Chapter 1

Introduction

1.1 INTRODUCTION

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As human beings have evolved from anthropoid species that lived in Africa several millions years ago, solving basic needs for food, clothing, and shelter have been the great concern for all humankind. As the living standard of humankind is being upgraded, the quantity of commodities is increased. All of these commodities are obtained by manufacturing natural resources or by recycling existing resources. In those processes, energy is indispensable. The civilization of human culture has evolved according to the source and form of energy. The farming culture was possible because of the energy and power of animals. The Industrial Revolution started with the invention of the steam engine in the 18th century. Since the invention of the internal combustion engine (ICE) in the 19th century, the productivity of the manufacturing has been greatly increased. In the 19th century, when electric machinery was invented, the mechanical power of the electric machine was the best source of the mechanical power that humankind ever had. It is the most widely used source of mechanical power excluding transportation area. Though the total efficiency of electricity from primary energy source to final stage is, at best, 40%, the electricity is the most convenient energy source to control and to convert to other form. Consequently, electromechanical power based on an electric machine is the basic source of mechanical power to support today's industrialized society. Recently, even in the transportation area, where the internal combustion engine has dominated for the past 100 years as a source of mechanical power, electric machines are applied as a main source of traction force in the electric vehicle, the hybrid vehicle, and the electrically propelled vessels. Through continuation of this trend, before the end of the first half of the 21st century, most of the mechanical power could be obtained from electromechanical power conversion.

Electric machinery has the following advantages compared to ICE and the gas turbine [1].

1. From an electric machine to run an electric watch to the electric machine to drive the pump of hydro pump storage, the power range can be extended from milliwatts to hundreds of Megawatts.

Control of Electric Machine Drive Systems, by Seung-Ki Sul

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2. From a high-speed centrifugal separator machine running at over several hundred thousand revolutions per minute to a main mill machine in a steel process line generating over several tens of Mega Newton-meters, the operating range of speed and torque is very wide.
3. An electric machine can be easily adapted to any external environment such as vacuum, water, and extreme weather condition. Compared to an internal combustion engine, it is emissionfree in itself, has less vibration and audible noise, and is environmental friendly.
4. The response of an electric machine is faster than that of an internal combustion engine and a gas turbine by at least 10 times.
5. The running efficiency is higher, and no load or standby loss is smaller.
6. The direction of force (torque) and movement (rotation) can be easily changed.
7. The force (torque) can be easily controlled regardless of the direction of movement (rotation).
8. An electric machine can be designed in various shapes such as thin disk type, long cylinder type, rotating type, and linear motion type. And it can be easily attached to the right place where mechanical power should be applied.
9. Its input is electricity and the control system of an electric machine is easily compatible with modern information processing devices.

The abovementioned advantages of the electric machine over the ICE and the gas turbine have been intensified with the development of power electronics, magnetic and insulation materials, and information technology. Especially with the recent progress of the rare earth magnet such as the niodium–iron–boron magnet, the force (torque) density of the electric machine is comparable to a hydraulic system. And, the many motion control systems based on hydraulic pressure are replaced with an electric machine. Moreover, with the development of power electronics, the electric machine drive system can be easily controlled directly from the information processing system, and the drive system would be automated without additional hardware. However, regardless of these merits of the electric machine, it has been applied to a very limited extent to the traction force of the transportation system because of its continuous connection to the utility line. Recently, to lessen the pollution problem of the urban area, the electric vehicle is getting attention; but because of the limited performance of the battery as an energy storage, it would take considerable time to use the pure electric vehicle widely. In these circumstances a hybrid electric vehicle, where after getting mechanical power from an ICE a part or all of the power from ICE is converted to electric power to run the electric machine, has been developed and has had practical use in the street.

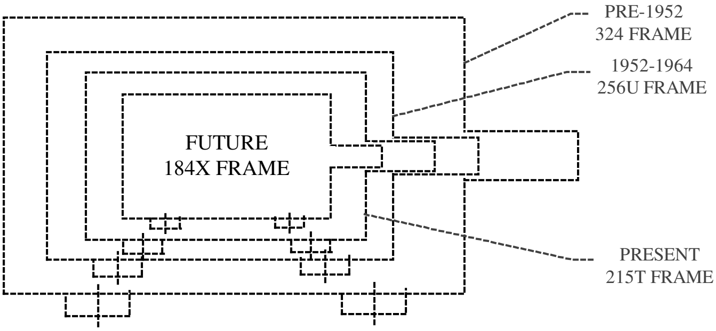
After Jacobi invented a DC machine in 1830 and Ferraris and Tesla invented an induction machine, the electric machine has been a prime source of mechanical power for the past 150 years. In modern industrialized society, more than 60% of electricity is used to run electric machines. Among them, more than 80% are used for induction machines [2]. The induction machine based on the rotating magnetic motive force

Figure 1.1 Induction machine at early stage of development.

Figure 1.2 Today's Induction machine.

during the early days of development is shown in Fig. 1.1, while in Fig. 1.2 a modern induction machine is shown. Due to the developments of the insulation materials and the magnetic materials, the power density, which is defined as the ratio between output power and weight, and the price has been remarkably improved. In 1890, the weight and price of a 5-horsepower (Hp) induction machine were 454 kg and \$900; in 1957, 60 kg and \$110; and in 1996, 22 kg and \$50 [3].

In Fig. 1.3, there are several outer sizes of a 10-hp, 4-pole, totally enclosed induction machine according to years [4]. These trends of smaller size and less weight would be continued, and the efficiency of the machine would be improved continuously to save electricity for a better environment. Ever since the induction machine



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324	343
256	267
215	222
184	191

Figure 1.3 Outer sizes of general-purpose, 10-hp, 4-pole, totally enclosed induction machines [4].

was invented 80 years ago, it had been run by a 50-Hz or 60-Hz utility line, and its rotating speed is almost constant. However, after the invention of the thyristor in 1960, the input voltage and frequency to the machine could be changed widely, and the machine itself has been designed to adapt to these variable voltage variable frequency (VVVF) sources [5].

1.1.1 Electric Machine Drive System [6]

An electric machine drive system usually consists of several parts such as driven mechanical system, electric machine, electric power converter, control system, and so on. For the design of the drive system, several other things including the electric machine itself should be considered as shown in Fig. 1.4. As usual engineering design, the drive system showing the same performance could be implemented in various ways. The final criterion for the best design would be not only economic reasons such as initial investment, running cost, and so on, but also noneconomic reasons such as environmental friendliness, ethics, and regulations. Recently, because of the concern of engineering to the social responsibility, the noneconomic reasons are becoming important.

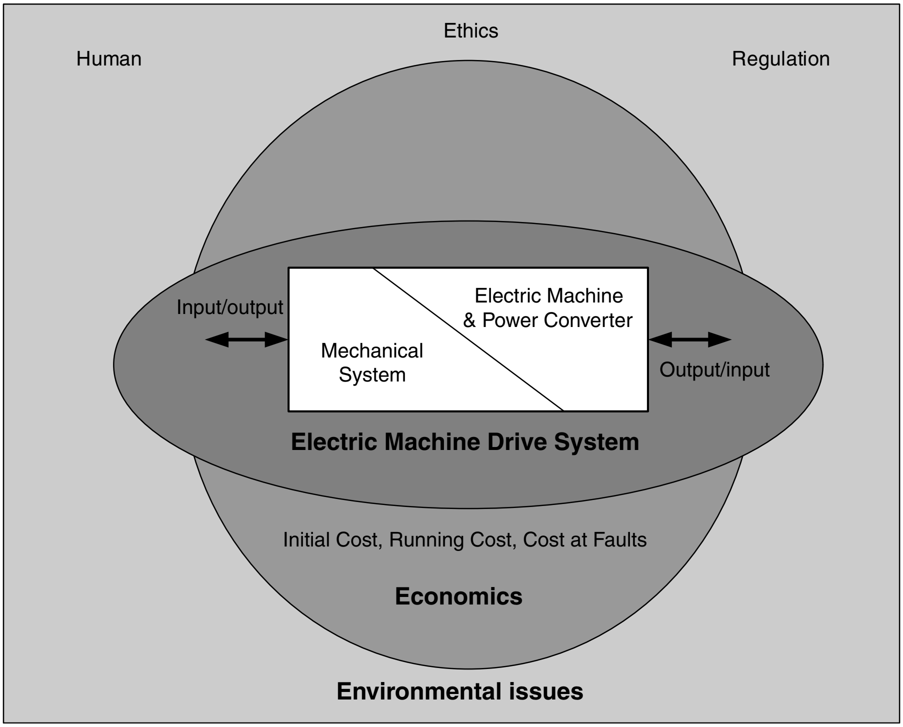


Figure 1.4 Consideration points in designing the electric machine drive system [6].

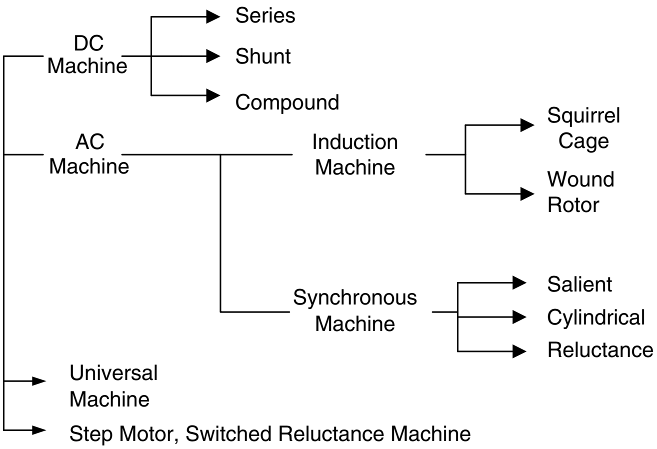


Figure 1.5 Classification of the electric machine according to power source and operating principles.

Through 100 years of development, the electric machines have diverse shapes, and a suitable shape is applied to the specific area according to the purpose of the machines. The machines can be classified as a rotary motion machine and a linear motion machine according to the motion of the rotor (mover). Also, if the machine is classified according to the electric source and operating principles of the machine, it can be classified as shown in Fig. 1.5. For typical rotational motion machine, the range of the output power and rotating speed has the relationship as shown in Fig. 1.6 [6]. If the output power of the machine is getting larger, the size, especially radius of the rotor, of the machine is larger and the centrifugal force is getting larger. Hence, a high-power and simultaneously high-speed machine is extremely difficult to make because of limited yield strength of rotor materials. Recently, with the development of computer-aided design techniques and the developments of materials, especially permanent magnet materials, a high-speed and high-power machine is appearing in some special applications such as turbo compressor [7], flywheel energy storage, and so on. And the range of the output power and speed of the permanent magnet synchrounous machine will be extended further.

