# Chapter 2
# Fundamentals

## 2.1 Introduction

The design and implementation of maglev systems fundamentally involves the interdisciplinary concepts of electromagnetism, electronics, mechanical engineering, measurement and control. In consideration of this, the fundamentals of such disciplines are summarized to help the reader understand the remaining chapters with ease.

## 2.2 Electromagnetics

Magnetic levitation is realized through magnetic fields between magnetic objects. This section summarizes the source of the magnetic field and its nature as well as the related terminologies.

- **Magnetic field**: In a maglev system, the magnetic field is the medium that lifts vehicle systems weighing hundreds of tons and running at high speeds up to 600 km/h. What is the source of this magnetic field? It is moving electric charges. A moving charge $q$, at a velocity of $\vec{v}$, produces a magnetic field around it (Fig. 2.1). The magnetic field $\vec{\boldsymbol{B}}$ is defined by

$$\vec{\boldsymbol{B}} = \frac{\mu_0}{4\pi} \frac{q\vec{v} \times (\vec{\boldsymbol{r}}/r)}{r^2} \tag{2.1}$$

From Eq. (2.1), the magnitude of the field at any field $\vec{\boldsymbol{B}}$ is given by

$$B = \frac{\mu_0}{4\pi} \frac{|q| v \sin\phi}{r^2} \tag{2.2}$$



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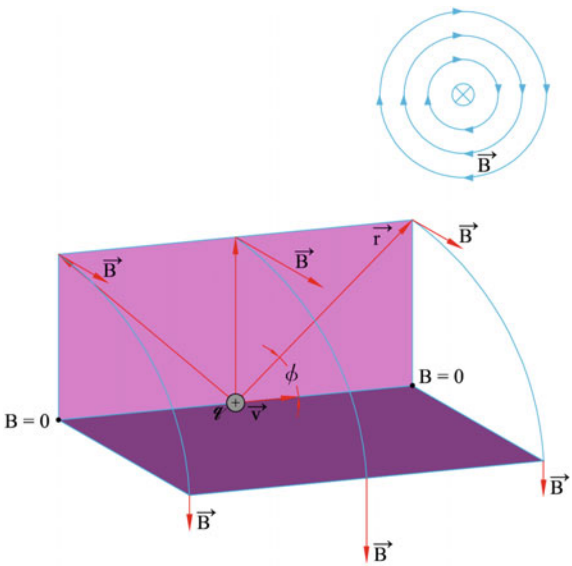



**Fig. 2.1** Magnetic field produced by a moving electric charge

Equation (2.2) indicates that $B$ is proportional to charge $q$ and is inversely proportional to $r^2$. It is worth noting this relationship because magnetic forces are proportional to $B$. The constant $\mu_0$ in the equation is described in other terms later.

Permanent magnets and solenoids also produce magnetic fields (Fig. 2.2). However, these magnetic fields are also produced by electric charges inside them made of magnetic materials. A magnetic field is formed by field lines. Field lines have no beginning or end, they always form closed loops. The field is spatial, as shown in Fig. 2.2. The field lines come from the North pole (N) and enter the South pole (S). The lines are continuous, and don't meet each other.

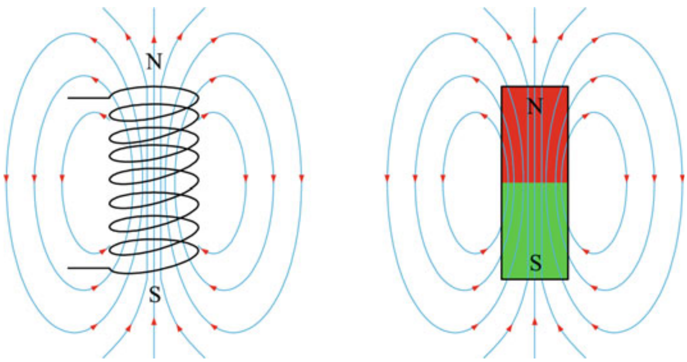



**Fig. 2.2** Magnetic fields in solenoid (*left*) and permanent magnet (*right*)

- **Attraction and repulsive forces**: An attractive force is generated between two magnetized objects when the field lines go from one to another (Fig. 1.2a). Whereas if the same poles are facing each other, the field lines are pressured, resulting in a repulsive force between them (Fig. 1.2b). These two kinds of forces are the sources of magnetic levitation systems. For example, the Transrapid uses attractive forces.
- **Magnetic substance**: Some materials can be magnetized by an external magnetic field. The most common types of these materials are iron, nickel, cobalt and most of their alloys. Ferromagnetic materials have the strongest capacity for magnetism. Diamagnetic materials do not respond to an applied magnetic field. Iron is widely used as the material for magnetization in magnetic systems.
- **Change of magnetic field**: A magnetic field has a property to be formed in more permeable material. For example, the diamagnetic material glass does not influence the magnetic field, but if iron is put into the field, the field lines around it go through it, rather than air (Fig. 2.3). This is because the permeability of iron is higher than that of air. Using this property, magnetic field shielding and electromagnet, produced by winding iron with conductor carrying current, can be made.
- **Flux and flux density**: A series of field lines is called flux $\phi$, and the number of the field lines is its value. A stronger magnetic field means a larger number of field lines, and consequently the value of flux becomes larger. That is, the flux value is the measure of a magnetic field's strength, and its unit is weber (Wb). 1 Wb indicates $10^8$ field lines. Flux density $B$ is defined as flux per unit area normal to magnetic field. Its unit is tesla (T). B is expressed as

$$B = \frac{\phi}{A}\left(\frac{Wb}{m^2}\right) \tag{2.3}$$

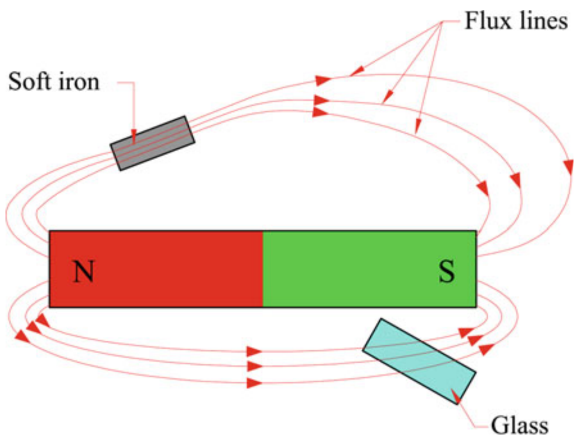



**Fig. 2.3** Change in the magnetic field with magnetic materials

- **Electromagnetic**: If electrons with negative charges flow through a conductor, a magnetic field is produced around it (Fig. 2.4). This field is called an electromagnetic field, and the properties of the field are the same as the properties of a permanent magnet. The direction of the electromagnetic field is perpendicular to the wire, and moves in the direction the fingers of your right hand would curl if you wrapped them around the wire with your thumb in the direction of the current.
- **Permeability** ($\mu$): Magnetic permeability represents the relative ease of establishing a magnetic field in a given material. The permeability of free space is called $\mu_0$, and its value is $\mu_0 = 4\pi \times 10^{-7} H/m$. Relative permeability of any material $\mu_r = \mu/\mu_0$ compared to $\mu_0$ is a convenient way to compare its magnetization. For steels, the relative permeabilities range from 2000 to 6000 or higher. Thus, if an iron core is wound by coils carrying currents, almost all of the flux produced by the coils goes through the iron core, not air, which has a smaller permeability than that of iron.
- **Reluctance** ($\mathscr{R}$): Reluctance is a magnetic resistance in materials, which is the counterpart of electrical resistance. It is defined as

$$\mathscr{R} = \frac{l}{\mu A} \tag{2.4}$$

  where, $l$ and $A$ are the length and area of flux path.
- **Magnetomotive force**(m.m.f.): This is an analogy of voltage or electromotive force since it is the cause of magnetic flux in a magnetic circuit (Fig. 2.5). Magnetomotive force $F_m$ is equal to the effective current flow applied to the core, that is

$$F_m = NI(ampere \cdot turns) \tag{2.5}$$

The relationship among electromagnetic properties is best illustrated by the magnetic circuit in Fig. 2.5. All of the magnetic field produced by the current will

