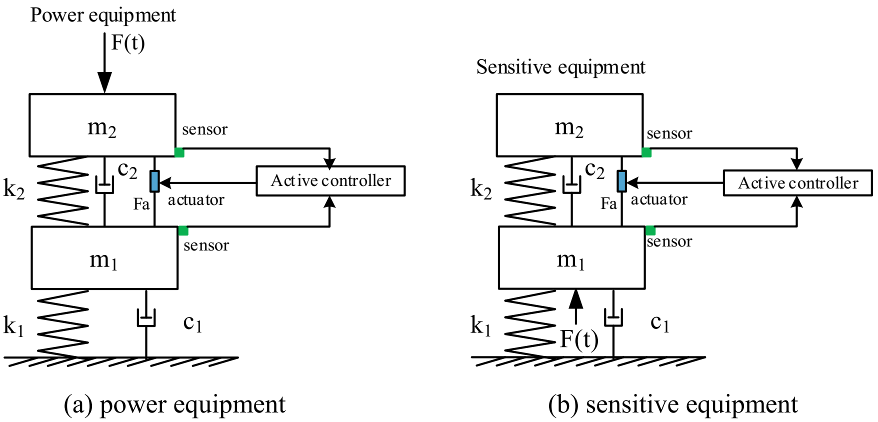
Fig. 1.3 Uncontrolled vibration isolation systems of two devices (single-stage)



(a) power equipment (b) sensitive equipment

Fig. 1.4 Uncontrolled vibration isolation systems of two devices (double-stage)

fixed. Besides, it cannot fully adapt to a wider operating frequency band. Certain limitations exist in passive control systems, such as not being conducive to vibration isolation design under low-frequency excitation and often failing to reach the expected vibration isolation effect. It cannot adaptively adjust to external interference, such as changes in amplitude, frequency, or excitation [9–12]. At this time, active control with energy input must be considered. Figure 1.5 depicts the active control for power and vibration-sensitive equipment with external controllers. This model was proposed by Farshidianfar [8] in 2012. Modern control methods, including proportion-integral-differential (PID) control [13], linear quadratic optimal control (such as the linear quadratic regulator, LQR [14], linear quadratic gauss, and LQG [15]), and H_2/H_∞ [16] control. The above control methods require establishing accurate computational models (such as transfer function or state space models). However, this method has some limitations when there is uncertainty in the mass, stiffness, or damping of the vibration system or when the system has strong nonlinearity [17]. For this reason, many scholars have carried out research on intelligent control methods, such as fuzzy logic control (FLC) [18], neural network control (NNC) [19], and fuzzy neural network control (FNNC) [20]. The above control methods have been widely used in vibration control fields such as vehicle vibration reduction, structural earthquake resistance, and structural wind resistance. Taghirad [21] carried out active control on the vehicle vibration reduction system based on the LQR/LQG control method. Kar et al. [22] conducted active control for thin plate structures using the H_∞ control method and developed a feedback controller to stabilize the control system. Pourzeynali et al. [23] studied the performance of the FLC control method



(a) power equipment (b) sensitive equipment

Fig. 1.5 Active control systems of two types of equipment

as an active control of a high-rise structure subjected to wind vibration. Nevertheless, these methods are rarely used for power and vibration-sensitive equipment in the active control field. Moreover, the literature still lacks research that forms a complete active control system for both types of equipment. Therefore, this method is mainly applied to the active control of typical equipment and is significant for engineering needs.

In the active control strategy, the actuator output is crucial to achieving a good control effect. However, it still has some disadvantages, such as complicated sensor/actuator system design, troublesome vibration data collection and processing approaches, large control energy consumption, and adverse economic effects. In addition, active control systems often have a time lag phenomenon. When the time lag is large, it may reduce the vibration control effect and diverges the system response [17, 24, 25]. For this reason, scholars have proposed a method between uncontrolled vibration isolation and active control known as semi-active control. This method requires only a small amount of energy to maintain the regular operation of the relevant electronic and electrical components. In these systems, the external power provides direct control, and the need for devices that induce the control forces and energy to support active control is eliminated [26]. From the international researchers' perspective, semi-active control mainly includes semi-active variable stiffness control and semi-active variable damping control. The semi-active variable stiffness control performs the calculations according to the preset control law and output control instructions and sends them to the mechanical device to finally apply the control strategy to the controlled object, as shown in Fig. 1.6 [27, 28]. On the other hand, the semi-active variable damping control is generally based on a hydraulic damper or a viscous fluid damper and a servo to form a damper with an adjustable fluid flow. It can continuously change the damping force and control a wide range of exciting vibration capabilities, as shown in Fig. 1.7 [29–31].