1.1.2 Trend of Development of Electric Machine Drive System

In the past, due to convenience of torque and speed control, the DC machine had been used widely for adjustable speed drive (ASD). However, recently, with the development of power electronics technology, the AC machine drive system such as the induction machine and the synchronous machine driven by a variable voltage variable frequency (VVVF) inverter have been used widely. The inverter can replace the commutuator and brush of DC machine, which need regular maintenance and

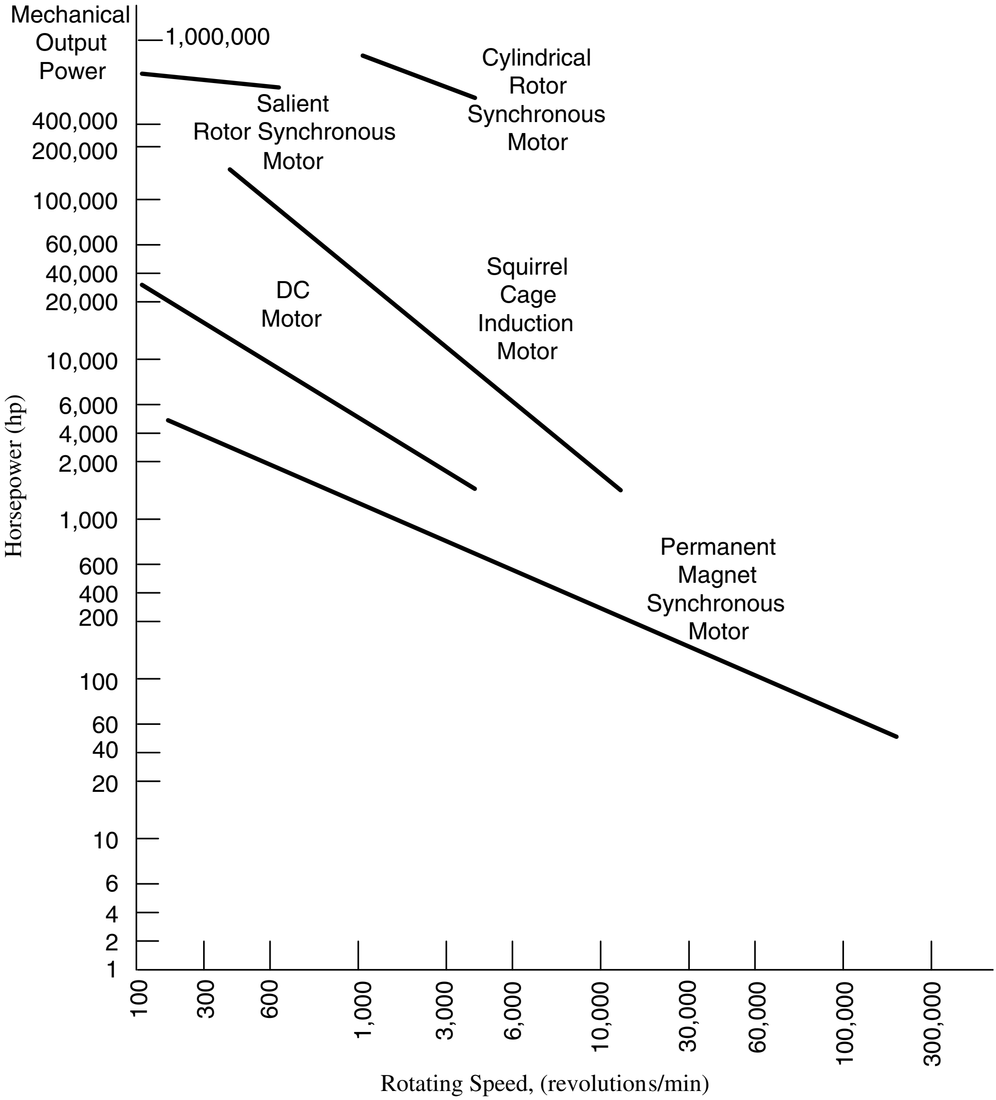


Figure 1.6 Boundary of speed and output power of rotating machines [6].

are the weak points of a DC machine. And this trend—the shift from DC machine to AC machine—would be continued because of the developmenent of not only the previously mentioned power electronics but also the control theory of AC machine such as field orientation control. In early times, DC and AC machines, both received the field flux from separated field windings. The field fluxes of both the DC machine and the synchronous machine come from the current flowing field windings, while the field flux of the induction machine comes from the part of the stator current. But with the use of a high-performance reliable permanent magnet, even in a megawatt-range machine, the field flux of the machine comes from the remanence flux of the permanent magnet. By replacing separate field winding with the permanent magnet, the torque and power density of the machine can be increased; and, simultaneously, the efficiency of the machine can be improved by eliminating the copper loss of the field winding. This trend—change from the field flux from external winding to the flux from the permanent magnet—would be continued. So, in the future, an AC machine with a permanent magnet will be used more widely.

In the beginning of the 20th century, because the price of the electric motor and its associated control system was very expensive, a large electric motor was used in the whole factory, and the mechanical power from the motor was distributed to every mechanical machine where the mechanical power is needed through gears and belts. According to the reduction of the price of the electric motor and the control system, an electric motor was used in each mechanical machine, which has several motions, and still the mechanical power from the motor was transmitted and converted to an appropriate form at each point of the motion in the machine. Recently, even in a single mechanical machine, multiple electric motors are used at each motion point. The motion required at that point could be obtained by the motor directly without speed or torque conversion from the motor. In this way, the efficiency of the system can be enhanced; furthermore, the motion control performance can be improved by eliminating all nonlinear effects and losses such as backlash, torsional oscillation, and friction. In the future, this tendency could be continued and the custom designed motor could be used widely at each moving part. For example, for high-speed operation, the high-speed motor could be used without amplification of the speed through gears. For linear motion, a linear motor can be used without a ball screw mechanism. For high-torque low-speed traction drive, the direct drive motor can be applied to reduce the size and loss of the system.

The control method of the machine drive system has been developed from manual operation to automatic control system. Recently, intelligent control techniques have been used and the control system itself can operate the system at optimal operating conditions without human intervention. Also, in the early stages of automatic control of the machine drive system, the simple supervisory control was implemented, and the control unit transferred the operating command set by the user to the machine drive system. Through the direct digital control, right now, distributed intelligent control techniques are used widely in the up-to-date motion control system.

1.1.3 Trend of Development of Power Semiconductor

In the late 1950s, with the invention of the thyristor, power electronics was born. The power semiconductor was the key of the power electronics. With the rapid improvement of performance against cost of the power semiconductors, the power electronics technology improved in a revolutionary way. The original thyristors of the 1950s and 1960s could only be turned on by an external signal to the gate but should be turned off by the external circuits. And it needs a complicated forced commutating circuit. In the

1970s, the gate turn-off (GTO) thyristor had been commercialized. And the GTO thyristor could be not only turned on but also turned off by external signal to the gate of the semiconductor. In the late 1970s, the bipolar power transistor opened a new horizon of the control of power because of its relatively simple on and off capabilities. With the transistor, general-purpose VVVF inverters had been commercialized and used in many ASD applications. Recently, with the introduction of the integrated gate controlled thyristor (IGCT) and the fifth-generation insulated gate bipolar transistor (IGBT) to the market, the performance of the electric machine drive system has been dramatically improved in the sense of output power of the system and the control bandwidth of the motion of the drive system. However, still, all the power semiconductors have been fabricated based on silicon, and its junction temperature has been limited up to 150°C in the most cases. Recently, the power semiconductor based on silicon carbide (SiC) has been introduced, and the operating temperature and operating voltage of the power semiconductor can be increased severalfold [8]. With this material, the semiconductor operating at above 300°C and at several thousand voltage can conduct several hundred amperes within one-tenth of the wafer size of the device made by silicon. In particular, the Schotky diode and field effect transistor (FET) based on SiC were the first devices in the field, and extraordinary performances of the devices have been reported.

1.1.4 Trend of Development of Control Electronics

In the early days of research and development, the control signal for the power semiconductors came from analog electronics circuits consisting of transistors, diodes, and R, L, C passive components. And, with the development of electronics technology, especially integrated circuit technology, the mixed digital and analog circuit consisting of operational amplifiers and TTL logic circuit was used. Recently, except for high-frequency switching power supplies, the major part of the power electronics system, especially the electric machine drive system, is controlled digitally by one or a few digital signal processors (DSP). Right now, a DSP chip can do over 1 gigaflop/s (one $\times 10^9$ floating point operation per second) [9], and versatile input and output (I/O) function can be achieved by the chip without any extra hardware. In the future, this tendency of full digital control with a single chip would be widespread because of the developments of microelectronics technology. The future control electronics for the power electronics system would be on a single chip, which can execute the complex algorithm based on the modern control theory in real time with a minimized extra measurement system. And it can accomplish the user's desire with minimum energy, and simultaneously it can adapt intelligently to the change of operating conditions and parameters of the plant under control.

1.2 BASICS OF MECHANICS

Electric machines are usually connected to mechanical system, and it converts the electrical energy to mechanical energy as a motor and converts mechanical energy to electrical energy as a generator. Hence, in these energy conversion processes, understanding of mechanics is essential.

1.2.1 Basic Laws [10]

1. A physical body will remain at rest, or continue to move at a constant velocity, if net force to the body is zero.
2. The net force on a body is proportional to the time rate of change of its linear momentum:

   $$f = \frac{d(Mv)}{dt} \tag{1.1}$$

   where M is the mass and v is the velocity of the body.
3. Whenever a particle A exerts a force on another particle B, B simultaneously exerts a force on A with the same magnitude in the opposite direction.
4. Between two particles, there is attractive force directly along the line of centers of the particles, and the force is proportional to the product of masses of the particles and inversely proportional to the square of distance of two particles:

   $$f = G\frac{M_1 M_2}{R^2} \tag{1.2}$$

   where M_1 and M_2 are the masses of the particles, R is the distance between two particles measured from the center to center of particle, and G is a proportional constant. When a particle is on the surface of earth, the force can be represented as $f = Mg$, where M is the mass of the particle and g is a gravitational constant.

1.2.2 Force and Torque [1]

In the linear motion system as shown in Fig. 1.7, the equation of the motion with external forces can be derived as (1.3) from (1.1):

$$f_d - f_L = \frac{d}{dt}(Mv) = M\frac{dv}{dt} + v\frac{dM}{dt} \tag{1.3}$$

If there is no change of the mass for the motion, which is true in the most of cases, (1.3) can be simplified as follows:

$$f_d - f_L = M\frac{dv}{dt} = M\frac{d^2 l}{dt^2} \tag{1.4}$$

where v is the velocity of the mass, and l is the moving distance.

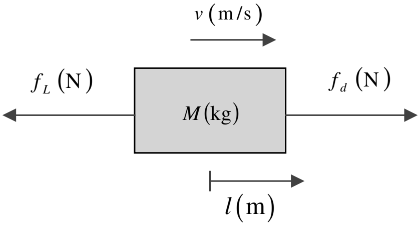


Figure 1.7 External forces in a linear motion system.

In rotating motion system as shown in Fig. 1.8, similar equation can be derived. In this equation, the rotational inertia, J, may vary according to the motion in some cases. Generally, to consider the variation of the inertia, (1.5) can be applied to the rotational motion.

$$\begin{aligned} T_d - T_L &= \frac{d}{dt}(J\omega) = J\frac{d\omega}{dt} + \omega\frac{dJ}{dt} \\ &= J\frac{d^2\theta}{dt^2} + \frac{d\theta}{dt}\frac{dJ}{dt} \end{aligned} \tag{1.5}$$

In many application cases of motion drives, as shown in Fig. 1.9 (which is a hoist drive), rotational motion and linear motion are coupled through some mechanical connections. In this system, the torque and the force have a relationship as shown in (1.6), considering gravitational force.