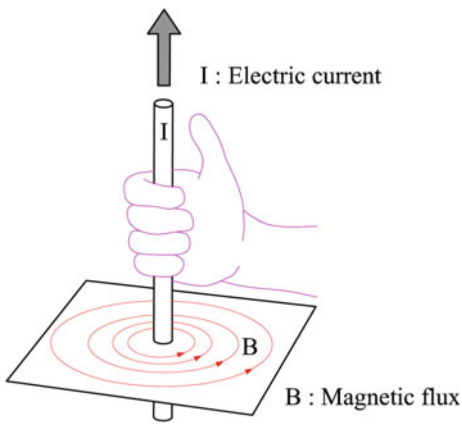



**Fig. 2.4** Magnetic field formed around a conductor carrying currents

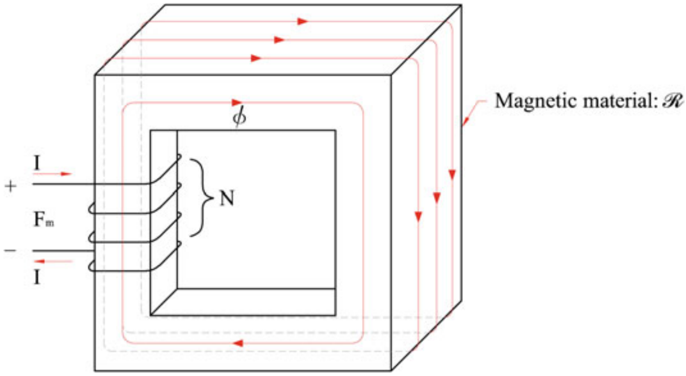



**Fig. 2.5** A simple magnetic circuit

remain inside the core because the core's permeability is higher than air. And the flux of the magnetic circuit is defined as

$$\phi = \frac{F_m}{\mathscr{R}} \tag{2.6}$$

- **Electromagnet**: The electromagnet, which is most widely used in magnetic levitation systems, is a type of magnet in which the magnetic field is produced by an electric current. Electromagnets usually consist of a large number of closely spaced turns of wire that create the magnetic field. The wire turns are often wound around a magnetic core made from ferromagnetic materials. The magnetic core concentrates the magnetic flux and makes a more powerful magnet. The main advantage of an electromagnet over a permanent magnet is that the magnetic field can be quickly changed by controlling the amount of electric current in the winding. The direction of a magnetic field is dependent on the direction of the electric current. A common simplifying assumption satisfied by many electromagnets, which will be used in Chap. 5, is worth noting here, as it can reasonably be used in the design and analysis of electromagnets. The magnetic field of a U-shaped iron core electromagnet is shown in Fig. 2.6. The drawing shows a section through the core of the electromagnet except for the windings, which are shown in three dimensions for clarity. The iron core of the electromagnet ($C$) forms a closed loop for the magnetic flux, with two airgaps ($G$) in it. Most of the magnetic field ($B$) is confined to the core circuit. However, some of the magnetic field lines ($B_L$) take "short cuts" and do not pass through the entire core circuit, and thus do not contribute to the force exerted by the magnet; this is called "leakage flux." This also includes magnetic field lines that encircle the wire windings without entering the core. In the gaps ($G$), the magnetic field lines are no longer confined by the core, so they "bulge" out of the edges of the gap before bending back to enter the next piece of core material.

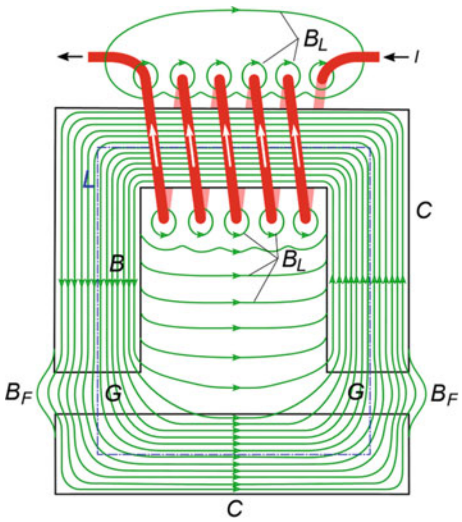



**Fig. 2.6** Diagram of the magnetic field of an electromagnet

These bulges ($B_F$) are called "fringing fields" and reduce the strength of the magnetic field in the gaps. The blue line $L$ is the average length of the flux path or magnetic circuit, and is used to calculate the magnetic field.

- **Magnetizing force**: The degree to which a magnetic field by a current can magnetize a material is called magnetizing force ($H$), and it is defined as m.m.f. per unit length of material. That is,

$$H = \frac{F_m}{l} = \frac{NI}{l} \quad (\text{Ampere} \cdot \text{Turn/meter}) \tag{2.7}$$

$H$ is not related to a material's property. The magnetic flux ($B$) induced in material by $H$ depends upon the nature of the material, and the relationship between $H$ and $B$ is defined by

$$B = \mu H \tag{2.8}$$

It is relevant here to relate all the parameters defined earlier as in Fig. 2.7.

- **Magnetic behavior of ferromagnetic materials**: Since the permeability of most ferromagnetic materials is not constant, the flux density $B$ as a function of magnetizing field $H$ is as shown in Fig. 2.8. Note that the flux in the materials is related linearly to the applied magnetomotive force in the unsaturated region, and approaches a constant value regardless of the magnetomotive force in the saturated region. Due to this behavior, the operational region of EMS systems should be located in the unsaturated region.
- **Hysteresis loop and residual flux**: Applying an alternating current to the windings on the core instead of a direct current with a frequency, the flux in the core traces out path *abcdeb* in Fig. 2.9. This is because the amount of flux

