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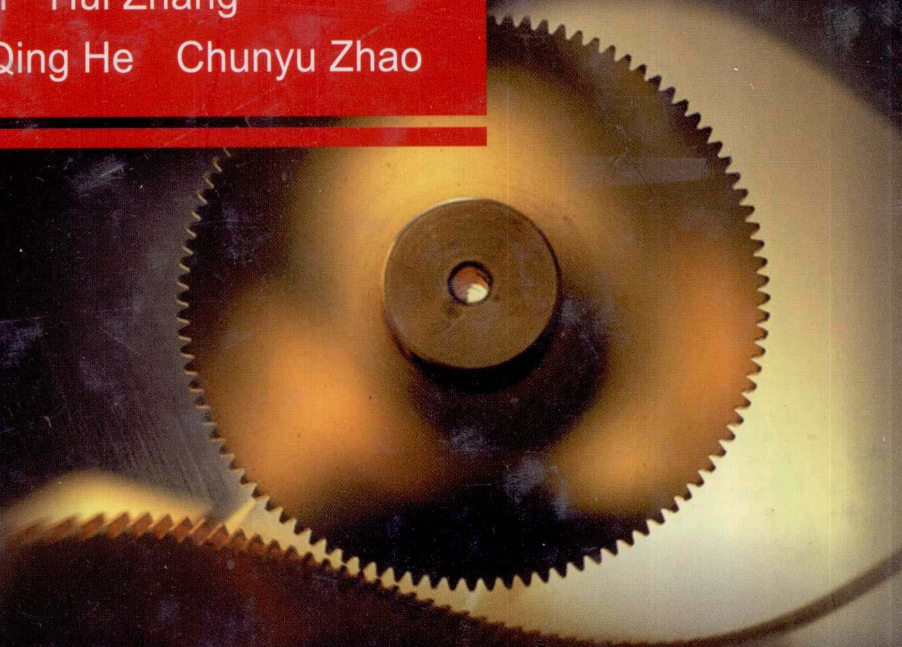

Theory and Techniques of Vibrating Machinery and Their Applications

振动机械理论、技术及其应用

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The working theory and techniques of vibrating machinery are described in this book. The applications, kinds, working principles and typical constructions of vibrating machines are introduced in the book briefly. This book describes the theories of several technical processes, the design and calculation methods of technical parameters, calculation and selection methods of the parameters of vibrating systems, the theories of vibratory synchronization and controlled synchronization of vibrating machines with dual- or multi-motor drives, the dynamic theories of linear and nonlinear vibrating machinery (including inertia vibrating machinery, flexible linkage vibrating machines and electromagnetic vibrating machines). Besides these some examples are introduced in this book.

This book can be used by the students and graduate-students of the universities to be as the study and reference reader. And this book also can be used by the researchers and designers of the research institute and design enterprises.

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Introduction to the First Author

WEN Bangchun, was born in Hangzhou city, Zhejiang Province, China, graduated as a postgraduate from Department of Mechanical Engineering at Northeast Technology of University (Now it is Northeastern University) in 1957. Mr. Wen now is professor in School of Mechanical Engineering and Automation, honorary director of Institute of Mechanical Design and Theory, Northeastern University, member of Chinese Committee of IFToMM, member of Technology Committee of International Rotor Dynamics Committee, member of Steering Committee for Asia-Pacific Vibration Committee, honorary chairman of Chinese Society of Vibration Engineering, honorary director of "Vibration, Impact and Noise" National Key Lab in Shanghai Jiaotong University. Professor Wen was a member of the 6th, 7th, 8th and 9th Chinese People's Political Consultative Conference, a review member of the 2nd, 3rd and 4th "Mechanical Engineering" course of Chinese State Consul Degree Committee, chairman of the Chinese Society of Vibration Engineering and chief editor of *Journal of Vibration Engineering*. Professor Wen was or is the advisory professor and honorary professors for more than 20 University. He received the honor of National Youth and Mid-aged Expert in 1984 and he was elected to be a member of Chinese Academy of Sciences.

