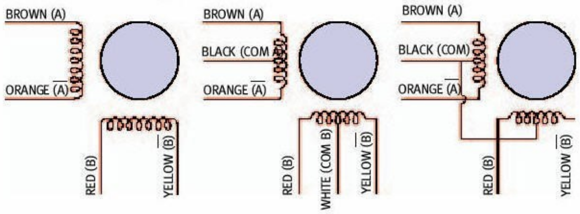
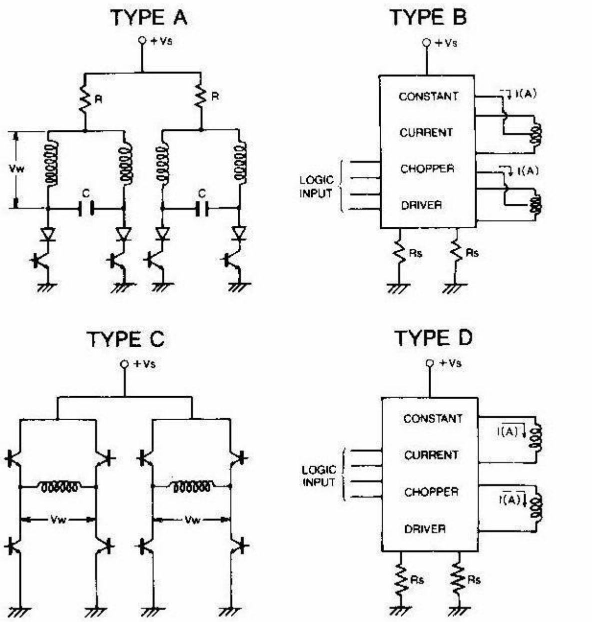
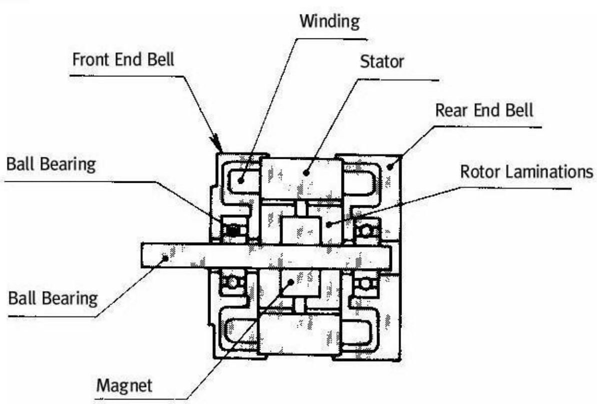
Stepper Motor Operation and Theory

Lead Wire Configuration and Color Guide



Typical Drive Circuits





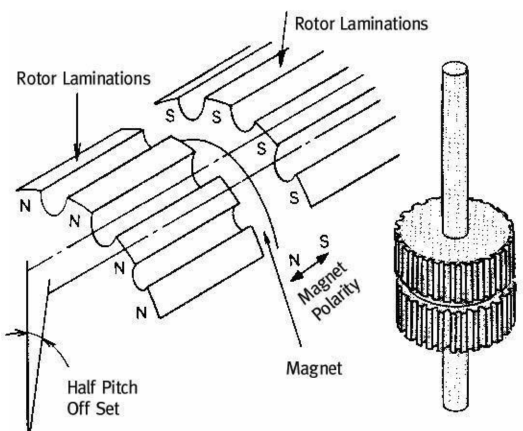


Fig. 5-2 Rotor Construction

Typical Stepping Motor Applications

For accurate positioning of X-Y tables, plotters, printers, facsimile machines, medical applications, robotics, barcode scanners, image scanners, copiers, etc.

Construction

There are three basic types of step motors: variable reluctance (VR), permanent magnet (PM) and hybrid. the hybrid type step motor design has the desirable features of both the VR and PM. It has high resolution, excellent holding and dynamic torque and can operate at high stepping rate.

In Fig. 5-1 construction of SKC stepping motor is shown.
In Fig. 5-2 the detail of rotor construction is shown.

Stepping Motor Theory

Using a 1.8 degree, unipolar, 4-phase stepping motor as an example, the following will explain the theory of operation. Referring to Fig. 6-1, the number of poles on the stator is 8 spaced at 45 degree intervals. Each pole face has 5 teeth spaced at 7.2 degree intervals. Each stator pole has a winding as shown in Fig. 6-1.