If there is no elongation of rope between mass, M, and sheave whose radius is r, and if the mass of rope is neglected, then (1.6) can be deduced:

$$T_d = J_{\text{sheave}}\frac{d\omega_m}{dt} + r\frac{d}{dt}(Mv) + Mgr \tag{1.6}$$

where J_{sheave} is the inertia of the sheave. The linear speed of the mass can be represented as $v = r\omega_m$. And if the radius of the sheave is constant, then from (1.6), we can derive (1.7):

$$\begin{aligned} T_d &= J_{\text{sheave}}\frac{d\omega_m}{dt} + r\frac{d(Mr\omega_m)}{dt} + Mgr \\ &= J_{\text{sheave}}\frac{d\omega_m}{dt} + Mr^2\frac{d\omega_m}{dt} + Mgr = J_{\text{sheave}}\frac{d\omega_m}{dt} + J_{\text{eq}}\frac{d\omega_m}{dt} + Mgr \end{aligned} \tag{1.7}$$

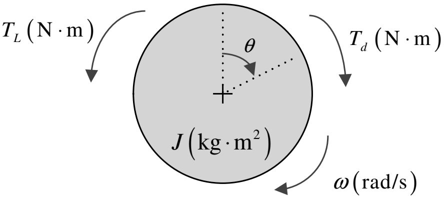


Figure 1.8 External torques in a rotating motion system.

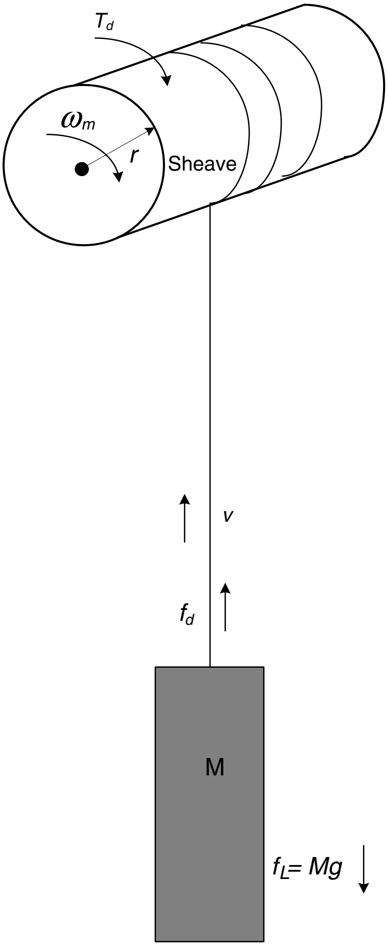


Figure 1.9 Coupling of linear and rotating motion.

where $J_{\mathrm{eq}} = Mr^2$. From (1.7), it can be seen that the mass, M, is converted to equivalent inertia, J_{eq}, at the rotational motion of sheave. And, similarly, the inertia in the rotational motion can be converted to equivalent mass in the linear motion, and it is called *equivalent inertia mass*.

1.2.3 Moment of Inertia of a Rotating Body [11]

The moment of inertia of the rotating body asymmetry to the rotating axis as shown in Fig. 1.10 can be deduced as follows. In general, every rotating body has some asymmetry to rotating axis. Hence, to find the force to the part supporting rotating motion such as bearings, the rotating inertia of arbitrary shape should be investigated.

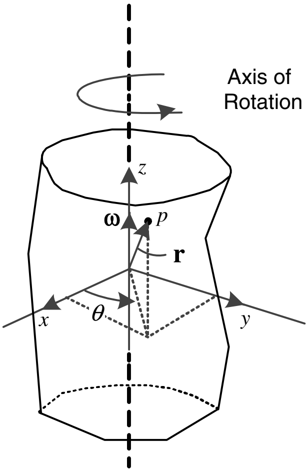


Figure 1.10 Asymmetric rigid rotating body.

$p(x, y, z)$ is the position of an infinitesimal mass, whose mass, δM, is expressed as (1.8). The position vector from the origin can be represented as (1.9). Also, the velocity vector, $\boldsymbol{\nu}$, of the mass is expressed as (1.10).

$$\delta M = \rho \delta V \tag{1.8}$$

where ρ is the density of body at $p(x, y, z)$ and δV is the volume of the infinitesimal mass at $p(x, y, z)$.

$$\mathbf{r} = \mathbf{i_x} x + \mathbf{i_y} y + \mathbf{i}_z z \tag{1.9}$$

where, $\mathbf{i_x}, \mathbf{i_y}$, and $\mathbf{i_z}$ are the unit vectors at each x, y, and z axis, respectively.

$$\boldsymbol{\nu} = \boldsymbol{\omega} \times \mathbf{r} \tag{1.10}$$

where $\boldsymbol{\omega}$ is the angular velocity vector, defined as $\boldsymbol{\omega} \equiv \frac{d\theta}{dt}\mathbf{i_z}$, of the infinitesimal mass, δM.

The accelerating force applied to the infinitesimal mass can be expressed as (1.11) from (1.1):

$$\delta \mathbf{f}_a = \frac{d}{dt}(\delta M \boldsymbol{\nu}) = \rho \delta V \frac{d\boldsymbol{\nu}}{dt} \tag{1.11}$$

By differentiating the velocity vector, $\boldsymbol{\nu}$, regarding time, (1.11) can be derived as (1.12) by using (1.10):

$$\delta \mathbf{f}_a = \rho \delta V \left[\frac{d\boldsymbol{\omega}}{dt} \times \mathbf{r} + \boldsymbol{\omega} \times (\boldsymbol{\omega} \times r) \right] \tag{1.12}$$

By using vector identity in (1.13), the force in (1.12) can be rewritten as (1.14):

$$\boldsymbol{\alpha} \times (\boldsymbol{\beta} \times \boldsymbol{\gamma}) = \boldsymbol{\beta}(\boldsymbol{\alpha} \times \boldsymbol{\gamma}) - \boldsymbol{\gamma}(\boldsymbol{\alpha} \times \boldsymbol{\beta}) \tag{1.13}$$

$$\delta \mathbf{f}_a = \rho \delta V \left[\frac{d\boldsymbol{\omega}}{dt} \times \mathbf{r} + \boldsymbol{\omega}(\boldsymbol{\omega} \cdot \mathbf{r}) - \mathbf{r}(\boldsymbol{\omega} \cdot \boldsymbol{\omega}) \right] \tag{1.14}$$

Because the torque vector is defined as the cross product of a force vector and a position vector as (1.15), the torque applied to the infinitesimal mass of the asymmetry body can be deduced as follows:

$$\delta \mathbf{T_e} = \mathbf{r} \times d\mathbf{f}_a \tag{1.15}$$

$$\delta \mathbf{T_e} = \rho \delta V \left[\mathbf{i}_z (x^2 + y^2) \frac{d^2\theta}{dt^2} - \mathbf{i}_x \left[xz \frac{d^2\theta}{dt^2} - yz \left(\frac{d\theta}{dt} \right)^2 \right] - \mathbf{i}_y \left[yz \frac{d^2\theta}{dt} + xz \left(\frac{d\theta}{dt} \right)^2 \right] \right] \tag{1.16}$$

where the inertia at each axis, with the assumption of rigid body, can be defined as

$$\begin{aligned} J_z &\equiv \int (x^2 + y^2) \rho \, dV \\ J_{xz} &\equiv \int xz\rho \, dV \\ J_{yz} &\equiv \int yz\rho \, dV \end{aligned} \tag{1.17}$$

where $\int_v \bullet \, dV$ means the integral of "•" over the entire volume, v.

Finally, the total torque vector applied to the whole body can be expressed as

$$\mathbf{T}_\mathrm{e} = \mathbf{i}_z J_z \frac{d^2\theta}{dt^2} - \mathbf{i}_x \left[J_{xz} \frac{d^2\theta}{dt^2} - J_{yz} \left(\frac{d\theta}{dt} \right)^2 \right] - \mathbf{i}_y \left[J_{yz} \frac{d^2\theta}{dt^2} + J_{xz} \left(\frac{d\theta}{dt} \right)^2 \right] \tag{1.18}$$

If the rotating body is symmetry to the rotating axis, then $J_{xz} = J_{yz} = 0$. So, (1.18) can be simplified as $\mathbf{T_e} = \mathbf{i}_z J_z \frac{d^2\theta}{dt^2}$. And only torque in **z** axis exists. In the case of asymmetry, there is always torque at **x** and **y** axes, and such torque would be applied to the parts supporting the rotating motion. It should be noted that as seen in (1.18) the torque due to asymmetry is proportional to the square of the rotating speed. Hence keeping symmetry to the rotating axis is getting important as the rotating speed is getting higher.

1.2.4 Equations of Motion for a Rigid Body

If a rigid body is acted upon by external forces and does not have any constraints, it shows a combinational motion of translation and rotation. This combinational motion of a rigid body can be represented by equations of motion that have six degrees of freedom (DOF): three independent axes for the translational motion and three independent axes for the rotational motion in a three-dimensional space. The acceleration of a body in each axis is expressed by a nonlinear combination of the external forces. This kinematic analysis of a rigid body is commonly used in the manufacturing equipment which requires highly precise motion control.

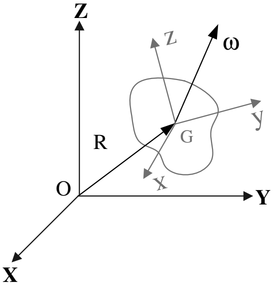


Figure 1.11 Inertial reference frame and body fixed reference frame.

In Fig. 1.11, a coordinate system for the kinematic analysis of a rigid body is shown. In the figure, *OXYZ* is an inertial reference frame that is attached to an absolute point and does not change its orientation to any external conditions. *oxyz* is a body fixed frame that is attached to the center of the mass of a rigid body, and it changes its orientation according to the rigid body's translational or rotational motion. *G* is the center of mass and also the center of rotation of the rigid body.

Euler angles that describe the rotational motion of a rigid body with three different angles are defined in Fig. 1.12. A rotation about the *Z* axis in the *XYZ* frame is defined as angle ψ, a rotation about the y_1 axis in the x_1y_1Z frame is defined as angle θ, and a rotation about the x_2 axis in the $x_2y_1z_2$ frame is defined as angle ϕ. The reference frame x_2yz is same as the body fixed frame xyz. Hence, any arbitrary rotation of a rigid body can be represented by (ϕ, θ, ψ).

The transformation matrix representing the rotation of a rigid body with Euler angle is shown in (1.19):

$\mathbf{u_X}, \mathbf{u_Y}, \mathbf{u_Z}$: Unit vector of **OXYZ** frame
$\mathbf{u_x}, \mathbf{u_y}, \mathbf{u_z}$: Unit vector of **oxyz** frame

$$\begin{bmatrix} \mathbf{u_X} \\ \mathbf{u_Y} \\ \mathbf{u_Z} \end{bmatrix} = \begin{bmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & -\sin\phi \\ 0 & \sin\phi & \cos\phi \end{bmatrix} \begin{bmatrix} \mathbf{u_x} \\ \mathbf{u_y} \\ \mathbf{u_z} \end{bmatrix} \tag{1.19}$$

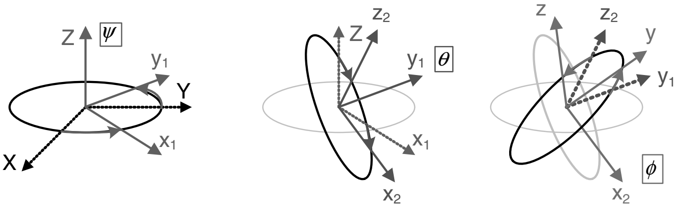


Figure 1.12 Euler angle(ϕ, θ, ψ).