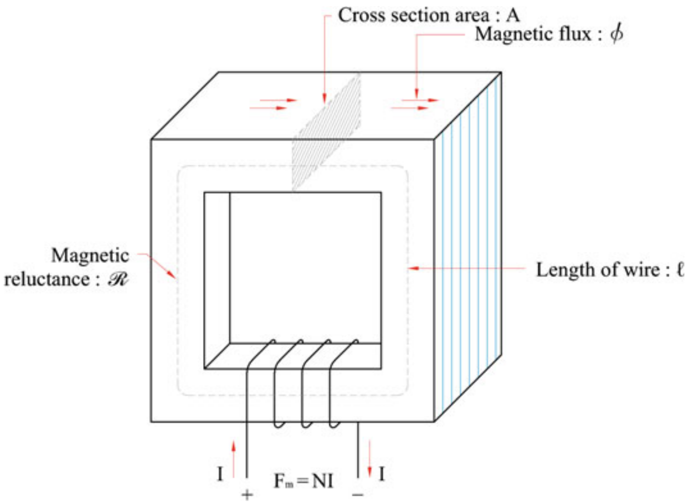



**Fig. 2.7** Parameters determining *H* and *B*

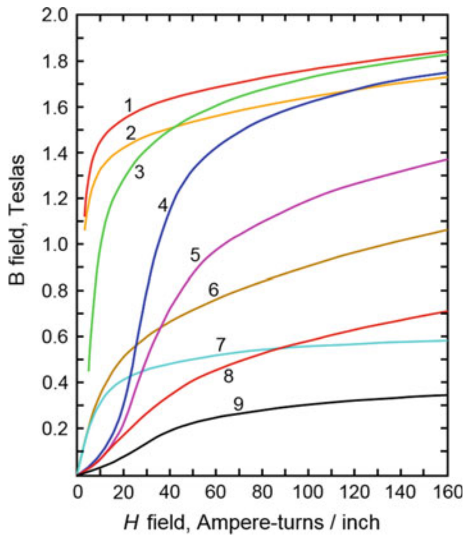



**Fig. 2.8** Magnetization curves of 9 ferromagnetic substances; The substances are: *1* standard sheet steel, annealed, *2* silicon sheet steel, annealed, Si 2.5 %, *3* soft steel casting, *4* tungsten steel, *5* magnet steel, *6* cast iron, *7* nickel, 99 %, *8* cast cobalt, *9* Magnetite, $Fe_2O_3$

present in the core depends not only on the amount of current applied to the winding of the core, but also on the previous history of the flux in the core. This dependence on the preceding flux history and the resulting failure to trace flux paths is called hysteresis. Path *bcdeb* traced out in Fig. 2.9 as the applied current changes is called a hysteresis loop. If the frequency of an alternating current is changed, the path is also changed with a different residual flux. This property may lower the control performance at higher frequencies in a levitation system with electromagnets.

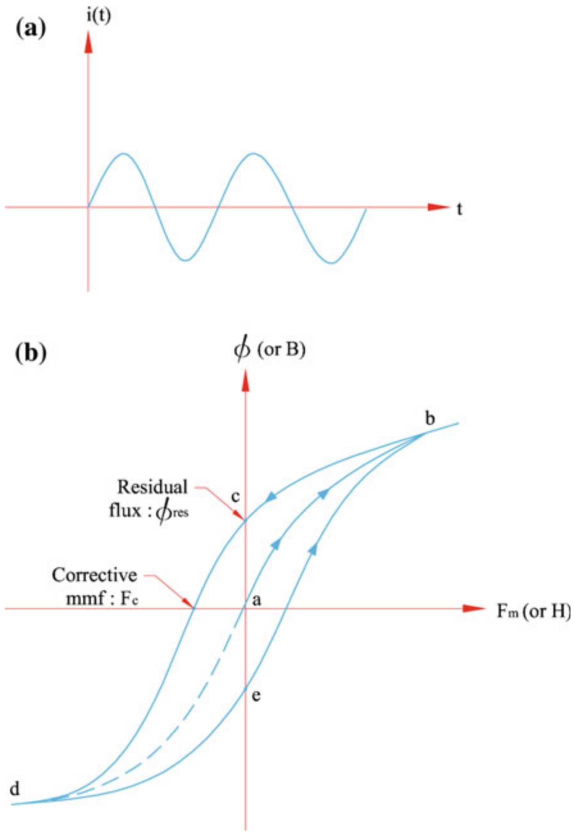



**Fig. 2.9** The hysteresis loop traced out by the flux in a core when the alternating current is applied to it: **a** alternating current and **b** hysteresis loop

- **Electromagnetic induction**: When a conductor is exposed to a time varying magnetic field, a voltage is induced across it, as shown in Fig. 2.10. This can be mathematically described using Faraday's law of induction. Electric generators and motors as well as magnetic levitation systems are based on this electromagnetic induction. The polarity of induced voltage depends on the direction of relative motion. Expressed in the form of an equation for induced voltage $e_{ind}$,

$$e_{ind} = -N\frac{d\phi}{dt} \tag{2.9}$$

  The minus sign in Eq. (2.9) is an expression of Lenz's law to be described below.
- **Induced current**: If a conductor in Fig. 2.11 has an electrical resistance, an electrical current flows in the conductor. This current is called induced current $i_{ind}$.
- **Force on a current carrying conductor in a magnetic field**: If the directions of the flux lines from magnets and conductor are the same, the flux density

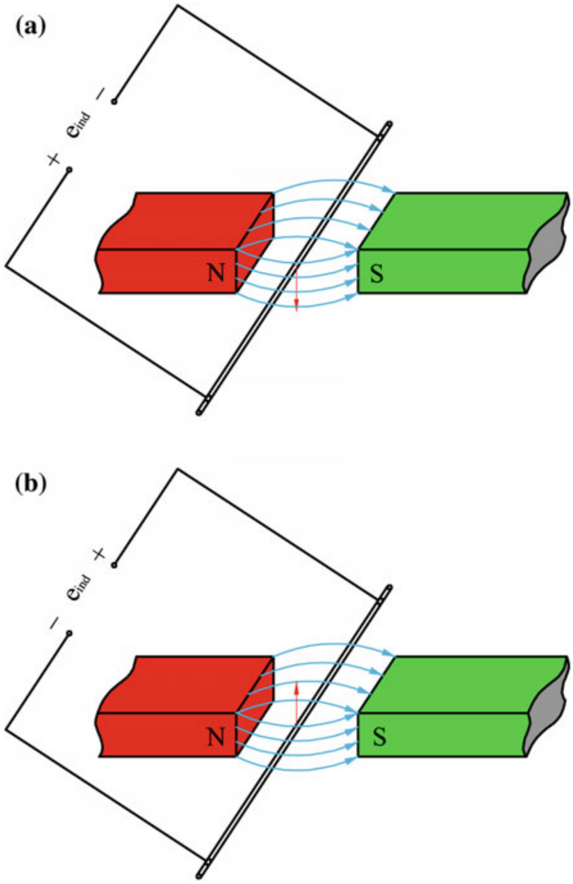



**Fig. 2.10** Electromagnetic induction

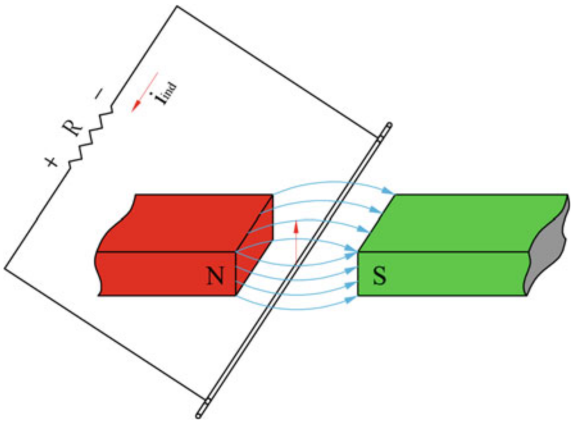



**Fig. 2.11** Induced current

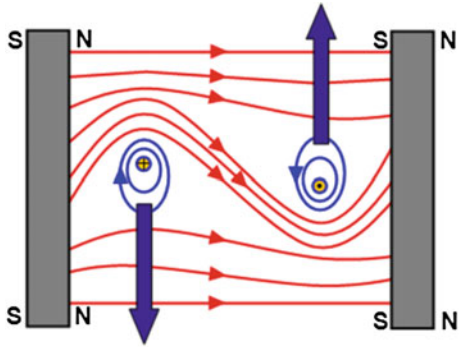



**Fig. 2.12** Forces on current carrying conductors in a magnetic field

increases. In contrast, if the directions are opposite, the flux density decreases. The resulting forces are exerted towards a weak magnetic pressure region from a stronger pressure region, as shown in Fig. 2.12. This is the operating principle of electric motors.