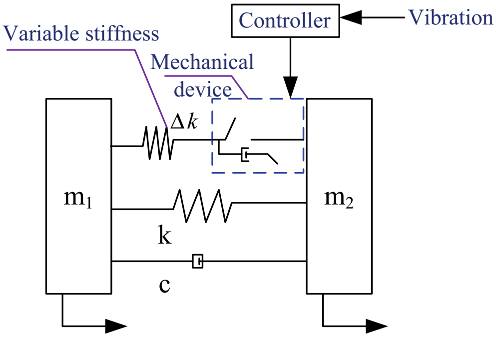


Fig. 1.6 Semi-active variable stiffness control

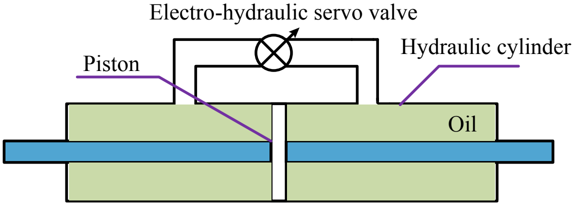


Fig. 1.7 Semi-active variable damping control

Recently, the traditional semi-active control technology has been greatly improved and promoted with the advancement of smart materials and dampers. Electro-rheological damper (ERD) is a new damper type that uses electro-rheological fluid (ERF) smart materials. As a result, its damping viscosity can change with the applied electric field strength. When lacking an electric field, the ER fluid flows freely. Once the applied electric field reaches a certain value, the ER fluid instantly gets into a gel state, with the response changing in milliseconds and reversible [32, 33]. Wang et al. [34] utilized the ERD device in building structures. Furthermore, Choi [35] applied the ERD system to study the semi-active control of fixed beam structures. Shortly after the invention of ERD, scientists discovered the magnetorheological fluid (MRF) and invented the magnetorheological damper (MRD). Compared to the ERF, MRF offers significant advantages in driving the ERF voltage substantially, up to several thousand volts, while MRF achieves a few volts to tens of volts [17]. Additionally, the MRF shear strength is much greater than ERF. Therefore, the volume of MRF in the damper is generally 100–1000 times smaller than ERF. Besides, the MRF is not sensitive to impurities in the body, and the temperature adaptation range is wider than the ERF. Therefore, in recent years, many scholars have utilized the MRD in semi-active control tasks. Yao et al. [36] applied MRD to semi-active control of the vehicle vibration reduction system and analyzed it with the Bouc-Wen model. Dyke et al. [37] established an MRD semi-active control system for structural seismic control based on sliding mode control. However, the current application of MRD in the semi-active control of power and sensitive equipment is scarce, which requires intensive research and exploration.

A dynamic vibration absorber (DVA) is a mass-spring-damping mechanism attached to the primary vibration system [38, 39]. In practical engineering applications, the passive vibration absorber exerts a better energy dissipation effect when the primary vibration system's vibration frequency remains unchanged. Due to the complex operating conditions of mechanical equipment and the changeable operating environment, it is not easy to meet this requirement in practical applications [40, 41]. In order to simulate the behavior of vibration absorbers, many scholars have improved traditional devices by adjusting and optimizing their essential parameters. With the introduction of new theories, technologies, and materials, some new research directions have emerged in vibration absorption, mainly including active vibration absorption technology, adaptive vibration absorption technology, and nonlinear vibration absorption technology [42–44]. An active vibration absorber adopts active intervention to reduce the demand on the primary vibration system, and its interior mainly includes components such as sensors, controllers, and actuators. Theoretically, the amplitude of the primary vibration system can be zero when the actuator force on the primary vibration system is equal to and opposite to the excitation force it receives. With the development of optimal control algorithms, studies on active vibration absorbers have dramatically progressed. Due to the lag between the feedback and actuator links, it is almost impossible to completely offset the force generated by the actuator and the exciting force in an ideal state. The primary vibration system may be unstable, especially for complex vibration systems. Therefore, active dynamic vibration absorber is mainly used in theoretical analysis, numerical simulation, and laboratory research stages, while it has relatively few actual engineering applications (Fig. 1.8).