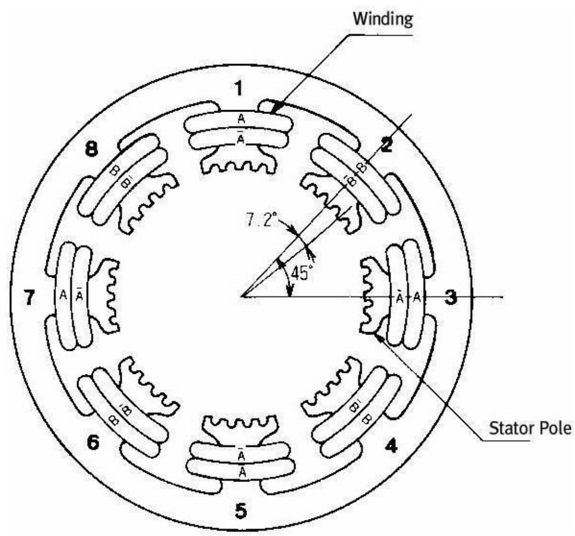


Fig. 6-1 Stator

When applying the current to the windings in the following sequence per Table 6-1, the stator can generate the rotating magnetic field as shown in Fig. 6-2 (steps 1 thru 4).

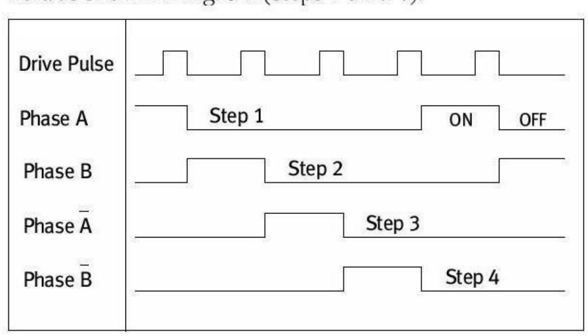
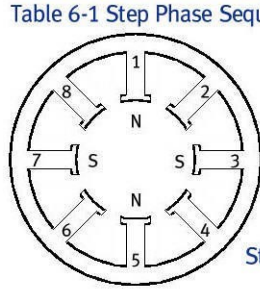
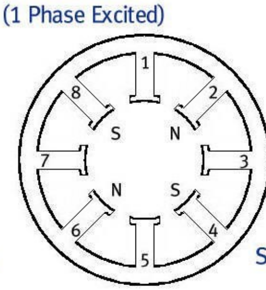


Table 6-1 Step Phase Sequence (1 Phase Excited)



Step 1



Step 2

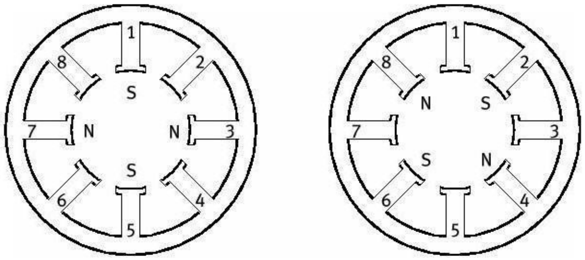


Fig. 6-2 Rotational Magnetic Field Generated by Phase Sequence

The hybrid rotor has 2 sets (stacks) of laminations separated by a permanent magnet. Each set of lams has 50 teeth and are offset from each other by ½ tooth pitch. This gives the rotor 50 N and 50 S poles at the rotor O.D.

Fig. 6-3 illustrates the movement of the rotor when the phase sequence is energized.

In step 1, phase A is excited so that the S pole of the rotor is attracted to pole 1,5 of the stator which is now a N pole, and the N pole of the rotor is attracted to pole 3,7 of the stator which is a S pole now. At this point there is an angle difference between the rotor and stator teeth of 1/4 pitch (1.8 degrees). For instance, the stator teeth of poles 2,6 and 4,8 are offset 1.8 degrees from the rotor teeth.

In step 2, there is a stable position when a S pole of the rotor is lined up with pole 2,6 of the stator and a N pole of the rotor lines up with pole 4,8 of stator. The rotor has moved 1.8 degrees of rotation from step 1.

The switching of phases per steps 3, 4 etc. produces 1.8 degrees of rotation per step.