- **Lenz's law**: A time varying magnetic field induces voltage and corresponding current in a conducting material described earlier. Lenz's law indicates that if an induced current (eddy current) flows, its direction is always such that it will oppose the change that produced it. Lenz's law is well applied to the permanent magnet and moving conductive sheet in Fig. 2.13. The diagram of eddy currents (*I*, red) induced in a conductive metal sheet (*C*) moving under a stationary magnet (*N*) shows the directions of the induced currents. The magnetic field lines (*B*, green) from the North pole of the magnet extend down through the sheet. The increasing field at the leading edge of the magnet (left) causes the currents to circle counterclockwise. Thus, based on Lenz's law they create their own magnetic field directed upward which opposes the magnet's field, thus exerting a drag and lift effect on the magnet. Similarly, at the trailing edge of the magnet the decreasing magnetic field induces eddy currents that circle clock-wise. This creates a magnetic field directed downward which attracts the

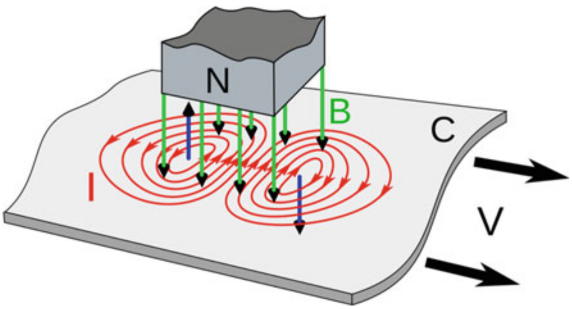



**Fig. 2.13** Diagram of eddy currents (*I*, *red*) induced in conductive metal sheet (*C*) moving under a stationary magnet

magnet, which also exerts a retarding force on the magnet. This is the principle of repulsive levitation in dynamic mode, with a moving magnet over a conductive sheet.

- **Inductance**: In electromagnetism and in electronics, inductance is the property of a conductor by which a change in current flowing through it induces (creates) a voltage (electromotive force) in both the conductor itself (self-inductance) and in any nearby conductors (mutual inductance). A changing electric current through a circuit that contains inductance induces a proportional voltage that opposes the change in current (self-inductance), as illustrated in Fig. 2.14. It is customary to use the symbol $L$ for inductance. The unit for inductance is the henry (H). The relationship among the parameters for a coil with an Inductance $L$ is defined as

$$V = IR - L\frac{dI}{dt} \tag{2.10}$$

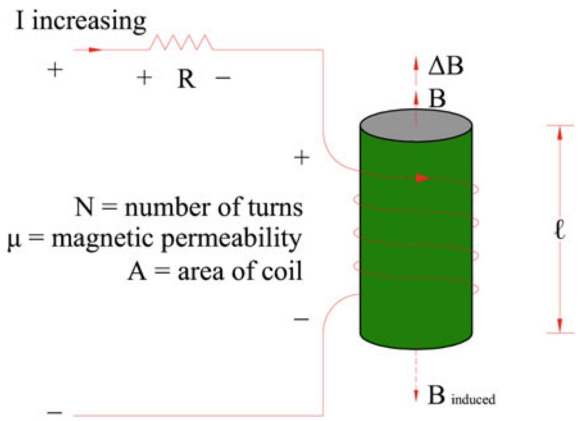
where

$$L = \frac{N^2 \mu A}{l}$$

Equation (2.10) indicates that Inductance opposes the applied voltage. This property to oppose building up currents influences the control performance of levitation systems with electromagnets.

- **Diamagnetic material**: Diamagnetic materials create an induced magnetic field in a direction that is opposite to an externally applied magnetic field, and are repelled by the applied magnetic field. Its magnetic permeability is less than $\mu_0$. In most materials, diamagnetism is a weak effect, but a superconductor repels the magnetic field entirely, apart from a thin layer at the surface.

**Fig. 2.14** Coil's reaction to increasing current



## 2.3 Electronics

In the implementation of maglev systems, some electrical equipment for power supply is combined with magnets and electric motors.

- **Chopper**: For the excitation of currents in an electromagnet, a chopper is used as a power amplifier. A chopper circuit is used to refer to numerous types of electronic switching devices and circuits used in power control and signal applications. A chopper is a switching device that directly converts fixed DC input to a variable DC output voltage. Essentially, a chopper is an electronic switch that is used to interrupt one signal under the control of another. For all the chopper configurations operating from a fixed DC input voltage, the average value of the output voltage is controlled by the periodic opening and closing of the switches used in the chopper circuit. The average output voltage can be controlled using different techniques. One of them is a PWM(pulse width modulation) technique. In the case of ECOBEE, the DC input voltage to a chopper operating in two quadrants is 350 V. A chopper circuit will be introduced in Sect. 5.5.10.
- **Inverter**: A power inverter, or inverter, is an electronic device or circuitry that changes direct current (DC) to alternating current (AC). The input voltage, output voltage and frequency, and overall power handling depend on the design of the specific device or circuitry. In maglev systems, VVVF (variable voltage variable frequency) inverters are used to drive linear motors and perform speed control.
- **Transformer and battery**: As in many electrical system, transformers and batteries are commonly used in maglev systems.

## 2.4 Mechanics

A maglev system consisting of mechanical and electrical components can be characterized as a dynamic system. In particular, the attractive maglev system with electromagnets may be treated as a forced vibration problem. The fundamentals of vibration analysis can be understood by studying the simple mass–spring–damper model. Indeed, even a complex structure such as a maglev train can be modeled as a "summation" of simple mass–spring–damper model. Thus, it may be useful to understand mechanical vibration for the design, analysis and control of a maglev system. Vibration is a mechanical phenomenon in which oscillations occur about an equilibrium point. There are two types of vibration, which are free and forced vibration. Free vibration occurs when a mechanical system is set off with an initial input and then allowed to vibrate freely. The mechanical system will then vibrate at one or more of its "natural frequencies" and damp down to zero. Forced vibration is when a time-varying disturbance (load, displacement or velocity) is applied to a mechanical system. For a maglev vehicle, the exciting electromagnet and uneven guideway surface profile are the main disturbances.

- **Free vibration without damping**: To start the investigation of the mass–spring–damper (Fig. 2.15), the damping is assumed to be negligible, and there is no external force applied to the mass (i.e. free vibration). The force applied to the mass by the spring is proportional to $x$ (m) of deflection.

$$F_s = -kx \quad (N) \tag{2.11}$$

where $k$ is the stiffness of the spring and has units of force/distance (N/m). The negative sign indicates that the force is always opposing the motion of the mass attached to it. According to Newton's second law of motion, the acceleration of the mass $m$ (kg) is related to the force generated by the spring.

$$\sum F = F_s = ma = m\ddot{x} = m\frac{d^2x}{dt^2} \tag{2.12}$$

$$m\ddot{x} + kx = 0 \tag{2.13}$$

The solution of Eq. (2.13) has the form of $x(t) = A\cos(2\pi f_n t)$. This solution says that it will oscillate with a simple harmonic motion that has an amplitude of $A$ and a frequency of $f_n$ (Hz). $f_n$ is called the undamped natural frequency. For the simple mass–spring system, $f_n$ is defined as:

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \tag{2.14}$$

In maglev systems, the natural frequency of the system may be determined by the relations described above. The concern is to obtain $k$ from the magnet's force-airgap characteristic for excursions around its nominal position. This may be achieved through the calibration of experimental or analytical force-airgap data.