From (1.19), we can derive (1.20):

$$\begin{bmatrix}\mathbf{u}_X\\ \mathbf{u}_Y\\ \mathbf{u}_Z\end{bmatrix}=\begin{bmatrix}\cos\theta\cos\psi & \cos\psi\sin\theta\sin\phi-\cos\phi\sin\psi & \cos\phi\cos\psi\sin\theta+\sin\phi\sin\psi\\ \cos\theta\sin\psi & \cos\phi\cos\psi+\sin\theta\sin\phi\sin\psi & -\cos\psi\sin\phi+\cos\phi\sin\theta\sin\psi\\ -\sin\theta & \cos\theta\sin\phi & \cos\theta\cos\phi\end{bmatrix}\begin{bmatrix}\mathbf{u}_x\\ \mathbf{u}_y\\ \mathbf{u}_z\end{bmatrix} \tag{1.20}$$

In (1.20), if all of the angles of rotation are small enough to approximate the value of sine function as the angle itself and the value of cosine function as unity, (1.20) can be approximated as a linearized matrix in (1.21):

$$\begin{bmatrix}\cos\theta\cos\psi & \cos\psi\sin\theta\sin\phi-\cos\phi\sin\psi & \cos\phi\cos\psi\sin\theta+\sin\phi\sin\psi\\ \cos\theta\sin\psi & \cos\phi\cos\psi+\sin\theta\sin\phi\sin\psi & -\cos\psi\sin\phi+\cos\phi\sin\theta\sin\psi\\ -\sin\theta & \cos\theta\sin\phi & \cos\theta\cos\phi\end{bmatrix}$$

$$\approx\begin{bmatrix}1 & -\psi & \theta\\ \psi & 1 & -\phi\\ -\theta & \phi & 1\end{bmatrix} \tag{1.21}$$

Using this simplified matrix, the relation between the unit vector of inertial reference frame and the unit vector of body fixed reference frame can be represented as (1.22):

$$\begin{bmatrix}\mathbf{u}_X\\ \mathbf{u}_Y\\ \mathbf{u}_Z\end{bmatrix}\approx\begin{bmatrix}1 & -\psi & \theta\\ \psi & 1 & -\phi\\ -\theta & \phi & 1\end{bmatrix}\begin{bmatrix}\mathbf{u}_x\\ \mathbf{u}_y\\ \mathbf{u}_z\end{bmatrix} \tag{1.22}$$

As mentioned earlier, if the center of mass is chosen as the center of rotation in a 6-DOF system, the equations of translational motion and rotational motion separately can be derived as (1.23) and (1.24):

$$\mathbf{F}=m\mathbf{a}+2m\mathbf{v}\times\boldsymbol{\omega} \tag{1.23}$$

$$\mathbf{T}_\mathbf{e}=\mathbf{J}\boldsymbol{\alpha}+\boldsymbol{\omega}\times\mathbf{J}\boldsymbol{\omega} \tag{1.24}$$

where $\mathbf{J}=\begin{bmatrix}J_{XX} & -J_{XY} & -J_{XZ}\\ -J_{XY} & J_{XX} & -J_{YZ}\\ -J_{XZ} & -J_{YZ} & J_{XX}\end{bmatrix}$

In (1.23), **F** stands for external force acting on a rigid body, M stands for mass of a rigid body, **a** stands for acceleration of the center of mass of a rigid body, **v** stands for velocity of the center of mass of a rigid body, $\mathbf{T}_\mathbf{e}$ stands for external torque acting on a rigid body, **J** stands for a tensor of the moment of inertia of a rigid body against to the center of mass, $\boldsymbol{\omega}$ stands for angular velocity of a rigid body against to the center of mass, and $\boldsymbol{\alpha}$ stands for angular acceleration of a rigid body against to the center of mass, G.

In (1.23) and (1.24), there are two nonlinear terms caused by the Coriolis effect and the gyroscopic effect. If the magnitude of these terms is very small compared to the magnitude of linear terms, the equations above can be linearized by ignoring the nonlinear terms. Then the equations of motion can be expressed as linear equations:

$$\begin{bmatrix} F_x \\ F_y \\ F_z \\ \hdashline T_{ex} \\ T_{ey} \\ T_{ez} \end{bmatrix} = \left[\begin{array}{ccc:ccc} m & 0 & 0 & 0 & 0 & 0 \\ 0 & m & 0 & 0 & 0 & 0 \\ 0 & 0 & m & 0 & 0 & 0 \\ \hdashline 0 & 0 & 0 & J_{xx} & -J_{xy} & -J_{xz} \\ 0 & 0 & 0 & -J_{xy} & J_{yy} & -J_{yz} \\ 0 & 0 & 0 & -J_{xz} & -J_{yz} & J_{zz} \end{array}\right] \begin{bmatrix} a_x \\ a_y \\ a_z \\ \hdashline \alpha_x \\ \alpha_y \\ \alpha_z \end{bmatrix} \tag{1.25}$$

If several external forces are acting upon a rigid body, each of them can be decomposed into three independent components against to the axes of the body fixed frame. The resultant force of a specific axis can be represented by the summation of all the components in that axis. Also, the resultant torque can be obtained by the multiplication of the magnitude of each force and the distance from the center of the body fixed frame to the point of application of a force. For example, it is shown in Fig. 1.13 that seven different forces are acting on a rigid body parallel to the each axis of a body fixed frame.

The summation of f_1 and f_2 is the **x**-axis force, $\mathbf{F_x}$, the summation of f_3 and f_4 is the **y**-axis force, $\mathbf{F_y}$, and the summation of f_5, f_6, and f_7 is the **z**-axis force, $\mathbf{F_z}$. Because the point of application of f_1 and f_2 is not on the **x** axis, these two forces induce **y-** and **z**-axis torque. For same reason, **y**-axis forces induce **x**- and **z**-axis torque and **z**-axis forces induce **x-** and **y**-axis torque. The torque acting on each axis of the body fixed frame can be expressed as $\mathbf{r}_i = (x_i, y_i, z_i)$, $1 \leq i \leq 7$, which is the distance from the center of rotation of the rigid body to the point of application of $f_1 \sim f_7$.

$$\begin{gathered} \mathbf{f}_i = (f_i, 0, 0),\ i = 1, 2;\ \mathbf{f}_i = (f_i, 0, 0), i = 3, 4;\ \mathbf{f}_i = (f_i, 0, 0), i = 5, 6, 7; \\ \mathbf{T}_e = (\,T_{ex},\ T_{ey},\ T_{ez}\,) = \sum_{i=1}^{7} \mathbf{r}_i \times \mathbf{f}_i \end{gathered} \tag{1.26}$$

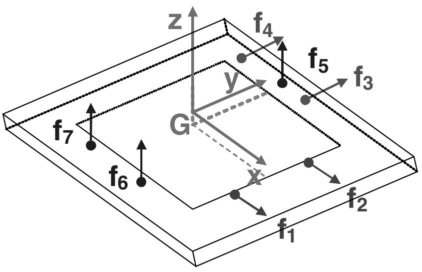


Figure 1.13 Seven external forces are acting on a rigid body.

The matrix form of the above equation is shown in (1.27)

$$\mathbf{u} = \mathbf{A}\mathbf{f} \tag{1.27}$$

$$\mathbf{A} = \left[\begin{array}{cc|cc|ccc} 1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 1 \\ \hline 0 & 0 & -z_3 & -z_4 & y_5 & y_6 & y_7 \\ z_1 & z_2 & 0 & 0 & -x_5 & -x_6 & -x_7 \\ -y_1 & -y_2 & x_3 & x_4 & 0 & 0 & 0 \end{array}\right] \tag{1.28}$$

$$\mathbf{u} = [F_x, \quad F_y, \quad F_z, \quad T_{ex}, \quad T_{ey}, \quad T_{ez}]^T \tag{1.29}$$

$$\mathbf{f} = [f_1 \quad f_2 \quad f_3 \quad f_4 \quad f_5 \quad f_6 \quad f_7]^T \tag{1.30}$$

In the above equations, $[\ldots]^T$ means transpose of vector or matrix $[\ldots]$.

In (1.27)–(1.30), the resultant forces and torques, which have 6-DOF in the body fixed frame, are represented by seven independent forces. In this case, to control the motion of the body only for a specific direction from the six different axes of motion, three or four forces among the seven independent forces should be controlled simultaneously. Then, there may be unintended forces or torques caused by the coupling effect of external forces. To implement precise control of 6-DOF rigid body motion, it should be done to decompose the motion of rigid body to the intended one and to the unintended one appropriately.

1.2.5 Power and Energy [1]

In linear motion system, the power, P, can be described as

$$P = f \cdot v \tag{1.31}$$

If the force, f, is constant during the motion, then the energy, E, is the product of the force, f, and the moving distance, l:

$$E = f \cdot l \tag{1.32}$$

Also, the energy is the integration of power regarding to the time. If the mass, M, does not vary during the motion, then the energy can be expressed as

$$E = \int P\,dt = \int f \cdot v\,dt = \int M\frac{dv}{dt} \cdot v\,dt = \frac{1}{2}Mv^2 \tag{1.33}$$

In a rotating motion, the power can expressed as

$$P = T_e \cdot \omega \tag{1.34}$$

As the linear motion, if the torque is constant during the motion, then the energy can be expressed as

$$E = T_e \cdot \theta \tag{1.35}$$

If the inertia, J, does not varies during the motion, then the energy can be expressed as

$$\begin{aligned} E &= \int T_e \cdot \omega \, dt = \int J \frac{d\omega}{dt} \cdot \omega \, dt \\ &= \int J\omega \, d\omega = \frac{1}{2} J\omega^2 \end{aligned} \tag{1.36}$$

If the inertia, J, varies during the motion, then the variation of the inertia should be considered as (1.5).

As shown in (1.36), the energy can be stored in a rotating body. Recently, there have been many applications of the energy storage system using a high-speed rotating body under the name of flywheel energy stoage [13].