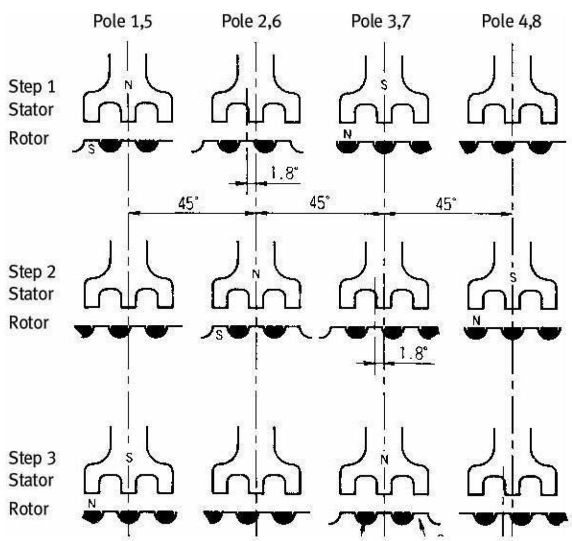


Fig. 6-3 1 Phase Excitation Sequence

Technical Data and Terminology

7-1 Holding Torque
The maximum steady torque that can be applied to the shaft of an energized motor without causing rotation.

7-2 Detent Torque
The maximum torque that can be applied to the shaft of a non-energized motor without causing rotation.

7-3 Speed-Torque Curve
The speed-torque characteristics of a stepping motor are a function of the drive circuit, excitation method and load inertia.

7-4 Maximum Slew Frequency
The maximum rate at which the step motor will run and remain in synchronism.

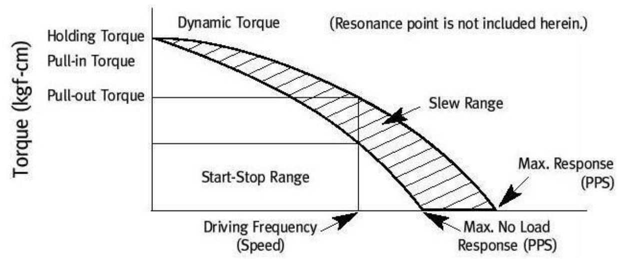


Fig. 7-1 Speed - Torque Curve

7-5 Maximum Starting Frequency
The maximum pulse rate (frequency) at which an unloaded step motor can start and run without missing steps or stop without missing steps.

7-6 Pull-out Torque
The maximum torque that can be applied to the shaft of a step motor (running at constant speed) and not cause it to lose step.

7-7 Pull-in Torque
The maximum torque at which a step motor can start, stop and reverse the direction of rotation without losing step. The maximum torque at which an energized step motor will start and run in synchronism, without losing steps, at constant speed.

7-8 Slewing Range
This is the area between the pull-in and pull-out torque curves where a step motor can run without losing step, when the speed is increased or decreased gradually. Motor must be brought up to the slew range with acceleration and deceleration technique known as ramping.

7-9 Start-Stop Range
This is the range where a stepping motor can start, stop and reverse the direction of rotation without losing step.

7-10 Accuracy
This is defined as the difference between the theoretical and actual rotor position expressed as a percentage of the step angle. Standard is ±5%. An accuracy of ±3% is available on special request. This positioning error is noncumulative.

7-11 Hysteresis Error
This is the maximum accumulated error from theoretical position for both forward and backward direction of rotation. See Fig 7-2.

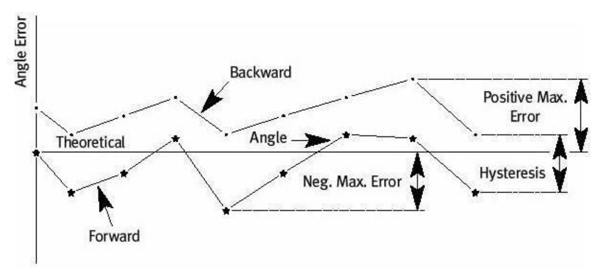


Fig. 7-2 Step Angle Accuracy

7-12 Resonance
A step motor operates on a series of input pulses, each pulse causing the rotor to advance one step. In this time the motor's rotor must accelerate and then decelerate to a stop. This causes oscillation, overshoot and vibration. There are some speeds at which the motor will not run. This is called its resonant frequency. The objective is to design the system so that no resonant frequencies appear in the operating speed range. This problem can be eliminated by means of using mechanical dampers, external electronics, drive methods and step angle changes.