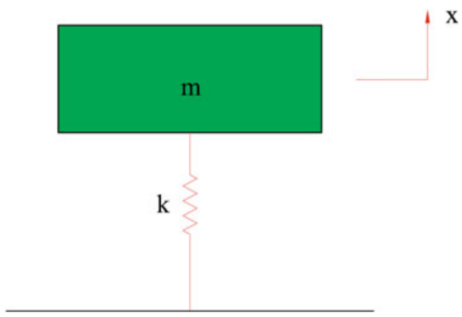



**Fig. 2.15** Mass-spring system without damping

- **Free vibration with damping**: Force by any damping element with damping coefficient $c$ (Ns/m) is determined by

$$F_d = -cv = -c\dot{x} = -c\frac{dx}{dt} \tag{2.15}$$

The resulting equation of motion of the system in Fig. 2.16 is expressed as:

$$m\ddot{x} + c\dot{x} + kx = 0 \tag{2.16}$$

This equation has the form of solution:

$$x(t) = Xe^{-\zeta\omega_n t}\cos(\sqrt{1-\zeta^2}\omega_n t - \phi), \omega_n = 2\pi f_n \tag{2.17}$$

where

| | |
|---|---|
| $X$ | initial position |
| $\zeta = \frac{c}{c_c}$ | damping ratio |
| $c_c = 2\sqrt{km}$ | critical damping |
| $\phi$ | phase shift |

The frequency in this case is called the "damped natural frequency", $f_d$ and is related to the undamped natural frequency by the following formula:

$$f_d = f_n\sqrt{1-\zeta^2} \tag{2.18}$$

What is often done in practice is to experimentally measure the free vibration after an impact (such as by a hammer) and then determine the natural frequency of the system by measuring the rate of oscillation as well as the damping ratio by measuring the rate of decay. The natural frequency and damping ratio are not only important in free vibration, but also characterize how a system will behave under forced vibration.

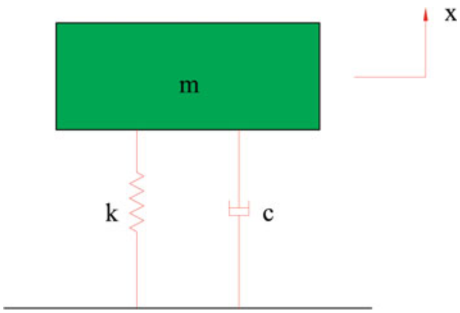



**Fig. 2.16** Mass-spring-damper model

- **Forced vibration with damping**: The dynamic behavior of the mass-spring-damper system varies with applied force. If the external force is assumed to be

$$F = F_0 \sin(2\pi ft) \tag{2.19}$$

Summing all the forces on the mass, the equation of motion leads to:

$$m\ddot{x} + c\dot{x} + kx = F_0 \sin(2\pi ft) \tag{2.20}$$

The solution of the equation in steady-state can be written as:

$$x(t) = X \sin(2\pi ft) \tag{2.21}$$

The solution indicates that the mass will oscillate at the same frequency, $f$, of the applied force, but with a phase shift $\phi$. The amplitude of the vibration "$X$" is defined by the following formula.

$$X = \frac{F_0}{k} \frac{1}{\sqrt{(1 - r^2)^2 + (2\zeta r)^2}} \tag{2.22}$$

where "$r = f/f_n$" is defined as the ratio of the harmonic force frequency over the undamped natural frequency of the mass–spring–damper model. The phase shift, $\phi$, is defined by $\phi = \arctan(2\zeta r/(1 - r^2))$. The plot of these functions in Fig. 2.17, called "the frequency response of the system," presents one of the most important features in forced vibration. In a slightly damped system, when the forcing frequency nears the natural frequency (r $\approx$ 1), the amplitude of the vibration can become extremely high. This phenomenon is called resonance (subsequently, the natural frequency of a system will often be referred to as the resonant frequency). In any maglev system, a time-varying disturbance with a speed that excites a resonant frequency is referred to as a critical speed. If resonance occurs in a mechanical system it can be very harmful. Consequently,

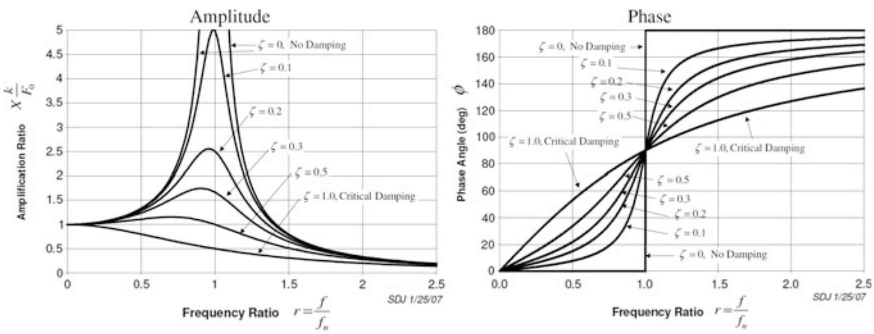



**Fig. 2.17** Frequency response of a mass-spring-damper system

one of the major reasons for vibration analysis is to predict when this type of resonance may occur, and then to determine what steps to take to prevent it from occurring. As the amplitude plot shows, adding damping can significantly reduce the magnitude of the vibration. The magnitude can also be reduced if the natural frequency can be shifted away from the forcing frequency by changing the stiffness or mass of the system. If the system cannot be changed, perhaps the forcing frequency can be shifted. These vibration characteristics and stabilization techniques can be equally applied to maglev systems.

Multiple degrees of freedom systems (MDOF) and mode shapes: In more complex systems, the system must be discretized into more masses which are allowed to move in more than one direction—adding degrees of freedom. Equations of motions of a MDOF can be in a matrix form, as in the following:

$$[\mathbf{M}]\{\ddot{\boldsymbol{x}}\} + [\mathbf{C}]\{\dot{\boldsymbol{x}}\} + [\mathbf{K}]\{\boldsymbol{x}\} = \{\boldsymbol{f}\} \tag{2.23}$$

where $[\boldsymbol{M}], [\boldsymbol{C}], \text{and} [\boldsymbol{K}]$ are symmetric matrices referred to respectively as the mass, damping, and stiffness matrices. The matrices are $N \times N$ square matrices where $N$ is the number of degrees of freedom of the system. If there is no damping and applied force (i.e. free vibration), the solutions of the system may be assumed to have the form of:

$$\{\boldsymbol{x}\} = \{\boldsymbol{X}\}e^{i\omega t} \tag{2.24}$$

With this solution, the system equations of motion Eq. (2.24) becomes

$$\left[-\omega^2[\boldsymbol{M}] + [\boldsymbol{K}]\right]\{\boldsymbol{X}\}e^{i\omega t} = 0 \tag{2.25}$$