1.2.6 Continuity of Physical Variables

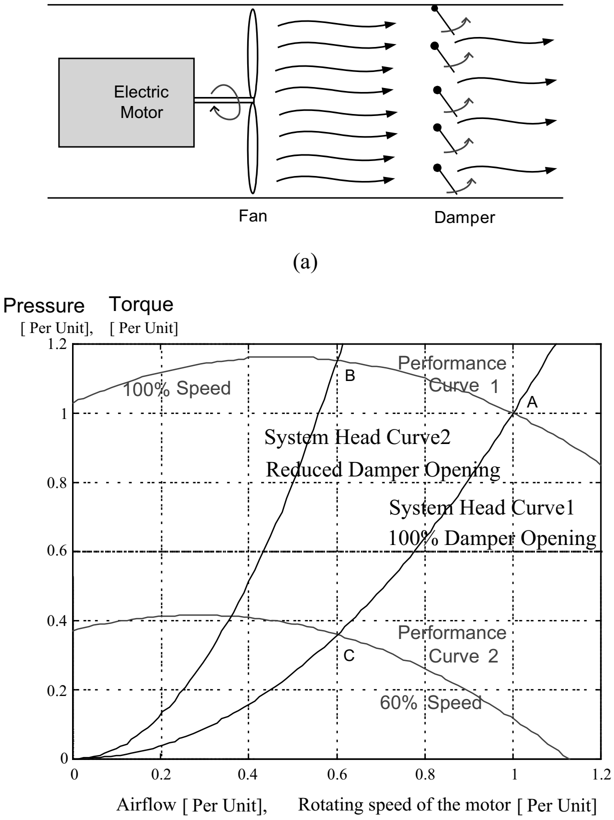
All physical vriables in the nature are finite, and a physical variable expressed as the time integral of another physical variable is always continuous. Because the force in the nature is always finite, the velocity and moving distance are always continuous in the linear motion and the angular velocity and moving angle are continuous in the rotating motion. In an electric machine, the thrust force and the torque are generated by the cross product of the current and its associated flux linkage. In the electromagnetic circuit, there is always inductance, and the flux and current are always continuous. Hence, the thrust force and the torque are also continuous. And, the linear acceleration and angular acceleration are also continuous. Therefore, the discontinuous function that can be implemented in reality is the jerk, which is time derivative of the acceleration. Furthermore, in the trajectory control, the planned trajectory (position or angle) can be obtained through the succesive time integration of the jerk. In this sucessive integration, the acceleration reference and velocity reference are easily obtained, and the references can be used to enhance the control performance of a postion regulation loop (see Section 4.4.2).

1.3 TORQUE SPEED CURVE OF TYPICAL MECHANICAL LOADS

The electric machines provide torque or force to operate the mechanical load or sometimes absorb torque or force from the mechanical load. The mechanical load employing the electrical machine as an actuator has its own torque–speed characteristics.

1.3.1 Fan, Pump, and Blower

Fan, pump, and blower are the loads that consume the most electricity in the developed countries. And those are used to move the fluids, and the torque of the loads in steady



(a)

(b)

Figure 1.14 Control of airflow of a fan. (a) Control of airflow by a damper. (b) Performance curves and system head curves.

state is proportional to the square of the speed of flow of the fluid. Also, the power of the electric machine to drive the load is proportional to the cubic of the speed of flow. In Fig. 1.14a, the conceptual diagram of airflow control system by damper and a fan driven by an electric motor is shown. And in Fig. 1.14b, the typical performance curve of the fan and its torque–speed curve (system head curve) are shown. The operating point lies at the crossing point of two curves. As shown in Fig. 1.14a, if the airflow is controlled by the damper of the fan, then the flow, Q, can be reduced, but the pressure applied to the blades of the fan would be increased. In this case, as shown in Fig. 1.14b, the operating point moves from A to B, and the mechanical power by the machine changes from $P_A = H_A Q_A$ to $P_B = H_B Q_B$.

If the speed of the machine is adjusted to control the airflow, as shown in Fig. 1.14b, the operating point moves from A to C, and the mechanical power by the machine changes from $P_A = H_A Q_A$ to $P_C = H_C Q_C$. In this case, the torque to drive the fan decreases as the speed of the machine decreases, and the power by the machine would be decreased proportionally to the cubic of the speed of the machine or to the cubic of the airflow.

1.3.2 Hoisting Load; Crane, Elevator

In the steady state, the hoisting load requires torque due to gravitational force and friction force of the load. The torque against the gravitational force is independent with the moving speed of the load. However, the friction force increases as the speed increases, and the torque to drive the hoisting load could increase as the speed increases. In high-speed gearless elevator drive system or high-power crane drive system, where the friction force is negligible compared to the gravitational force or to the acceleration force, the torque is almost constant regardless of the speed. In Fig. 1.15, the torque–speed curves of the typical hoisting load are shown as a solid line and as a dashed line. The curve by the solid line curve is the case where the friction torque can be neglected, while the curve by the dashed line represents the case where the friction torque is proportional to the speed. If Coulomb friction is also considered in this case, the curve may have discontinuity at null speed. In the case of the elevator system, at the steady state the torque due the difference of the weight of the cage and counter weight is covered by the electric machine. In the high-speed elevator drive system, at acceleration and deceleration, 50% to 200% of the torque of the steady-state torque is needed to get the required acceleration and deceleration force to accelerate/decelerate the total mass including the masses of the cage and the counter weight. Hence, the electric machine to drive the elevator should have at least 150% to 300% overload capability for a short time, which is usually less than 10 s, to handle this torque. The peak motoring power of the machine occurs at just before the finishing point of the acceleration. In these hoisting loads, the electric machine should generate not only positive torque but also negative torque at either direction of rotation. Hence,

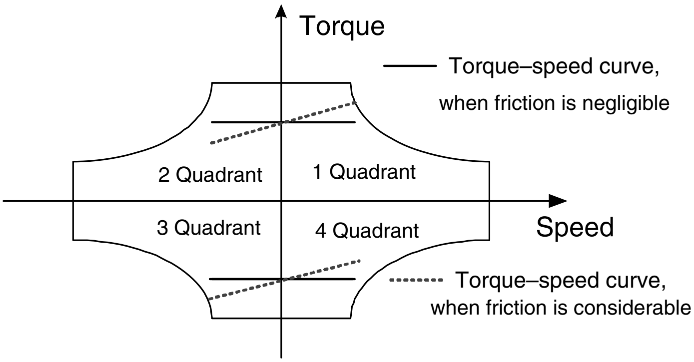


Figure 1.15 Torque–speed curve of a typical hoisting load.

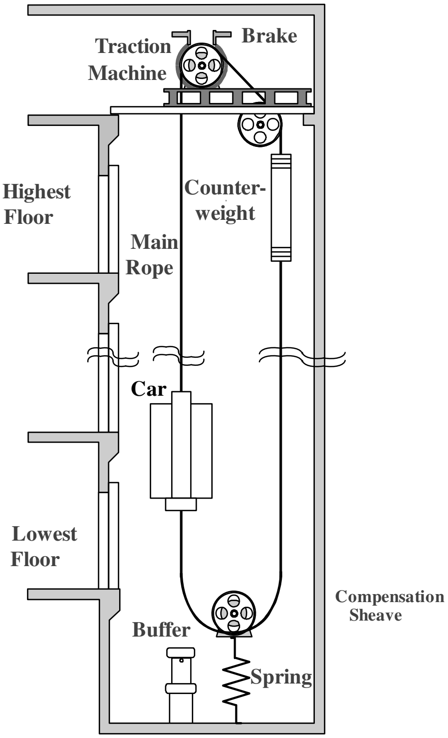


Figure 1.16 Gearless direct drive elevator system.

as shown in Fig. 1.15, the four-quadrant operation in a torque–speed plane is necessary in these hoisting loads.

In Fig. 1.16, a conceptual diagram of an elevator drive system is shown. As shown in the figure, the cage or car, where the passengers are, and a counterweight, whose weight is usually a half of the full weight of cage and passengers, are connected by a rope through the sheave of the traction machine driven by the electric machine. And by the rotation of the electric machine, the cage moves up or down.

1.3.3 Traction Load (Electric Vehicle, Electric Train)

The machine, used as the traction machine of the electric vehicle or the electric train, requires high torque at starting and low speed and requires low torque at high speed, as shown in Fig. 1.17. In the conventional internal combustion engine (ICE), the torque–speed range with reasonable efficiency is quite narrow, and the multi-ratio gear system—so-called transmission—is used to match the torque and speed of ICE to the operating condition of the vehicle. However, the electric machine can provide the required torque–speed characteristics without complex gear system. The required characteristics can be easily obtained by field (flux) weakening control of the machine. Also, the electric machine for the traction application can operate at four quadrants in a torque-speed plane contrast to ICE.

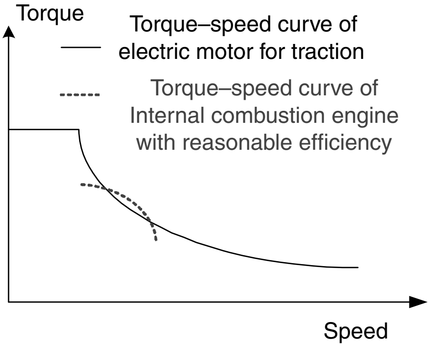
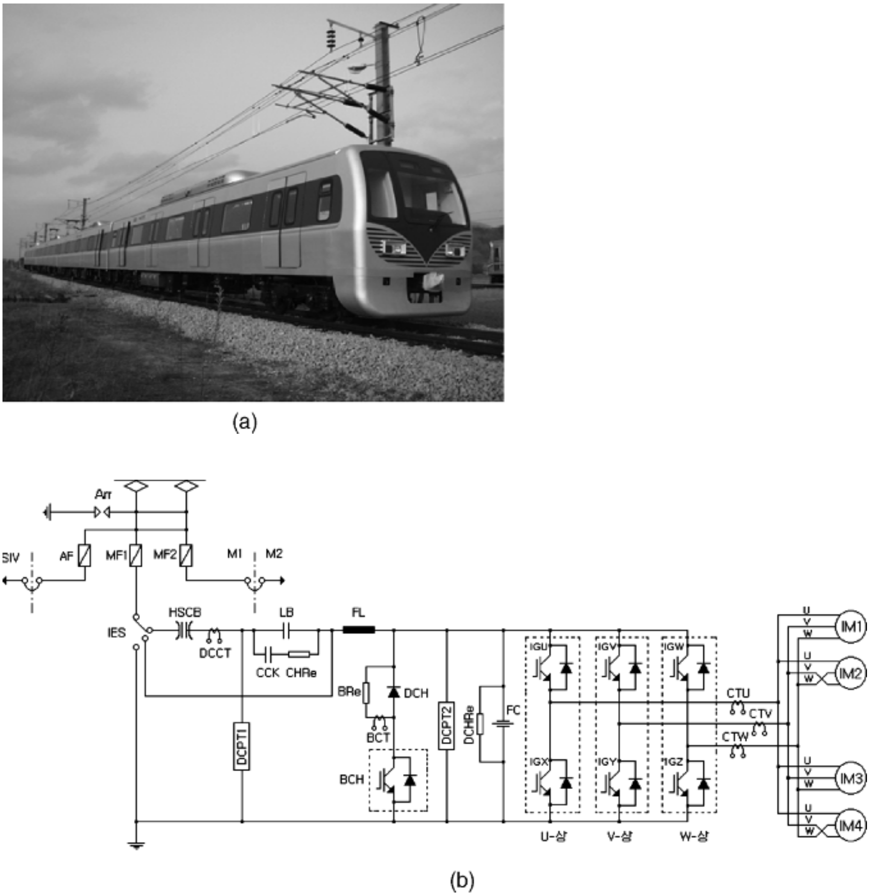


Figure 1.17 Torque–speed curves of an electric machine and internal combustion engine for traction application.


(a)

(b)

Figure 1.18 (a) Outer view of a subway train and (b) Main power circuit of a motor car of the subway train.