Drive Methods

8-1 Drive Circuits

The operation of a step motor is dependent upon an indexer (pulse source) and driver. The indexer feeds pulses to the driver which applies power to the appropriate motor windings. The number and rate of pulses determines the speed, direction of rotation and the amount of rotation of the motor output shaft. The selection of the proper driver is critical to the optimum performance of a step motor. Fig. 8-1 shows some typical drive circuits.

These circuits also illustrate some of the methods used to protect the power switches against reverse voltage transients.

8-1.1 Damping Methods

These circuits can also be used to improve the damping and noise characteristics of a step motor. However, the torque at higher pulse rates (frequency) can be reduced so careful consideration must be exercised when selecting one of these methods.

Examples:

1. Diode Method — Fig. 8-1 (a)
2. Diode + Resistance Method — Fig. 8-1 (b)
3. Diode + Zener Diode Method — Fig. 8-1 (c)
4. Capacitor Method — Fig. 8-1 (d)

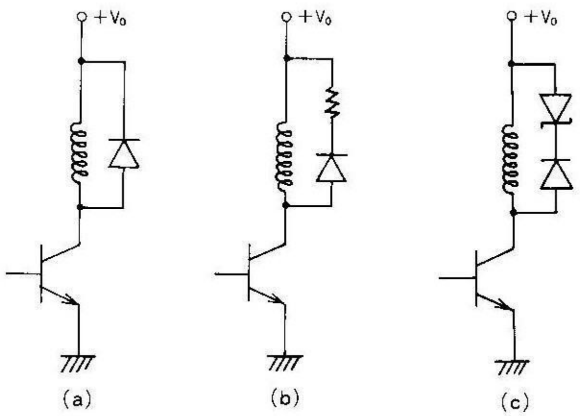


Fig. 8-1

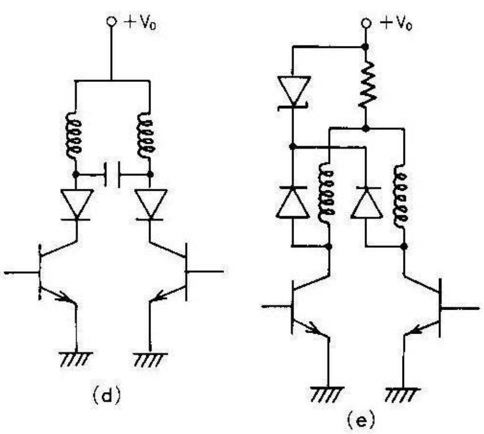


Fig. 8-1

8-1.2 Stepping Rate

A step motor operated at a fixed voltage has a decreasing torque curve as the frequency or step rate increases. This is due to the rise time of the motor winding which limits the value of the coil current. This is determined by the ratio of inductance to resistance (L/R) of the motor and driver as illustrated in Fig 8-2 (a).

Compensation for the L/R of a circuit can be accomplished as follows:

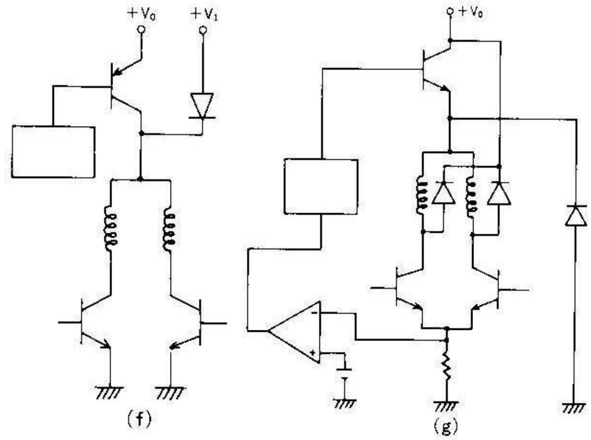


Fig. 8-1

a) Increase the supply voltage and add a series resistor, Fig 8-2 (b), to maintain rated motor current and reduce the L/R of the circuit.

b) Increase the supply voltage, Fig 8-2 (c), improving the time constant (L/R) of the circuit. However, it is necessary to limit the motor current with a bi-level or chopped supply voltage.