Since $e^{i\omega t}$ cannot be zero, the equation reduces to the following.

$$\left[[\boldsymbol{K}] - \omega^2[\boldsymbol{M}]\right]\{\boldsymbol{X}\} = 0 \tag{2.26}$$

This equation becomes an eigenvalue problem. It can be put in the standard format by pre-multiplying the equation by $[\boldsymbol{M}]^{-1}$.

$$\left[[\boldsymbol{M}]^{-1}[\boldsymbol{K}] - \omega^2[\boldsymbol{M}]^{-1}[\boldsymbol{M}]\right]\{\boldsymbol{X}\} = 0 \tag{2.27}$$

If $[\boldsymbol{M}]^{-1}[\boldsymbol{K}] = \{\boldsymbol{A}\}$ and $\lambda = \omega^2$, the resulting eigenvalue problem is obtained as:

$$[[\boldsymbol{A}] - \lambda[\boldsymbol{I}]\{\boldsymbol{X}\}] = 0 \tag{2.28}$$

The solution to the problem results in $N$ eigenvalues (i.e. $\omega_1^2, \ldots, \omega_N^2$), where $N$ corresponds to the number of degrees of freedom. The eigenvalues provide the natural frequencies of the system. When these eigenvalues are substituted back into the original set of equations, the values of $\{X\}$ that correspond to each

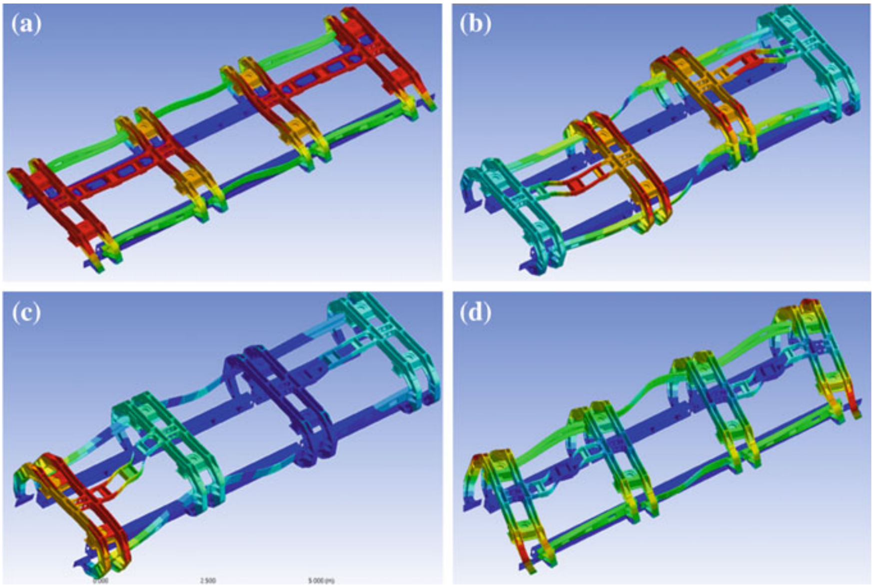



**Fig. 2.18** Vibration mode shapes

eigenvalue are called the eigenvectors. These eigenvectors represent the mode shapes of the system. Since manually deriving the eigenvalues and eigenvectors for a large scale system may be too time consuming or involved, FEM programs are widely used. As an example, Fig. 2.18 shows a set of vibration modes of the experimental maglev vehicle, in Sect. 5.3, obtained by a FEM program. Understanding the vibrational characteristics of MDOFs is more important for the stabilization of electromagnetic systems. This topic will be discussed in Chap. 5.

## 2.5 Control and Measurement

Especially in electromagnetic suspension systems, taking the measurements of position, velocity and acceleration for the feedback control loop is the first stage from an operational viewpoint. Once the needed signals are measured, after appropriate signal processing, they are input to a control loop. The fundamentals in levitation controller design and its implementation are briefly outlined in this section.

- **Sensors**: For maglev systems, contactless transducers are required for the measurement of position, velocity, and acceleration. In practice, position sensors and accelerometers are mostly used, especially in vehicles. The criteria for selecting a suitable transducer include bandwidth, robustness and stability under all operating conditions, linearity over the operating range, and immunity from noise, radiation and stray magnetic fields. Among the various contact position sensors, inductive transducers are outlined here because of their wide use in low-speed maglev vehicles. This transducer consists of two coils wound on a form of non-magnetic material, the primary coil being energized by an alternating current. The magnetic field produced by the primary coil induces eddy current in the metal track. The eddy current induced, in turn, produces a magnetic field, which results in an induced voltage in the secondary coil. As the track moves closer to the secondary coil, the opposing eddy-current field increases, and the output of the secondary coil is reduced. Through the use of an appropriate feedback control circuit, the output of the transducer can be made linear, from 0 to 20 mm clearance. The bandwidth of this device is dependent on the carrier frequency. When such devices are used with ferromagnetic track as target material, however, unacceptable transient responses for steps or gaps at rail joints may result. To overcome this problem, a pair of gap sensors may be used with a switching logic for selecting a normal signal. The sensing element of an accelerometer usually consists of a mass-spring-damper system that deflects when subjected to acceleration in the direction of its sensitive axis. The deflection of the seismic mass is a linear function of applied acceleration, according to Newton's second law, within the constraints imposed by the natural frequency and the damping ratio of the seismic system. The natural frequency and damping ratio of the devices are determined by mass, stiffness of spring equivalent, and damping in the device. Piezoelectric accelerometers are also available for the feedback control loop. In these accelerometers, the sensing element is a small disc of piezoelectric material that generates an electric charge when it is compressed or extended by a mass. Primary selection criteria for accelerometers are frequency response and range. For most accelerometers, bandwidth is dependent on the range of operating acceleration levels. In maglev vehicles, the range of 3 to 5 g may be chosen, though acceleration during normal operation is not expected to be higher than 0.1 g. Consequently, in selecting adequate sensors one must consider the factors of the particular application.

- **Transfer function:** The transfer function of a linear system is defined as the ratio of the Laplace transformation of the output variable to the Laplace transform of the input variable, with all initial conditions assumed to be zero. The transfer function of system *G(s)*, shown in Fig. 2.19, represents the relationship describing the dynamics of the system under consideration. It is expressed as follows:

$$G(s) = \frac{\textit{Laplace transform of output variable } y(t)}{\textit{Laplace transform of input variable } r(t)} = \frac{Y(s)}{R(s)}$$

$$G(s) = \frac{b_0 s^m + b_1 s^{m-1} + \cdots + b_{m-1} s + b_m}{a_0 s^n + a_1 s^{n-1} + \cdots + a_{n-1} s + a_n} \tag{2.29}$$

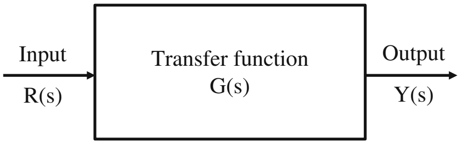



**Fig. 2.19** Transfer function

- **Pole and zero**: The poles of the transfer function defined above are roots of the denominator polynomial, and the zeros are roots of the numerator polynomial. Poles significantly influence both steady-state and transient response. The effects of poles can be summarized as follows:
  - A system is stable if a pole is located in the left half-plane, whereas it is unstable if the pole is in the right half-plane.
  - When a pole lies in the left half-plane, the response decays rapidly as it moves away from the imaginary axis.
  - When a pole lies in the right half-plane, the response diverges rapidly as the pole moves away from the imaginary axis.
  - The frequency of a response increases as a pole moves away from the real axis.