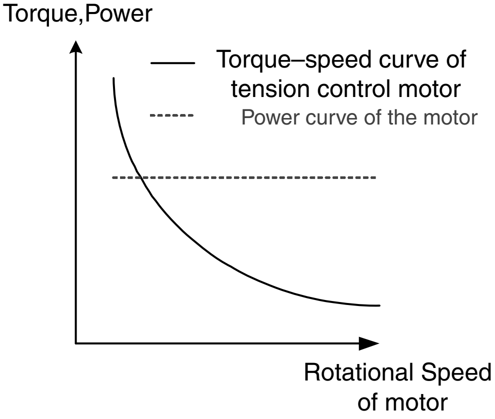


Figure 1.19 Torque–speed–power curve of tension control machine.

A circuit diagram of a motor car of the subway train is shown in Fig. 1.18, where an inverter driving four traction machines is powered by the catenary. With the development of the power electronics, to enhance performance and efficiency of the drive system, a new drive system, where each electric machine is driven by an inverter separately, is already applied in the field.

1.3.4 Tension Control Load

Usually, in the driving of the paper mill, steel mill, pay-off roll, and tension roll, the tension should be controlled as constant in the steady state. In this case, if the transportation speed of a paper sheet or a metal sheet is constant, the rotational speed of the machine decreases as the radius of the roll increases. Also, the output power of the machine is constant. However, in the acceleration or deceleration time, due to the torque for the acceleration and deceleration the constant power operation cannot be kept. In Fig. 1.19, the curves of torque and power of the electric machine driving a typical tension control system, where the metal sheet is moving at the constant speed, are shown. As an example of a tension control system, a continuous annealing line is shown in Fig. 1.20. In this line, the accuracy and bandwidth of the torque and speed control of the electric machine is crucial in the productivity of the process and the quality of the product.

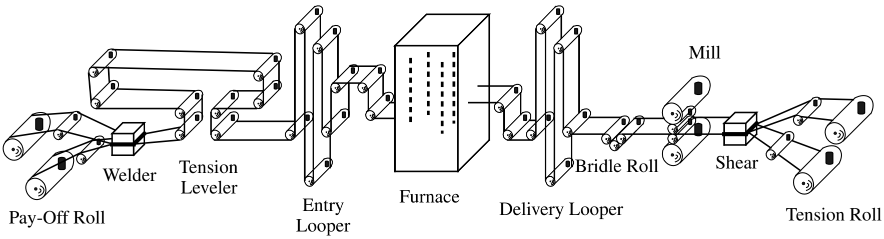


Figure 1.20 Continuous annealing processing line.

PROBLEMS

1. Calculate the moment of inertia of rotating cylinder as shown in Fig. P1.1. The density of the cylinder is ρ. Describe how to maximize the ratio, *J/M* under the condition of $r_1 + r_2 = \text{constant}$. Here, *J* stands for the inertia of the cylinder and *M* for the mass of the cylinder.

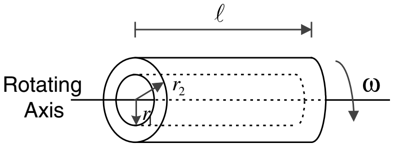


Figure P1.1 Moment of inertia of rotating cylinder.

2. As shown in Fig. P1.2, a disk is rotating regarding the *z* axis. The origin of the Cartesian coordinate is apart from the center of the mass, *G*, by 2(mm), 2(mm), 1(mm) as shown in the figure. The *G* can be represented by (–2 mm, –2 mm, –1 mm) in the coordinate. The radius of the disk, *r*, is 100(mm) and thickness of the disk is 10(mm).

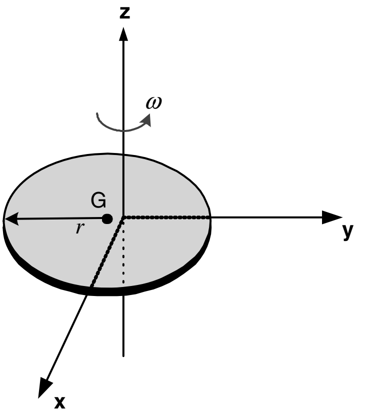


Figure P1.2 Rotating disk, whose rotating axis is slightly offset from the center of mass.

(1) In this case, calculate rotating inertia, $\mathbf{J_{xz}}$, $\mathbf{J_{yz}}$, $\mathbf{J_z}$, defined as (1.17).

(2) If the rotating speed of the disk, ω, is 1000 r/min, calculate torque at each **x, y, z** axis. Also calculate energy stored in this disk due to the rotation.

(3) Repeat problem 2 when the rotating speed is 100,000 r/min.

3. As shown in Fig. 1.13, there is a rigid body moving by seven forces. The body is not constraint in any axis of motion. The gravitational force is acting in the direction of the **z** axis. At the starting instant, the body reference frame coincides with the inertial reference frame. The lengths of the body in the **x** and **y** direction are 100 mm and the length in the **z** direction is 5 mm. The material of the body is stainless steel and the shape of the body is a rectangular parallelepiped. The initial position of the center of mass, simultaneously center of the rotation, *G*, is expressed in Cartesian coordinate in two reference frame as (**x**, **y**, **z**) = (**X**, **Y**, **Z**) = (0, 0, 0), respectively. And the operating points, $\mathbf{r}_1$–$\mathbf{r}_7$, of forces, $\mathbf{f}_1$–$\mathbf{f}_7$, in the body reference frame are followings. All of the angles of rotation are small enough to

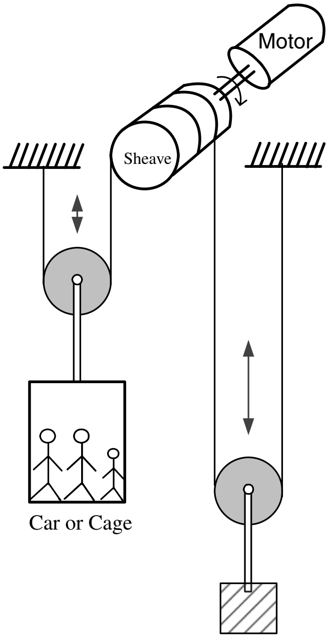


Figure P1.3 Conceptual diagram of a high-speed gearless elevator.

approximate the value of sine function as the angle itself and the value of cosine function as unity, and the nonlinear matrix in (1.20) can be linearized as (1.21).

$\mathbf{r}_1 = (40, -20, -2.5)\text{mm}, \quad \mathbf{r}_2 = (40, 20, -2.5)\text{mm}, \quad \mathbf{r}_3 = (20, 40, 2.5)\text{mm},$

$\mathbf{r}_4 = (-20, 40, 2.5)\text{mm}$

$\mathbf{r}_5 = (0, 40, 2.5)\text{mm}, \quad \mathbf{r}_6 = (20, -40, 2.5)\text{mm}, \quad \mathbf{r}_7 = (-20, -40, 2.5)\text{mm}$

(1) Find the matrix **A** in (1.27), which transforms the force, $\mathbf{f}_1$–$\mathbf{f}_7$, to the force and torque acting in each axis of the motion independently.

(2) Find the inertia matrix regarding three rotating axes.

$$J = \left[\begin{array}{ccc:ccc} m & 0 & 0 & 0 & 0 & 0 \\ 0 & m & 0 & 0 & 0 & 0 \\ 0 & 0 & m & 0 & 0 & 0 \\ \hdashline 0 & 0 & 0 & J_{xx} & -J_{xy} & -J_{xz} \\ 0 & 0 & 0 & -J_{xy} & J_{yy} & -J_{yz} \\ 0 & 0 & 0 & -J_{xz} & -J_{yz} & J_{zz} \end{array}\right]$$

(3) If the acceleration regarding only the **X** axis is 1 m/s^2 in the inertial reference frame and regarding all other axes there is no acceleration and movement except **X** axis translational motion, then find force $\mathbf{f}_1$–$\mathbf{f}_7$ for such a motion. *Hint*: $\mathbf{f} = \mathbf{A}^{\mathbf{T}}(\mathbf{A}\mathbf{A}^{\mathbf{T}})^{-1}\mathbf{u}$.

(4) If angular acceleration regarding only the **x** axis is 1 rad/s^2 in body fixed frame and regarding all other axes there is no acceleration and movement except **x**-axis rotational motion, then find force $\mathbf{f}_1$–$\mathbf{f}_7$ for such a motion.

(5) Describe the method regarding how to control the linear and angular acceleration independently by manipulating only the forces $\mathbf{f}_1$–$\mathbf{f}_7$.

4. In the cooling fan drive system for a thermal power plant, the airflow and air pressure has the following relationship (performance curve).

$H = 1.03N^2 + 0.56NQ - 0.59Q^2$, where N is the rotational speed of the fan, and Q stands for flow rate, H stands for air pressure, and all units are per unit (P.U.). The 1 P.U. of the speed of the electric machine corresponds to 1800 r/min, 1 P.U. flow rate corresponds to 1000 m^3/min, and 1 P.U. air pressure corresponds to 4243 N/m^2. The efficiency of the fan is given by $\eta = 0.5 + 0.3Q$, where η is per unit. The system head curve of the fan can be expressed as $H = Q^2$ when the damper is fully opened. And according to the damper opening the curve can be represented by $H = KQ^2$, where K depends on the damper opening. The operating point of the fan lies at the crossing point of the performance curve and the system head curve. The flow rate can be controlled by adjusting damper opening or by adjusting the rotating speed of the electric machine driving the fan. The required flow rate is proportional to the load factor of the generator of the power plant. If the required airflow for a year is assumed as follows, then answer the following questions:

$$50\%, 4000\,\text{hours}; \quad 30\%, 2000\,\text{hours}; \quad 20\%, 2000\,\text{hours}$$

(1) Select an electric machine to drive the fan from following choices. The fan should provide 100% flow rate. The rated speed of the all machines at following choices is 1800 r/min.
(a) 100 Hp (b) 125 hp (c) 150 Hp (d) 200 Hp (e) 250 Hp (f) 300 Hp

(2) Calculate total electricity (kWh) to drive the fan during a year for the following cases to control flow rate. It is assumed that the efficiency of the electric machine is 90% constant regardless of the load factor.

- **(a)** Calculate the electricity consumed for a year in the case of control of the damper opening.
- **(b)** Calculate the electricity consumed for a year in the case of adjusting speed of the electric machine. In this case, it is assumed that the efficiency of the VVVF system for the adjustable speed drive of the electric machine is 95% constant regardless of load factor, and damper is fully opened.
- **(c)** If the rate for the electricity is 0.1$/kWh, how much is the cost of electricity saved for a year by the adjustable speed control compared to damper opening control?

(3) Describe the advantages and disadvantages of adjustable speed control compared to damper opening control.

(4) Describe the reason why the flow rate of the fan is equal to or less than 50% in the case of the normal operation.

5. The high-speed elevator system, shown in Fig. P1.3, has following specifications. Answer the following questions.

- Rated speed: 240 m/min, 24 passengers (weight of payload: 1600 kg), maximum number of floor for movement: 30 floors

- Distance between floors: 3 m
- Mass of counterweight: 3134 kg
- Mass of cage: 2345 kg
- Inertia of sheave: 95 kg-m^2
- Inertia of machine: 25 kg-m^2
- Diameter of sheave: 710 mm

The mass of rope and inertia of the pulley on the cage can be neglected. The jerk profile at ascending operation is shown in Fig. P1.4.