Professor Wen systematically studied and developed the new course of "Vibration Utilization Engineering" combined with vibration theory and machinery. In addition he also studied some problems of rotor dynamics, nonlinear vibration and applications, vibration diagnostics of the machine fault, and the machinery design theories. He has written more than 700 papers and in which 250 papers are in SCI, EI and ISTP index systems. He has written more than 20 books and edited collected papers.

Professor Wen advised more than 160 graduates in which 90 students obtained their master degree, 70 doctoral degrees. He advised 10 post-doctors, a Russia and a Kazakhstan visiting scholar.

Professor Wen was invited to give lectures to Japan, Germany, Australia, etc., participated international conferences in US, UK, Japan, Australia, Italy, Korea, Bulgaria, Hungary, Singapore, Malaysia, Finland, Former USSR, Spain, etc. and presented more than 50 papers and invited to make some keynote speeches. He has organized 4 international conferences and was chief editor for 4 international conference proceedings.

Professor Wen accomplished many national key research projects, including key projects from National Fund of Natural Science, 973, 863 Projects. He received 2 International awards, 4 National Invention and Science and Technology Progress awards, more than 10 Province or Department awards, and he filed 10 National patents. Some of the projects have reached international levels.

This book is one of the important research results in his and his team work for more than 30 years.

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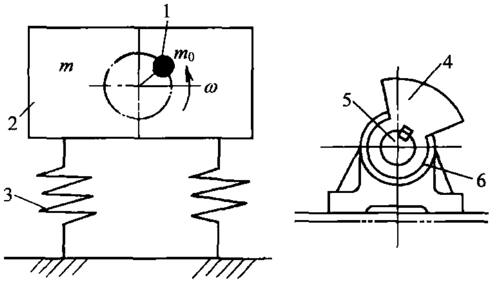
Chapter 1 Applications, Classifications, Principles and Structures of Vibrating Machines

1.1 Applications and classifications of vibrating machines

In many cases, vibration is harmful and must be avoided. However, in some cases, it is useful. For example, vibration can be utilized to perform a lot of processes, or increase operating efficiency for some types of machines. In recent 30 years, machines utilizing vibration principles (vibrating machines for short) have been developed rapidly. They are widely used in many fields, such as mining and metallurgy plants, coal processing plants, chemical plants, power generation plants, casting plants, construction sites, cement plants, as well as food and food processing industries. At present, there are more than several tens of types of vibrating machines used in industry, such as vibrating feeders, vibrating conveyers, vibrating screens, probability screens, vibrating centrifugal dehydrators, vibrating cooling machines, vibrating ball grinders, vibrating polishers, vibrating compactors, concrete vibrators, vibrating rollers, vibrating pile-drawers, vibrating pile-drivers, vibrating test machines, dynamic balancing equipments, and various types of vibrating exciters. These vibrating machines have been playing an important role in industry.

1.1.1 Components of vibrating machines

A vibrating machine consists of exciters, working frames and springs, as shown in Fig. 1.1(a).



(a) Inertial vibrating machine sketch (b) Inertial exciter

Figure 1.1 An inertial vibrating machine

1—exciter 2—working frame 3—elastic element 4—eccentric mass 5—shaft 6—bearing and bearing housing

1. Exciters

An exciter produces the periodic exciting force, which excites vibration of the machine frame. Common used exciters are inertial exciters, flexible linkage exciters, electromagnetic exciters, hydraulic or pneumatic exciters, or cam exciters.

2. Working frames

A working frame may be a feeding trough, a screen box, a platform, a balancing frame, etc. However, some vibrating machines do not have a working frame. In order to achieve performances of vibrating machines, the vibrating frames must vibrate periodically.

3. Springs

Springs may be isolation springs, primary vibrating springs, and flexible linkages. Some vibrating machines even don't have any spring.

Compared with other types of machines, vibrating machines have the following advantages and disadvantages.

Advantages:

Simple construction.

Easy manufacturing.

Light weight.

Less metal material consumption.

Low manufacturing cost.

Low energy consumption.

Easy installation.

Less and easy maintenance.

Disadvantages:

Unstable vibration amplitude.

Complex and difficult adjustment.

Large vibration transmitted to foundations.

Low service lives of components.

High noise.