  The influence of zero on the response of the system is transient. The influence can be summarized as follows:
  - Zero does not significantly affect the response when zero is placed far from the imaginary axis.
  - Overshoot increases as zero moves closer to the imaginary axis while zero is in the left hand-plane.
  - When overshoot on the down side appears, the magnitude increases as zero moves closer to the imaginary axis.
- **Bode plot**: A Bode plot is a very useful way to study a frequency response of the transfer function with analytic or experimental results. The transfer function in the frequency domain is

$$G(s = j\omega) = |G(\omega)|e^{j\phi(\omega)} \tag{2.30}$$

  where the units are decibels (dB). The logarithmic gain in dB and the angle $\phi(\omega)$ can be plotted versus the frequency $\omega$. Control bandwidth, Gain margin and Phase margin related to the Bode plot are important parameters for the stabilization of electromagnetic suspension. As an example, Bode plot for Butterworth filter is given in Fig. 2.20.
- **Filters**: The feedback control system of electromagnetic systems needs signal processing to accurately derive airgap, velocity or acceleration from the sensor output signals. In signal processing, a filter is a device or process that removes some unwanted component or feature from a signal. Filtering is a class of signal

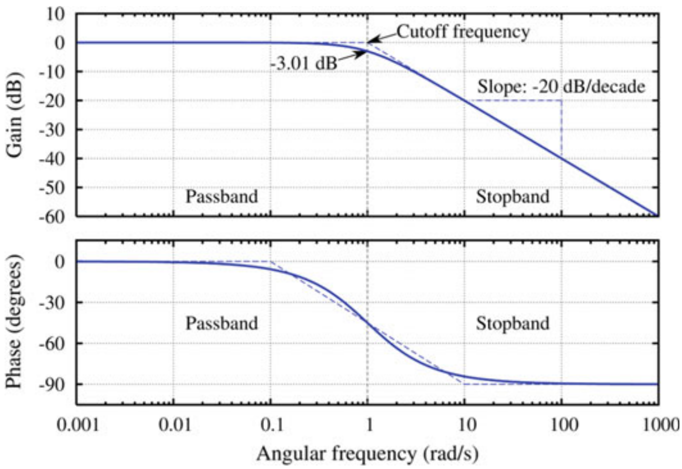



**Fig. 2.20** Exemplary Bode plot for Butterworth filter

processing, the defining feature of filters being the complete or partial suppression of some aspect of the signal. Most often, this means removing some frequencies and not others in order to suppress interfering signals and reduce background noise. The frequency response of filters can be classified into a number of different bandforms, as shown in Fig. 2.21, describing which frequency bands the filter passes (the passband) and which it rejects (the stopband). Cutoff frequency is the frequency beyond which the filter will not pass signals. It is usually measured at a specific attenuation, such as 3 dB. Roll-off is the rate at which attenuation increases beyond the cut-off frequency. Transition band is the (usually narrow) band of frequencies between a passband and stopband. Ripple is the variation of the filter's insertion loss in the passband. The parameters such as cutoff frequency must be chosen based on considerations for the particular system. Deriving accurate signals is the primary work in levitation stabilization.

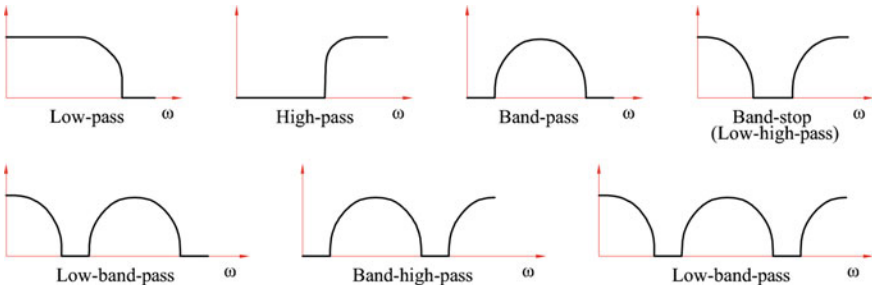



**Fig. 2.21** Filter bandform diagrams

- **Numerical differentiation**: In the implementation of a control loop, one may need derivatives of a signal, like airgap, using numerical analysis techniques. Taylor series expansions are most commonly employed to derive these. Since those are well known formulas, the resulting ones are just given here. The well-known linearization technique is the same as the following centered finite-divided difference formulas of first derivatives. Because errors in approximations depend on step size (time step), the step size must be verified by evaluating errors. The following numerical differentiation formula are well illustrated in Fig. 2.22.

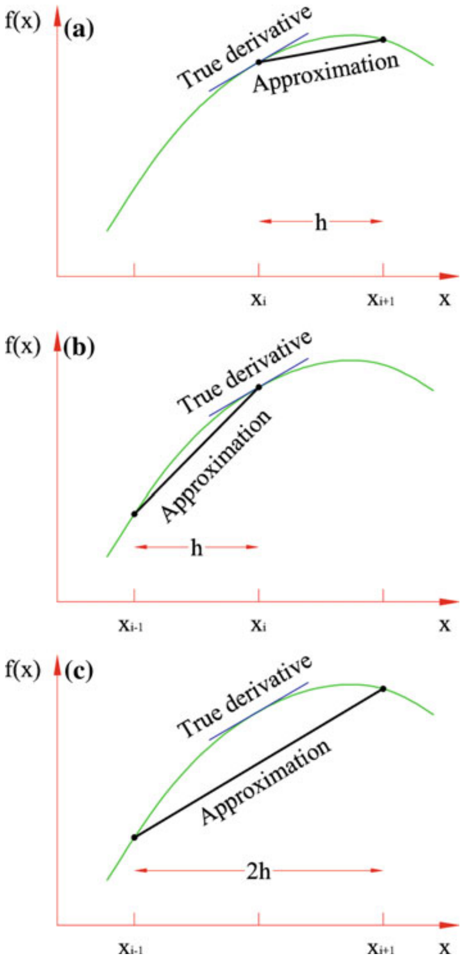



**Fig. 2.22** Graphical depiction: **a** forward, **b** backward, and **c** centered finite-divided-difference approximations of the first derivative