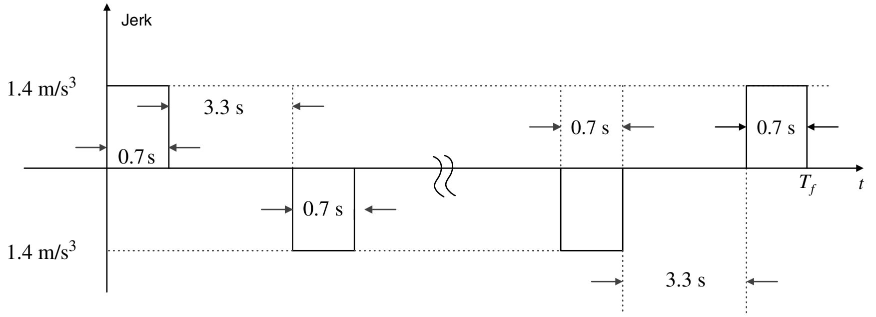


Figure P1.4 Jerk profile of the elevator at ascending operation.

(1) When the elevator moves from the first floor to the thirty-first floor (30 floors × 3 *m*/floor) with the jerk profile as shown in Fig. P1.4, calculate the total travel time, T_f.

(2) In the case of part 1, plot the acceleration, velocity, and position of the cage according to the time.

(3) If the traction machine of the elevator can withstand 200% overload for 10 s, select the minimum capacity of an electric machine to drive the elevator from the following choices:
(a) 40 Hp (b) 50 Hp (c) 60 Hp (d) 70 Hp (e) 80 Hp

(4) From the following choices, what are the number of poles and rated frequency of the machine selected from part 3? Here, there is no slip between machine, sheave, and rope. The maximum speed of the machine is decided by "rated frequency × 60/(number of poles/2)" (revolutions/min).
(a) 15 Hz, 4 poles (b) 15 Hz, 8 poles (c) 30 Hz, 4 poles (d) 30 Hz, 8 poles (e) 60 Hz, 8 poles (f) 60 Hz, 16 poles

(5) Plot the output power of the motor according to the time in case of part 1. In this problem, the slip between rope, sheave, and pulley can be neglected and the friction of all moving parts also can be ignored. The weight of the payload is 1600 kg.

6. Answer the following questions for a crane, shown in Fig. P1.5 under the following assumptions and specification.

- The torque transfer efficiency of each pulley is 98%.
- The gear ratio is 400:1 and efficiency is 90%. And the inertia of gear itself can be neglected. There is no slip between sheaves, rope, and pulleys.

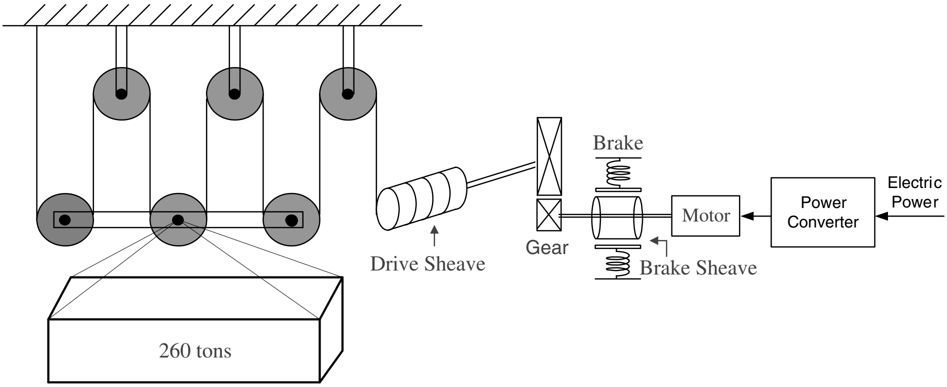


Figure P1.5 Conceptual block diagram of a crane.

- The drive sheave is a solid cylinder whose length is 1.2 m; its diameter is 1 m and its density is 7800 kg/m^3.
- The density of the steel part of the brake sheave, which is a hollow cylinder as shown in Fig. P1.6, is 7800 kg/m^3.

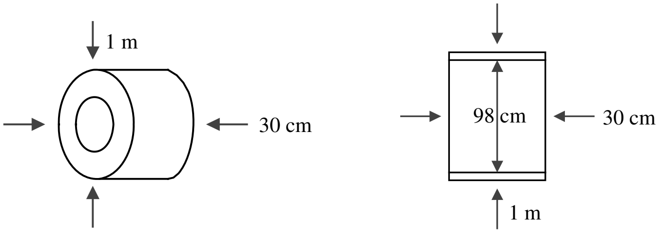


Figure P1.6 Structure of the brake sheave.

- The mass of the rope and the elongation of the rope can be neglected.
- The maximum speed of the machine is decided by “rated frequency × 60/(number of poles/2)” (revolutions/min).

The speed pattern to move a 260-metric-ton payload is shown in Fig. P1.7.

(1) Plot the rotational speed of the machine according to the time for the given speed pattern.

(2) Plot the torque of the machine according to the time for the given speed pattern.

(3) It is assumed that the total efficiency of the electric power conversion system (VVVF drive ASD sytem) including electric motor is 90% regardless of the load factor of the system. Plot the power to the electric power conversion system according to the time.

(4) Select a suitable electric motor from following choices. The motor can withstand 150% overload, which means 2.5 times of rated power of the machine, for 30 seconds. The pole numbers of the machine is four and the rated frequency of the machine is 60 Hz. There is no slip between pulleys, machine, and sheave. The maximum speed of the

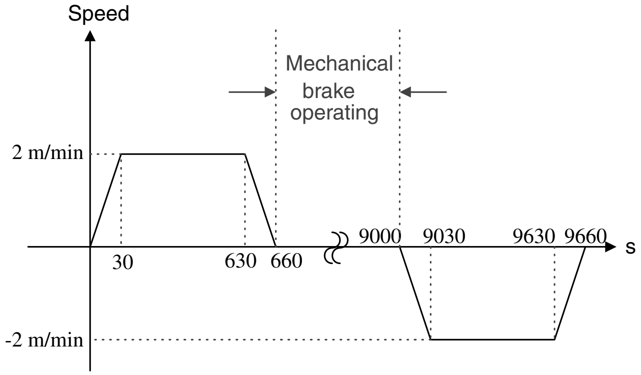


Figure P1.7 Speed pattern of a 260 ton payload

machine is decided by "rated frequency × 60/(number of poles/2)" (revolutions/min).
(a) 75 kW (b) 90 kW (c) 110 kW (d) 132 kW

7. As shown in Figure 1.P8, there is a commuter train consisted with four motor cars (M car) and four trailer cars (T car).

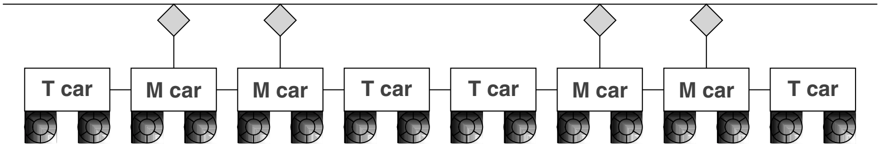


Figure P1.8 Typical configuration of the commutating train

The mass of T car is 28 metric tons, and that of M car is 30 metric tons. The maximum payload of each car is 20 metric tons. The rolling resistance of the train is given by the following equation:

$$R = 1.867 + 0.0359\, v_a + 0.000745\, v_a^2$$

where the unit of R is kg-G/ton = 9.8 N/ton, v_a is the speed of the train, and its unit is km/h.

The train accelerates up to 35 km/h with the maximum acceleration, 3.0 km/h/s. The maximum speed of the train is 100 km/h. During acceleration, the inertia of the rotating parts of the train such as wheels, gears, and electric machines can be converted to an equivalent mass in calculating of the traction force. The converted inertia to the mass is called "inertia mass." The compensation factor of the inertia mass to consider the traction force due to the rotating parts of each car is 6% in the case of a T car and 14% in the case of an M car. Hence, the equivalent total mass (including the inertia mass) to consider the torque due to the rotating parts of the car can be given by following equation.

Equivalent mass at acceleration = Total mass of car including payload + (Compensation factor for the inertia mass $*$ Mass of each car itself)

Only 97% of the mechanical torque from the machine is transfered to the rail and that is used as the tractive force to move the train. Each M car has four traction motors.

- **(1)** Calculate the power rating of the motor in kilowatts. The power rating of the motor is decided at the operating speed where the tractive force is the maximum (in this problem it is 35 km/h).
- **(2)** The gear ratio between motor and wheel is 7.07:1 and the gear is reducing gear. When the average speed of the train is 48 km/h, the rotating speed of the motor is the rated value. The diameter of the wheel is 0.82 m constant.
  - **(a)** What is the rated rotating speed (revolutions/min) of the traction motor?
  - **(b)** At maximum train speed, 100 km/h, what is the rotating speed (revolutions/min) of the motor?
  - **(c)** At the operating condition given in part 1, if the efficiency of the AC traction motor is 92% and the power factor is 85%, then calculate the apparent input power (kVA) to the machine.

8. In Fig. P1.29, a conceptual diagram of the recoil line of steel mill processing system.

The total inertia of the rotor of the motor including gearbox, referred to the axis of the rotor of the motor, is $J = 200$ kg-m^2. The density of steel web is 7870 kg/m^{3,} and the web is tightly wound on the drums and there is no empty space in the steel roll. The density of the drum, whose minimum diameter is 0.61 m, is the same with that of steel web. And the drum is a solid cylinder. Also, the minimum diameter of the roll is 0.61 m when no web on the drum, and the maximum diameter of the roll is 2.6 m when the web is fully wound on the drum. The thickness of the steel web is 2 mm, the width, 900 mm, and the profile of the speed of the web is shown in Fig. P1.10. The constant 64,000 N tension is always applied to the steel web by pay-off and tension rolls.

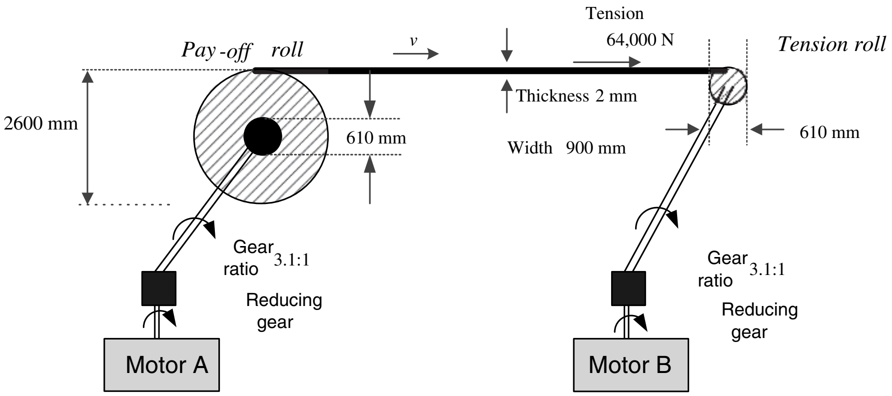


Figure P1.9 Conceptual diagram of a recoil line of a steel mill processing system.

- **(1)** Plot the radius of the tension roll according to the time from minimum value to the maximum value.
- **(2)** With consideration of gear ratio, plot the rotational speed (r/min) of the motor B according to the time.
- **(3)** Plot the torque (N-m) of the motor B according to the time.
- **(4)** Plot output power (kW) of the motor B according to the time.