Examples:

1. Constant Voltage Drive — Fig. 8-1 (e)
2. Dual Voltage (Bi-level) Drive — Fig. 8-1 (f)
3. Chopper Drive — Fig. 8-1 (g)

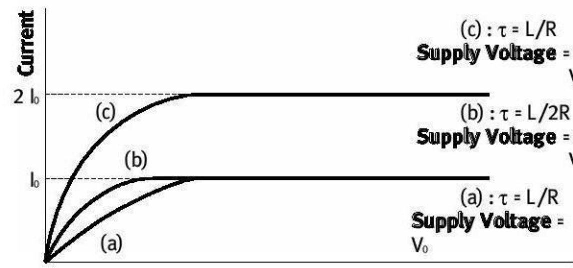


Fig. 8-2

8-2 Excitation Methods

In Table 8-1 are descriptions and features of each method.

		Excitation Method		
		Single Phase	Dual Phase	1-2 Phase
Switching sequence	Pulse			
	phase A			
	phase B			
	phase A			
	phase B			
Features		Hold & running torque reduced by 39% Increased efficiency. Poor step accuracy.	High torque Good step accuracy.	Poor step accuracy. Good resonance characteristics. Higher pulse rates. Half stepping

8-3 Bipolar and Unipolar Operation

Bipolar Winding - the stator flux is reversed by reversing the current in the winding. It requires a push-pull bipolar drive as shown in Fig. 8-3. Care must be taken to design the circuit so that the transistors in series do not short the power supply by coming on at the same time. Properly operated, the bipolar winding gives the optimum performance at low to medium step rates.

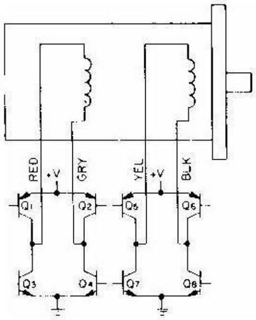


Fig. 8-3 Bipolar Method

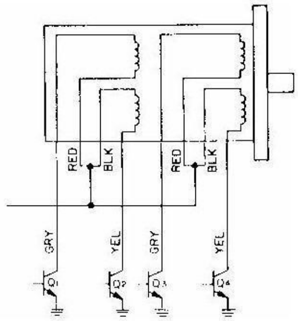


Fig. 8-4 Unipolar Method

Unipolar Winding - has two coils wound on the same bobbin per stator half. Flux is reversed by energizing one coil or the other coil from a single power supply. The use of a unipolar winding, sometimes called a bifilar winding, allows the drive circuit to be simplified. Not only are one-half as many power switches required (4 vs. 8), but the timing is not as critical to prevent a current short through two transistors as is possible with a bipolar drive. Unipolar motors have approxi mately 30% less torque at low step rates. However, at higher rates the torque outputs are equivalent.

Step Motor Load Calculations and Selection

To select the proper step motor, the following must be determined:

1. Load Conditions
   - 1-a. Friction Load
   - 1-b. Load Inertia
2. Dynamic Load Conditions
   - 2-a. Drive Circuit
   - 2-b. Maximum Speed (PPS/Frequency)
   - 2-c. Acceleration/Deceleration Pattern

   With the above load information the proper step motor can be selected.

9-1 Load Inertia

The following is an example for calculating the inertia of a hollow cylinder.

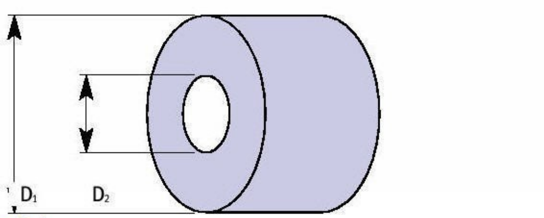


Fig. 9-1

$J = \frac{1}{8} \cdot M \cdot (D1^2 + D2^2)$ (kg-cm^2)

Where M: mass of pulley (kg)
D1: outside diameter (cm)
D2: inside diameter (cm)

9-2 Linear systems can be related to rotational systems by utilizing the kinetic energy equations for the two systems. For linear translations:

$\text{Energy} = \frac{1}{2} M v^2 = \frac{1}{2} J w^2$

Where M: mass
v: velocity
J: inertia
w: angular velocity

1) Gear drive system
When gears are used to drive a load, the inertia reflected to the motor is expressed by the following equation:

$J = (Z1/Z2)^2 \cdot (J2 + J3) + J1$

Where Z1, Z2: No. of gear teeth
J1, J2, J3: inertia (kg-cm^2)
J: reflected inertia, (kg-cm^2)