Industrial equipment and civil structures are inseparable. Taking into account the vibration of equipment and structures as a composite system has important practical significance Yang et al. [45] studied the composite vibration system of structure and equipment under seismic excitation, Igusa et al. [46] modeled the composite vibration system of equipment and structure as a two-degree-of-freedom system to

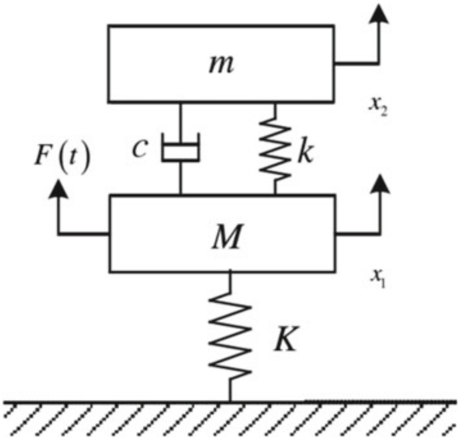


Fig. 1.8 Mechanical model of the dynamic absorber

perform a seismic control investigation. Xu et al. [47] assessed the vibration control effect of precision equipment attached to frame structure under seismic vibration. Ismail et al. [48] proposed a new vibration isolator to study the disturbance of equipment in the structure under seismic load. Murnal et al. [49] introduced a variable frequency pendulum vibration isolator to study the damping effect of equipment in structures under seismic loads. Currently, the literature lacks extensive research on the engineering vibration of structures caused by power equipment. Besides, seismic input shaking intensity is primarily considered in the vibration input, whereas other interference forms affecting sensitive equipment and vibration control methods are rarely taken into account. Generally, the equipment and structure are considered a two-degree-of-freedom system for calculation. Therefore, research on the composite system of equipment and building structures has great practical significance for the vibration control of modern industrial engineering.

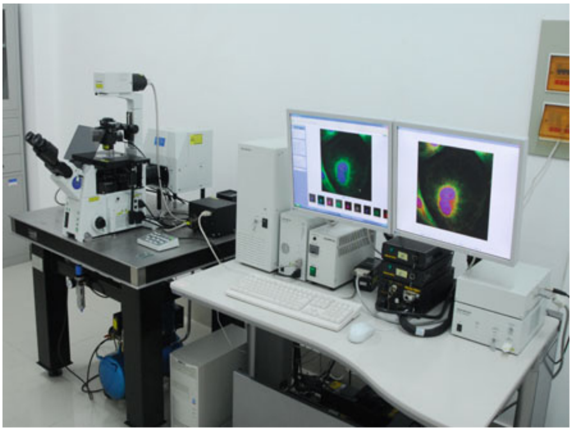
High-tech equipment used in producing semiconductors and optical microscopes is very expensive. In order to ensure the high quality of ultra-precision products, high-tech equipment used to manufacture these products requires a normal working environment with minimal vibration intensities. Accordingly, the top priority herein is to find an effective way to ensure that the functions of high-tech equipment are not affected by the micro-vibration of the building structure. The main sources of micro-vibration that affect the normal operation of high-tech equipment are ground motion caused by traffic, ground vibration caused by machinery, and direct interference [50]. Previously, many researchers have studied the measurement and prediction of ground motion caused by traffic and vibration caused by machinery [50–52]. The main frequency range of building structure floor vibration caused by machinery mainly depends on the machinery's rotation speed and the characteristics of the beams and slabs in the building.