1.1.2 Applications of vibrating machines

1. Material conveying

Utilizing the vibrating tubes or troughs, vibrating machines make materials perform a sliding or projection motion to convey materials. A vibrating machine with a sealed trough or tube conveying frame can be used to transport toxic or dusty materials that are harmful to environment and human health.

2. Material screening, separating, dehydrating, cooling and drying

Vibration can make material discrete and distribute uniformly on the working surface. At the same time, under the action of gravity, impacting force, friction and inertia forces, vibrating machines can perform screening, separating, dehydrating, cooling, etc.

3. Material grinding, work piece cleaning and polishing

Vibration can make materials crack and crackles spread rapidly inside the materials. It can also intensify the friction and impact among grinding (polishing, cleaning) medium and particles of processed material or work pieces to perform material (work piece) grinding, cleaning, casting component shaking, workpiece polishing, etc.

4. Discrete material shaping and compacting

Vibration reduces the coefficient of friction inside material remarkably so that "flowability" is increased, and makes material shaping easily and more compact.

5. Soil, sand and gravel compacting, concrete vibrating, pile driving and drawing

Vibration can reduce internal friction force that soils, gravels and other mixed materials exert on penetrating objects (such as piles and pipes) so that soil and gravel compacting process, concrete vibrating process, and pile driving and drawing processes can be performed effectively. Hence, the human labor intensity can be reduced remarkably.

6. Instrument, machine and their components testing

Vibration can also be used to perform vibration test of machine components. Vibrating testing machines and vibrating measuring instruments are widely used to measure parameters of measuring instruments, machines and their components. Vibration principle is also used to perform dynamic balance of rotating components.

7. Other applications

Vibration can be used to accelerate the process of crystal re-construction in casting or welding machine elements so that the residual stress releasing time can be reduced remarkably.

The applications of vibrating machines have been widened significantly. Types and specifications of them have been increased rapidly.

1.1.3 Classifications of vibrating machines

Different types of vibrating machines have different dynamic characteristics, which lead to different working performance. Based on applications, structures and dynamic characteristics, vibrating machines can be classified as the following categories:

1. Classification based on applications

Table 1.1 lists classifications of vibrating machines.

Table 1.1 Vibrating classifications based on applications

Class	Application	Machine name
Conveying and feeding	Feeding, pile dome eliminating, strobes	1. Vibrating feeders 2. Horizontal vibrating conveyers 3. Vibrating fillers 4. Vertical vibrating conveyers 5. Storehouse wall vibrators
Separating and cooling	Screening, separating, dehydrating, cooling and drying	1. Vibrating screens 2. Resonant vibrating screens 3. Spring shakers 4. Inertial four shaft shakers 5. Vibrating centrifugal shakers 6. Heavy medium vibrating troughs 7. Vibrating centrifugal dehydrators 8. Vibrating trough cooling machines 9. Vibrating tower cooling machines 10. Vibrating dryers
Rubbing and cleaning	Powder grinding, polishing, sand shaking, cleaning, dust removing	1. Vibrating grinders 2. Vibrating polishers 3. Vibrating shakers 4. Vibrating dust removers 5. Tramear bottom vibrators
Shaping and compacting	Shaping, compacting	1. Vibrating graphite electrode shaping machines 2. Vibrating refractory brick shaping machines 3. Vibrating concrete element shaping machines 4. Vibrating sculpting machines
Impacting, driving and drawing	Soil compacting, impacting, road rolling, pile driving and drawing, excavating, loading, rock drilling	1. Vibrating compacting machines 2. Penetrating concrete vibrators 3. Attaching concrete vibrators 4. Vibrating road rollers 5. Vibrating pile driver and drawers 6. Vibrating electric shovel bucket tooths 7. Vibrating loaders 8. Pneumatic or hydraulic impactors
Testing and measuring	Measuring, testing	1. Testing exciters 2. Vibrating stands 3. Dynamic balancing machines 4. Vibration measuring instruments
Others	Residual stress relieving	1. Vibrating residual stress relieving machines

2. Classification based on types of exciters

(1) Inertial vibrating machines.

An inertial vibrating machine, as shown in Fig. 1.1, is driven by an inertial exciter. As illustrated in Fig. 1.1(b), it consists of an eccentric mass, a basic shaft, bearings and bearing housings.