– Forward finite-divided difference formulas:
First derivative

$$f'(x_i) = \frac{f(x_{i+1}) - f(x_i)}{h}$$

Second derivative

$$f''(x_i) = \frac{f(x_{i+2}) - 2f(x_{i+1}) + f(x_i)}{h^2}$$

Third derivative

$$f'''(x_i) = \frac{f(x_{i+3}) - 3f(x_{i+2}) + 3f(x_{i+1}) - f(x_i)}{h^3}$$

– Backward finite-divided-difference formulas:
First derivative

$$f'(x_i) = \frac{f(x_i) - f(x_{i-1})}{h}$$

Second derivative

$$f''(x_i) = \frac{f(x_i) - 2f(x_{i-1}) + f(x_{i-2})}{h^2}$$

Third derivative

$$f'''(x_i) = \frac{f(x_i) - 3f(x_{i-1}) + 3f(x_{i-2}) - f(x_{i-3})}{h^3}$$

– Centered finite-divided difference formulas:
First derivative

$$f'(x_i) = \frac{f(x_{i+1}) - f(x_{i-1})}{2h}$$

Second derivative

$$f''(x_i) = \frac{f(x_{i+1}) - 2f(x_i) + f(x_{i-1})}{h^2}$$

Third derivative

$$f'''(x_i) = \frac{f(x_{i+2}) - 2f(x_{i+1}) + 2f(x_{i-1}) - f(x_{i-2})}{2h^3}$$

- **Integration of differential equations**: Dynamics equations describing maglev systems are a type of differential equation, i.e. $y'(x,t) = f(x,t)$, and thus the solutions for them are usually derived through a numerical integration scheme. Though there is a wide numerical integration scheme, only Euler's method, a one-step method, and the Runge-Kutta method, a multistep method, are summarized because they are most frequently used in maglev systems. Because errors in approximations depend on step size (time step $h$), the step size must also be verified by evaluating errors.
  - Euler method:

$$y_{i+1} = y_i + f(x_i, y_i)h, f(x_i, y_i) = dy/dx \tag{2.31}$$

  - Fourth-order Runge-Kutta method:

$$y_{i+1} = y_i + \frac{1}{6}(k_1 + 2k_2 + 2k_3 + k_4)h \tag{2.32}$$

where

$$\begin{aligned} k_1 &= f(x_i, y_i) \\ k_2 &= f(x_i + \frac{1}{2}h, y_i + \frac{1}{2}k_1 h) \\ k_3 &= f(x_i + \frac{1}{2}h, y_i + \frac{1}{2}k_2 h) \\ k_4 &= f(x_i + h, y_i + k_3 h) \end{aligned}$$

## 2.6 Linear Motors

Once a system is levitated, linear motors are naturally chosen to propel it. Of the various available types, LIM (linear induction motor)and LSM(linear synchronous motor) appear to be the most suitable for maglev systems.

Linear motors can be conceptually described as unrolled versions of the familiar rotary machine. This means that the design and operation features of linear motors are the same as those of rotary motors. For this reason, it is recommended to refer to the literature on rotary machines. The application of linear motors to vehicles is given in subsequent chapters. Three possible configurations of LIMs in Fig. 2.23 can be used in any maglev system. Stator (primary) or rotor (secondary) can be installed on a moving object or fixed guideway, and vice versa. These configurations offer considerable simplicity in determining the guideway installation cost. The principle of a LIM in use for urban maglev vehicles is conceptually

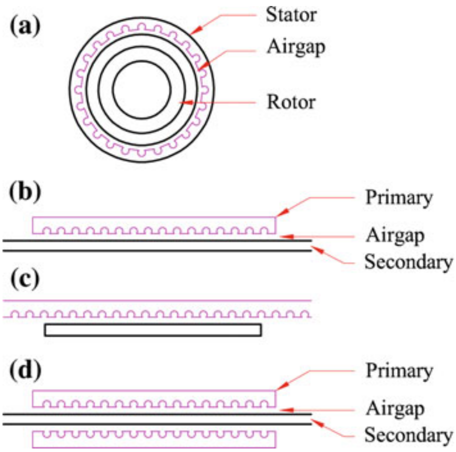



**Fig. 2.23** Transformation of rotary induction motors into linear versions: **a** drag cup rotary, **b** single-sided linear: short stator, **c** single-sided linear: long stator, **d** double-sided linear with two short stator windings

demonstrated in Fig. 2.24. The interaction between the traveling magnetic field of the 3-phase winding on-board and the field produced by eddy-currents in the aluminum plate on guideway, induced by the traveling magnetic field, gives thrust to accelerate vehicle. The magnitude of the thrust can be controlled with varying the current and excitation frequency in the 3-phase winding (primary). The reactive power of LIM is usually high, and goes up as the airgap increases, reducing its power factor. This makes these motors well suited for attraction type system with airgaps around 15–20 mm. LSM consists of multiphase iron- or air-cored winding and field magnets, which are permanents or electromagnets. For the combination of iron-cored winding and an electromagnet as a field magnet, the principle of thrust is illustrated in Fig. 2.25. The three-phase winding can propel a vehicle that travels in synchronism with the electromagnetic wave. The slip speed is zero, but there is a current angle ($\theta$, Fig. 2.25), which indicates the position of the vehicle with respect to the travelling wave, the thrust being maximum when $\theta = 90°$. By controlling the current and frequency of the primary excitation, as a function of the current angle,

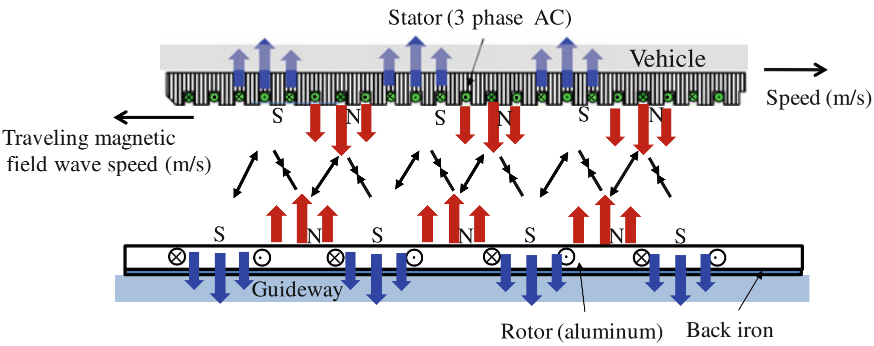



**Fig. 2.24** Principle of a LIM for use in urban maglev vehicle

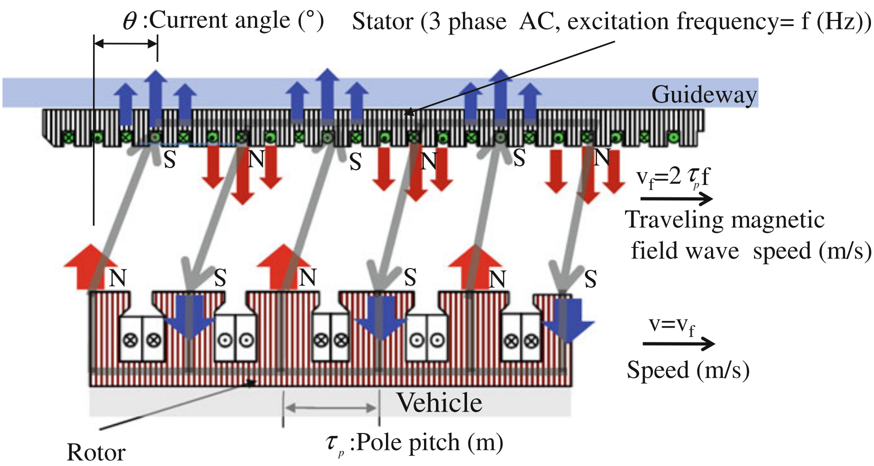



**Fig. 2.25** Principle of a LSM for use in high-speed maglev vehicle

the desired longitudinal speed/acceleration may be obtained. In addition, since θ also influences the vertical force, it may be used to introduce additional damping into the suspension loops. The winding configuration of the primary (armature) and the secondary (field coil) as well as wavelength/pole pitch are key important parameters of this system which is estimated to have an overall efficiency of around 85 %. Although ideally suited for large airgaps, the LSM may also be used with the attraction system in which the airgaps are likely to be below 25 mm. In maglev vehicles currently in service, LIM is being used for low-to-medium speeds, with LSM being used for high speeds.

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