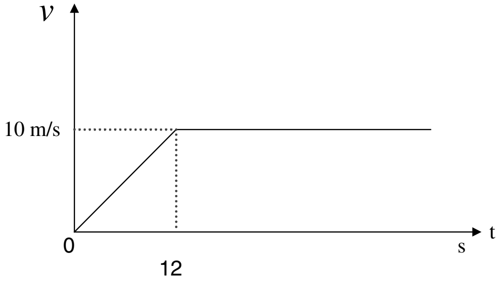


Figure P1.10 Speed profile of the movement of steel web.

9. In Fig. P1.11 a photo of a rubber-tired gantry crane (RTGC) used for handling containers in a port is shown. The mass of a spreader, which is used to catch the container, is 11 metric tons. The mass of trolley is 23 metric tons [14].

Figure P1.11 Photo of a rubber-tired gantry crane.

The mechanical system of RTGC including an electric machine is similar to that shown in Fig. P1.25. At hoist motion the total inertia, including gears, brake drum, rope, sheave, and machine itself reflected to the rotating axis of electric machine is 11 kg-m^2. Regardless of torque and direction of motion, the total efficiency of the mechanical system for hoist motion is 86% constant and that of the electric machine is 95% constant. And there is no slip between all moving components. The weight of the rope can be neglected. The speed, 800 r/min, of the hoist motor, used for the vertical motion of the container, means 60 m/min of hoisting speed of the container.In trolley motion, the total inertia including gears, brake drum, rope, sheave, and electric machine itself reflected to the rotor of the machine is 0.4 kg-m^2. Regardless of torque and direction, the total efficiency of the mechanical system for trolley motion is 90% constant and that of the electric machine is 92% constant. The speed, 1750 r/min, of the trolley motor, used for the horizontal motion of the container, means 70 m/min of hoisting speed of the container. In trolley motion, the hoist motor is locked by the mechanical brake, and the power to the hoist motor is null.

(1) The spreader of the RTGC is moving from Layer 4, Column 6 to Layer 4, Column 1, shown in Fig. 1.12, without a container. First (1) the spreader moves vertically up from

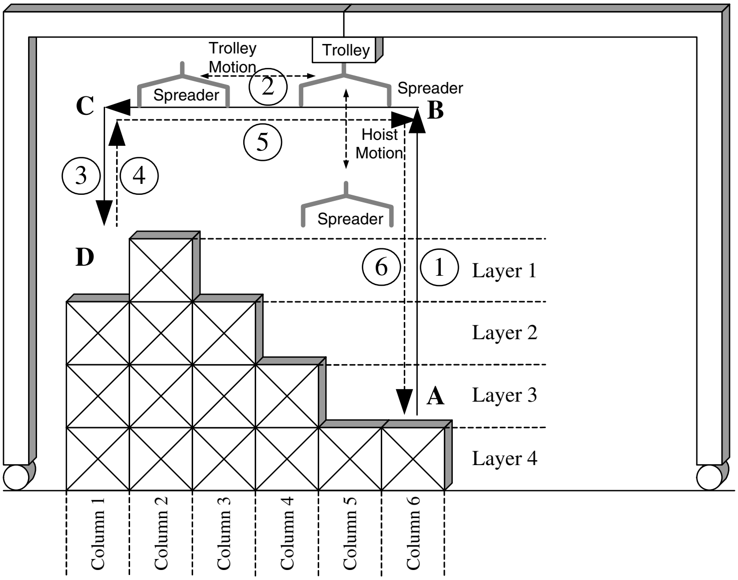


Figure P1.12 Operation of RTGC (rubber-tired gantry crane).

Layer 4 to the top (line between point A and point B), for 7.95 m, and then (2) the spreader moves horizontally to Column 6 (line between point B and point C), for 17.24 m; finally (3) the spreader moves vertically down to Layer 4 (line between point C and point D). In the hoist motion, the acceleration is (60 m/min)/2.5 s constant and deceleration is (60 m/min)/3.5 s constant. The maximum speed of the hoist motion is 60 m/min. In the trolley motion, the acceleration and deceleration are both (70 m/min)/5.5 s constant. The maximum speed of the trolley motion is 70 m/min. During trolley motion, the spreader and trolley can be considered as a single mass. Plot the torque and speed of the hoist machine and trolley machine according to the time, respectively. Also plot the sum of input power to the machines according to the time.

(2) The spreader of the crane is now holding a container whose mass is 40 metric tons, and moves in reverse (from point D, C, B, and A as the motion described in part 1). Plot the torque and speed of the hoist machine and trolley machine according to the time, respectively. Also, plot the sum of input power to the machines according to the time. During trolley motion, the spreader, trolley, and container can be considered as a single mass. The acceleration and deceleration of the hoist motion is the same with the case of part 1, but the maximum speed of the hoist motion is 24 m/min.

10. For RTGC in problem 9, the electric power to the machine is provided by a 400-kW engine generator set as shown in Fig. P1.13.

(1) When the hoist machine is a six-pole, permanent-magnet synchronous machine, plot the input frequency to the hoist machine according to the time at the motion described in problem 9.

In trolley motion, the machine for hoist motion is stopped. (The speed of the machine is decided by “input frequency × 60/(number of poles/2)” (r/min).)

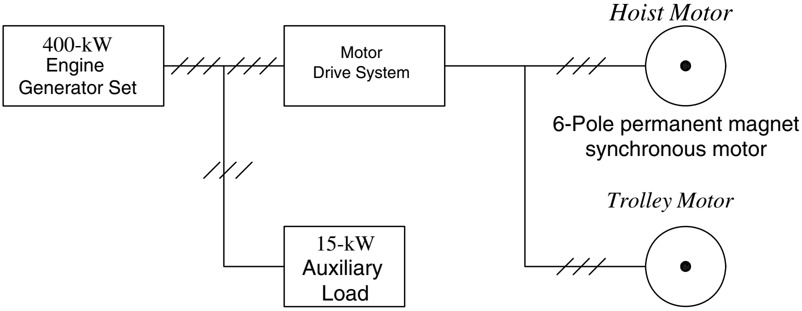


Figure P1.13 Electric power supply system of RTGC based on an engine generator set.

(2) The fuel consumption of the engine generator is given by $y = \frac{14.16}{3600} + \frac{0.163}{3600}x$, where "$x$" means output power of the generator in kW and "y" means consumption of diesel fuel in liter/s. The auxiliary load is a 15-kW constant, and the regenerated power at the vertical down motion of the load (the spreader and the container) cannot be transferred to the auxiliary load or not to the generator. Hence, the regenerated power is dissipated at the resistor box, which is separately installed in the drive system. The efficiency of the motor drive system is 90% constant regardless of the load factor.

- **(a)** For the motion described in problem 9, part 1, calculate total quantity of the consumed diesel fuel.
- **(b)** For the motion described in problem 9, part 2, calculate total quantity of the consumed diesel fuel.
- **(c)** For an hour, 8 times of motion described in problem 9, part 1 and 8 times of the motion described in problem 9, part 2 have been done, and for other times of the hour the generator only supplies the electricity to the auxiliary load. For such operation, calculate total quantity of the consumed diesel fuel for an hour.

(3) The electric power system for RTGC has been changed to the system shown in Fig. P1.14.

The engine generator can supply up to 150 kW, and its response is fast enough. The response of the power converter is also fast enough. And the response time of the engine and power converter can be neglected. The efficiency of the power converter is 90% constant regardless of the load factor and direction of power flow. Before the hoist motion the super-capacitor, C_s, is charged to 600 V, always. And the capacitance of the capacitor is 25 F. The power needed for the electric machine drive system is, at the first, supplied from the engine generator set as much as possible, and then the additional power to the drive system is supplied from super-capacitor through the power converter. The efficiency of the electric machine drive system is 90% constant regardless of the load factor and direction of power flow. The regenerated power at the vertical down motion of the load (the spreader and the container) can be used to charge the super-capacitor. And if the voltage of the super-capacitor is less than 600 V after the hoist motion, the capacitor should be charged to 600 V using the power from the generator through the power converter. The super-capacitor, C_s, can be assumed as

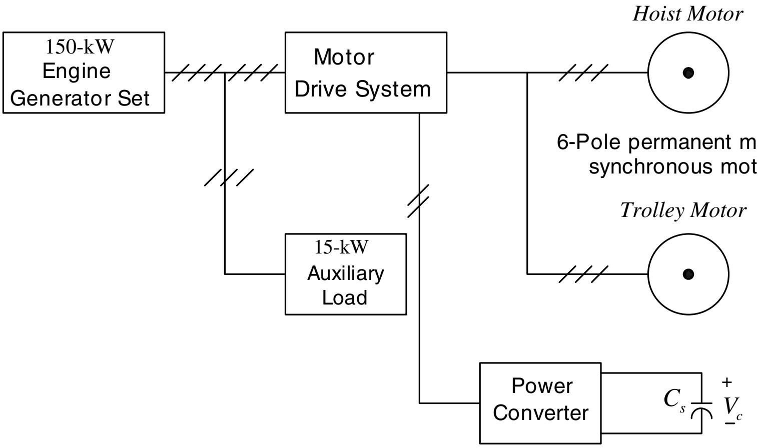


Figure P1.14 Power supply system of RTGC based on engine generator and an energy storage system based on the super-capacitor.

an ideal capacitor. The stored energy in the capacitor and the power to the capacitor are given by following equations.

$$E = \frac{1}{2} C_s V_c^2 [\mathrm{J}]$$

$$P = C_s V_c \cdot \frac{dV_c}{dt} [\mathrm{W}]$$

Also, the power converter for charging and discharging of the super-capacitor operates only for hoisting motion. At the other operation, the power converter turns off and there is no loss at the power converter and at super-capacitor. The fuel consumption of the 150-kW engine–generator set is given by $y = \frac{7.76}{3600} + \frac{0.156}{3600} x$, where "$x$" means output power of the generator in kilowatts and "y" means consumption of diesel fuel in liters per second.

- **(a)** For the motion described in problem 9, part 1, calculate total quantity of the consumed diesel fuel.
- **(b)** For the motion described in problem 9, part 2, calculate total quantity of the consumed diesel fuel
- **(c)** For the motion described in problem 9, part 2, plot the voltage of the super-capacitor according to the time. In here, the initial and final value of the voltage of the capacitor should be 600 V.
- **(d)** For an hour, 8 times of motion described in problem 9, part 1 and 8 times of motion described in problem 9, part 2 have been done, and for other times of the hour the generator only supplies the electricity to the auxiliary load. For such operation, calculate total quantity of the consumed diesel fuel for an hour.

(4) For a year, calculate the saving of diesel fuel cost of the system shown in Fig. P1.14 compared to the system shown in Fig. P1.13 under the following assumptions.

The price of diesel fuel is $1/liter, and the operation time of RTGC is 5000 h/year, the operating patterns are given by parts 2(c) and 3(d), respectively.

(5) Compare the advantages and disadvantages of the system shown in Fig. P1.14 against the system shown in Fig. P1.13 in the following viewpoints:

- **(a)** Total life cycle cost (Initial cost and running cost)
- **(b)** Effects to environment
- **(c)** Control performance

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