The vibration of the working frame stems from a centrifugal force of the rotating eccentric mass. Inertial vibrating machines are widely used in various industries, such as vibrating screens, vibrating ball grinders, vibrating shakers, vibrating shapers, and concrete vibrators.

(2) Flexible linkage vibrating machines.

As shown in Fig. 1.2, a flexible linkage vibrating machine is driven by a flexible linkage exciter which consists of a eccentric shaft, a flexible linkage, and springs. The vibration of the vibrating frame is excited by the flexible linkage. This type of vibrating machines includes flexible linkage vibrating conveyers, flexible linkage vibrating cooling machines, and heavy medium vibrating chutes. They are often used for long distance conveying.

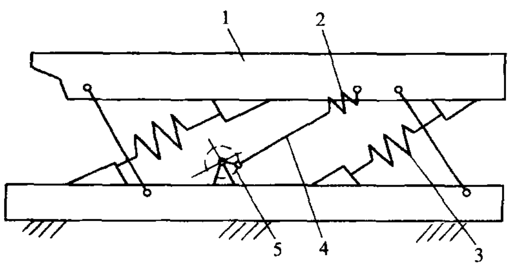


Figure 1.2 A flexible linkage vibrating machine

1—working frame 2—flexible linkage spring 3—elastic element 4—linkage 5—eccentric shaft

(3) Electromagnetic vibrating machines.

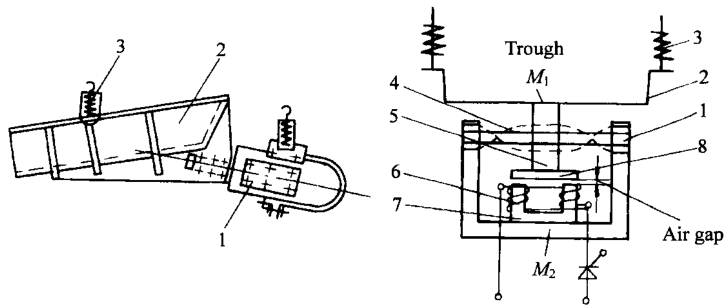
As shown in Fig. 1.3, an electromagnetic vibrating machine is driven by an electromagnetic exciter, which consists of an iron core, a winding and an amature. Alternate current or pulse current flows through the winding, and produces a periodic electromagnetic force which makes the working frame vibrate. This type of vibrating machines includes electromagnetic vibrating feeders, electromagnetic vibrating conveyers, electromagnetic vibrating screens, and electromagnetic vibrating testing machines.

(4) Other vibrating machines.

There are some other types of vibrating machine, such as pneumatic exciters, hydraulic exciters, cam exciters, etc. Since their working principles and calculation methods are quite different from the above-mentioned vibrating machines, they will not be discussed in this book.

3. Classification based on dynamic characteristics

Table 1.2 lists the classification of vibrating machines based on their dynamic



(a) Construction (b) Electromagnetic exciter

Figure 1.3 An electromagnetic vibrating machine

1—exciter 2—working frame 3—elastic element 4—leaf spring
5—connecting fork 6—winding 7—iron core 8—amature