Power equipment placed upstairs in structure is inevitable for modern industrial and social development. Power equipment station rooms, air conditioners, range hoods, and power pipes cause excessive building vibration, severely reduce the comfort of personnel, induce operational failure in the building's precision equipment, and even cause structural damage (Fig. 1.9).

Sensor deployment is widely used in modern industrial engineering structures. The main concept herein is to arrange a certain number of sensors in a limited two-dimensional plane or three-dimensional space structure to adequately cover the entire monitored area. This problem in engineering is called optimal sensors deployment (OSD). The OSD technique is widely used in large civil engineering structures' health monitoring and data collection [53–58]. There are many types of sensor deployment strategies, including modal kinetic energy (MKE) [59], MinMAC [60], QR decomposition [61], and probabilistic sensing models [62]. For a structure in which the equipment is installed in industrial engineering, there are two types of situations in which sensors are arranged on planar and three-dimensional space structures. Solving the OSD problems of these two conditions is of great significance for modern industrial engineering.

This book mainly focuses on passive vibration isolation and optimized active and semi-active control systems for power and precision equipment. In this regard,

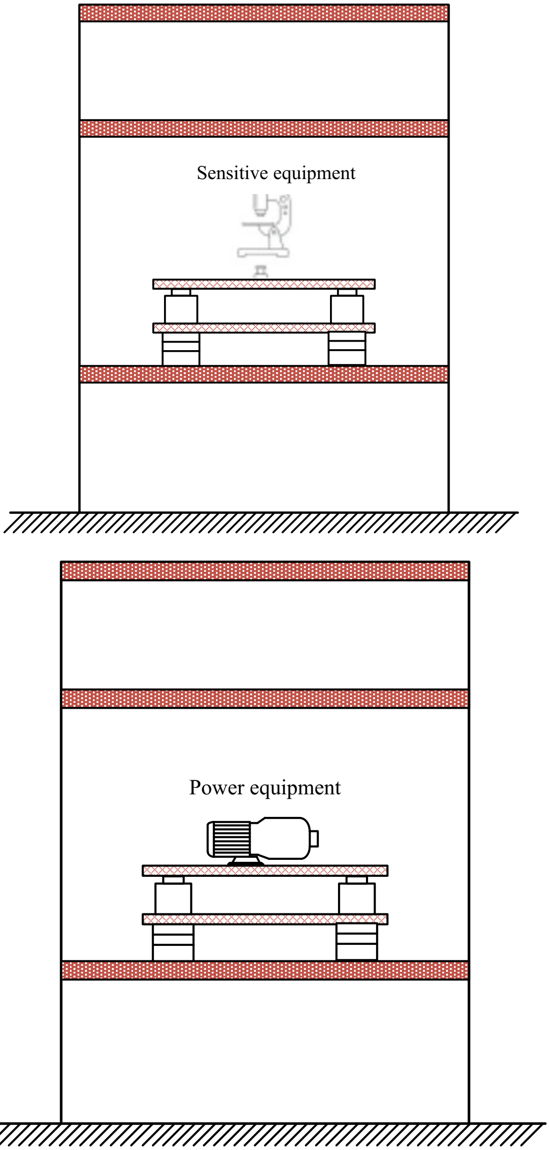
Fig. 1.9 Vibration and isolation for building structure with equipment



(a) A building with sensitive equipment

(b) A building with power equipment

Fig. 1.9 (continued)



(c) Schematic diagram of vibration and isolation model for building with equipment magnetorheological semi-active control based on tracking the active control effect, active control and semi-active control of coupled building equipment vibration system, and fine active control using finite element analysis, decoupling passive and active control, quasi-zero stiffness passive and active control, passive and active dynamic vibration absorption for buildings and equipment, optimal sensor deployment on 2D planner structure and in special 3D structure will be discussed. Within this series of studies, particle swarm optimization and multi-objective particle swarm optimization technology will play an essential role in the optimization strategy.

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Chapter 2
Particle Swarm Optimization

Abstract In this chapter, a new artificial intelligence optimization tool, a detailed introduction for particle swarm optimization (PSO) is presented here. The basic structure and the main characteristics of PSO algorithm and the multi-objective PSO (MOPSO) algorithm is described and elaborated, and some standard numerical examples for PSO and MOPSO are tested.