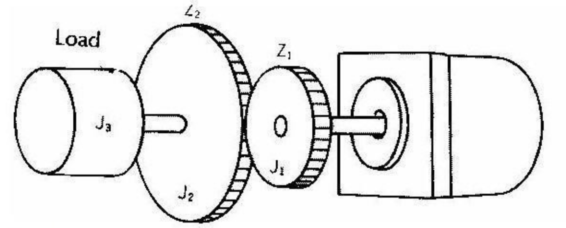


Fig. 9-2

2) Pulley & belt system. A motor and belt drive arrangement is used for linear load translation

$J = 2\,J1 + \frac{1}{4} M\,D2$

Where J: Total inertia reflected to motor
J1: inertia of pulley (kg-cm^2)
D: diameter of pulley (cm^2)
M: weight of load (kg)

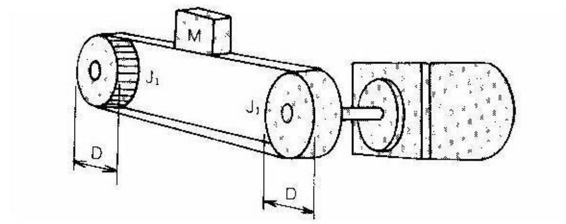


Fig. 9-3

9-3 Determination of load acceleration/deceleration pattern.

9-3-1 Load Calculation
To determine the torque required to drive the load the following equation should be satisfied.

$Tm = Tf + Tj$

Where: Tm: Pullout torque (kgf-cm)
Tf: Friction torque (kgf-cm)
Tj: Inertia load (kgf-cm)

$TJ = (JR + JL)/g \cdot (p \cdot q \cdot s)/180 \cdot df/dt$

JR: Rotor inertia [kg-cm^2]
JL: Load inertia [kg-cm^2]
q: Step angle [deg]
g: Gravity acceleration = 980 [cm/sec^2]
f: Drive frequency [PPS]

Example: A 1.8 degree step motor is to be accelerated from 100 to 1,000 pulses per second (PPS) in 50 ms, JR = 100 g-cm^2, J1 = 1 kg-cm^2. The necessary pullout torque is:

$TJ = (0.1 + 1)/980 \cdot (p \cdot 1.8)/180 \cdot (1000 - 100)/0.05$
$= 0.635$ (kgf-cm)

9-3-2 Linear acceleration
For linear acceleration as shown in Fig. 9-4 frequency f(t), inertial system frequency fj(t) and inertia load Tj are expressed as follows:

f(t) = (f1 - f0)/t1 · t + f0
TJ = (JR + JL)/g · (p · q · s)/180 · (f1 - f0)/t1

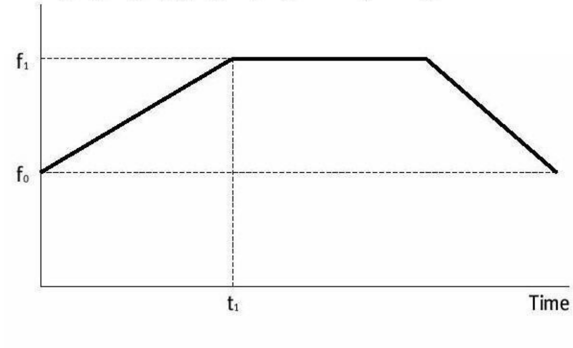


Fig. 9-4 Linear Acceleration

9-3-3 Exponential acceleration
For exponential as shown in Fig. 9-5, drive frequency f(t) and inertia load Tj are expressed as follows:

f(t) = f1 · (1 - e^-(t/t)) + f0
TJ = (JR + JL)/g · (p · q · s)/180 · f1/t · e^-(t/t)

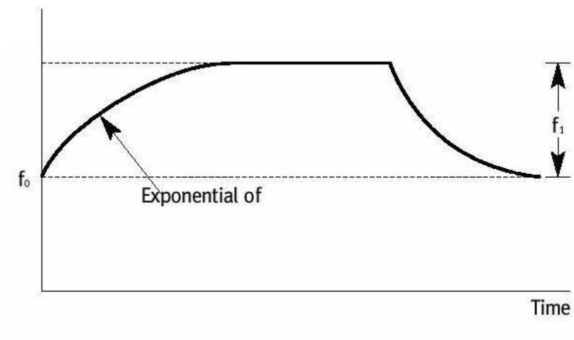


Fig. 9-5 Exponential Acceleration

Dynetics
DYNAMIC IN MECHATRONICS