Table 1.2 Classification of vibrating machines based on dynamic characteristics

Type	Characteristics	Type of exciters	Vibrating machines
Linear non-resonant	Linear or near-linear, non-resonant ($\omega \gg \omega_0$)	Inertial exciter, pneumatic exciter, hydraulic exciter	1. Single shaft or dual shaft inertial vibrating machines 2. Self-synchronization probability screens 3. Self-synchronization vibrating feeders 4. Dual shaft vibrating conveyers 5. Dual shaft vibrating shakers 6. Single shaft vibrating ball grinders 7. Inertial vibrating polishers 8. Inertial vibrating shaping machines 9. Penetrating concrete vibrators 10. Vibrating road rollers 11. Inertial vibrating testing machines 12. Inertial vibrating cooling machines
Linear near resonant	Linear or near-linear, near-resonant ($\omega \approx \omega_0$)	Inertial exciter, flexible linkage exciter, electromagnetic exciter	1. Electromagnetic vibrating feeders 2. Inertial near-resonant vibrating feeders 3. Flexible linkage inertial or electromagnetic vibrating conveyers 4. Linear resonant vibrating screens 5. Near-resonant vibrating trough cooling machines 6. Vibrating furnace hearths 7. Linear vibrating centrifugal dehydrators 8. Electromagnetic vibrating helical vertical feeders
Non-linear	Non-linear, non-resonant ($\omega \gg \omega_0$), or near resonant ($\omega \approx \omega_0$)	Inertial exciter, flexible linkage exciter, electromagnetic exciter	1. Non-linear vibrating feeders 2. Non-linear vibrating conveyers 3. Non-linear resonant vibrating screens 4. Spring shakers 5. Vibrating centrifugal shakers 6. Attaching concrete vibrators 7. Non-linear vibrating centrifugal dehydrators 8. Vibrating pile driver and drawers
Impacting	Non-linear, non-resonant ($\omega \gg \omega_0$), or near-resonant ($\omega \approx \omega_0$)	Inertial exciter, electromagnetic exciter, pneumatic exciter or hydraulic exciter	1. Self-propelled vibrating compacting machines 2. Vibrating drilling machines 3. Vibrating forging machines 4. Impacting electromagnetic vibrating shakers 5. Impacting vibrating shaping machines 6. Vibrating projectile compacting machines 7. Pneumatic impacting machines 8. Hydraulic impacting machines

characteristics. They are divided into linear non-resonant vibrating machines, linear near-resonant vibrating machines, non-linear vibrating machines and impacting vibrating machines.

Besides the above-mentioned classification methods, sometimes, vibrating machines are classified according to the number of vibrating masses and degrees of freedom.

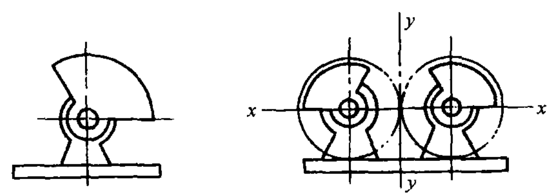
1.2 Principle and structure of inertial vibrating machines

1.2.1 Types of inertial exciters

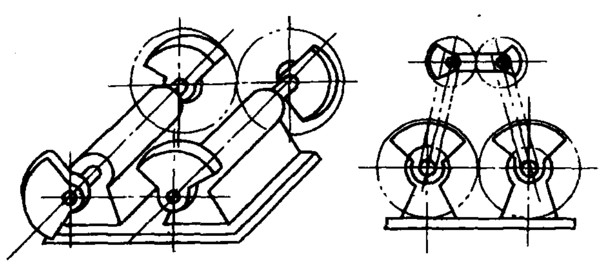
An inertial vibrating machine is driven by one or more exciters with eccentric masses. Inertial exciters can be classified as the following types:

1. Single-shaft inertial exciters

A typical single-shaft inertial exciter is shown in Fig. 1.4(a). It produces an exciting force that varies periodically. When two eccentric masses on a shaft are not installed at the same phase, they also produce an exciting torque that varies periodically.



(a) A single-shaft inertial exciter (b) A dual-shaft inertial exciter



(c) A dual-shaft inertial exciter (d) A multi-shaft inertial exciter

Figure 1.4 Various inertial exciters

2. Dual-shaft inertial exciters

Figure 1.4(b) shows a typical dual-shaft exciter. The two shafts rotate at the same rotational speed in opposite directions. Therefore, when the masses and the eccentric distances on the two shafts are equal, the inertial forces in the y direction stemming from the two shafts are added together, and those in the x direction are cancelled each other. Thus, the resultant exciting force of the two inertia shafts is a sinusoidal force in the y direction. When the phase angles of two masses on the same shaft are different, as shown in Fig. 1.4(c), sinusoidal exciting torque can be produced.

3. Multi-shaft inertial exciters

Figure 1.4(d) shows a four-shaft inertial exciter. It produces an exciting force of two frequencies.

Single- and dual-shaft inertial exciters are widely used in industries. Multi-shaft exciters are only used in a few vibrating machines.

1.2.2 Linear or near-linear non-resonant inertial vibrating machines

This type of vibrating machines has the following features:

(1) Spring stiffness is constant or near constant.