Natural systems, such as flocks of birds and schools of fish, often have some impressive, collision-free, synchronized interactions. This behavior is based on the inherent reaction of everyone in the group, although the reason is quite complicated from a macro perspective. For instance, by keeping an appropriate distance between each bird in the flock and its neighbors, the flock's migration behavior can be simulated accurately. This distance depends on the bird's size and behavior. On the other hand, when a school of fish swims freely, the individuals maintain a large mutual distance, whereas when there is a predator, the school of fish will gather into a very close group.

A similar phenomenon also exists in physical systems. A typical example is particle aggregation due to Brownian motion or fluid shear force. Human beings also have homogenous behavior characteristics, especially in forming social organization hierarchies and beliefs. However, unlike physical systems, people can hold the same idea or viewpoint without disagreement. These simplified aggregation behaviors in natural, physical, and human social systems enable researchers to conduct more in-depth experiments and simulation studies, thereby laying a foundation for developing swarm intelligence. Although the material structures of these systems are different, they have common properties with the following five basic swarm intelligence principles:

(1) Distance: the ability to perform space and time calculations.
(2) Quality: the ability to respond to environmental quality factors.
(3) Diverse reactions: the ability to make various reactions.
(4) Stability: the ability to maintain stable behavior under slight environmental changes.
(5) Adaptability: the ability to change behavior under the decision of external factors.

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Furthermore, sharing social information between individuals in the system provides evolutionary advantages. Based on the studies mentioned above, in 1995, J. Kennedy and R. C. Eberhan officially published an article titled Particle swarm optimization at the IEEE International Neural Network Academic Conference, which marked the birth of the PSO algorithm. Since then, this algorithm has been extensively used, promoted, and generalized in the literature [1–7].

The research on vibration control of industrial engineering equipment involves many disciplines, such as civil engineering, machinery, automation, and computer engineering. Simple and effective optimization tools are significant for solving such complex problems. Traditional gradient-based optimization [8] requires continuously calculating sensitivity factors and eigenvectors during the iteration process, which greatly increases the computational cost, reduces the convergence speed, and makes determining the optimal solution challenging [9]. The proposal of GA can effectively solve this issue. However, when there are situations where the target is a highly recognized optimization object, the parameters to be optimized have a high intercorrelation. Besides, the GA optimization ability is insufficient when the parameter's dimension is large. Eberhart and Kennedy [10] proposed a new swarm intelligence optimization algorithm, the particle swarm optimization (PSO) algorithm, in 1995 to overcome these shortcomings. The main idea herein is to find the optimal solution (particle) based on the interparticles' cooperation and competition. This algorithm has the advantages of simplicity, easy implementation, fast convergence, and few adjustable parameters. As a result, it has been widely used for handling optimization tasks in the engineering field [11, 12]. Coello et al. [13] proposed a multi-objective particle swarm optimization algorithm (MOPSO), whose main idea is to determine the particle flight directly through the Pareto optimal solution set and obtain the previously found non-domination in the global knowledge base vector to guide other particles in flying. Generally, PSO and MOPSO can deal with single-objective and multi-objective optimization problems, respectively. Their intersection and cooperation constitute a new chapter in modern engineering optimization [14].

The PSO algorithm starts by initializing a group of particles without volume and mass, where each particle is considered a potential solution to the optimization problem. Thereafter, a pre-defined fitness function is used to determine the particles' quality. In general, all particles move in the problem's search space, and the speed variable limits the particles' direction and distance. Usually, the particle seeks the current optimal position in each generation, where each particle follows the individual and neighbor optimal position. The particle swarm optimization algorithm is a new intelligent optimization algorithm that comes from the simple social simulation of birds and fish schools. Therefore, particle swarm optimization algorithms can be used. Simulating this interactive process provides a new way to solve decision-making issues in complex environments.

The PSO is a random optimization method that can be considered an artificial intelligence method. As mentioned above, this algorithm is inspired by the social behavior of animals and insects, such as bird flocks and fish schools. The PSO generally employs a swarm of multiple particles, each with its position and velocity. All particles share information with each other, and efficient searching is obtained