(2) This type of vibrating machines works in a far-over-resonant state. The ratio z_0 of its working frequency ω to the natural frequency ω_0 is usually taken in the range of 2 to 10.

(3) Since the natural frequency is much smaller than the working frequency, the stiffness of the spring is very small. Therefore, the dynamic load transmitted to its foundation is small. The machine has excellent performance of vibration isolation.

(4) The type of vibrating machines is a single-mass vibrating system, which simplify the structures of vibrating machines.

For its simple structure and excellent performance of vibration isolation, this type of machines is widely used in industries.

1. Single-shaft inertial vibrating machines

(1) Single-shaft inertial vibrating screens.

As shown in Fig. 1.5, a vibrating screen consists of a single-shaft inertial exciter 1, a screening box 2 and a suspension system 3 with isolation springs. A single-shaft inertial exciter consists of a basic shaft with eccentric masses or eccentric wheels, bearings and bearing housings. The screening box is a box of steel shape weldment or riveted plates. The side guard plates are connected by seamless pipes or steel shapes. A screen mesh or screen plate is installed in the screening box. The screening box is suspended on a supported frame or a floor plate by four isolating springs. It can also be installed on the foundation through isolating springs. Screening boxes of single-shaft inertial vibrating screens perform circular or elliptic (near circular) motion. They are widely used in ore separating plants, coal separating plants, cement plants, and chemical plants to perform screening tasks.

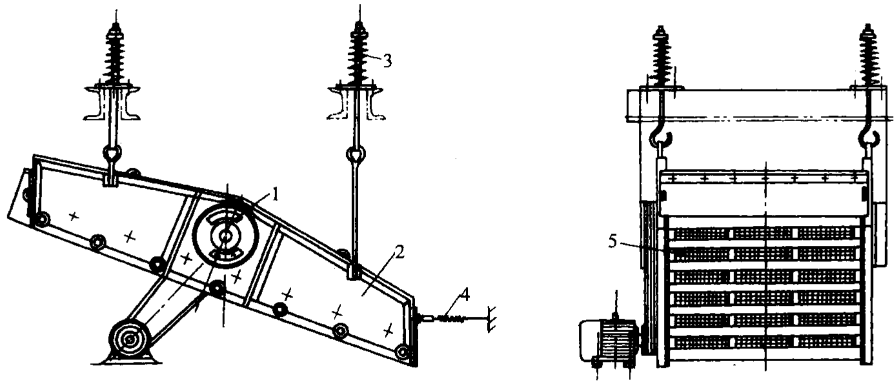


Figure 1.5 Structure of a single-shaft inertial vibrating machine
1—single shaft inertial exciter 2—screening box 3—isolating spring
4—front tension spring 5—screen mesh

(2) Vibrating ball grinders.

The structure of a typical vibrating ball grinder is shown in Fig. 1.6. It consists of a working cylinder 6 in which grinding medium (steel balls) and grinded material are filled, a single shaft exciter 3, and an isolation spring 7. The motor 1 drives the shaft of the single-shaft exciter through a flexible coupling 2. As the shaft rotates, the eccentric mass 5 on the shaft produces a centrifugal force to make the working cylinder vibrate circularly. The locus of any point on the working cylinder is in the plane normal to the axis of the exciter.

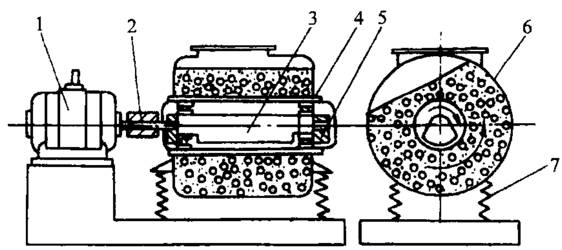


Figure 1.6 A vibrating ball grinder
1—motor 2—flexible coupling 3—single shaft exciter 4—bearing
5—eccentric mass 6—working cylinder 7—isolation spring

The vibration of the working cylinder makes grinding medium and grinded material impact each other. The impacting force makes material powdered. However, when the vibration frequency is lower than a certain value (critical frequency), each