Dr. Norbert Cheung's Lecture Series

Level 5 Topic no: 5

Motion Actuators

Contents

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1. Introduction

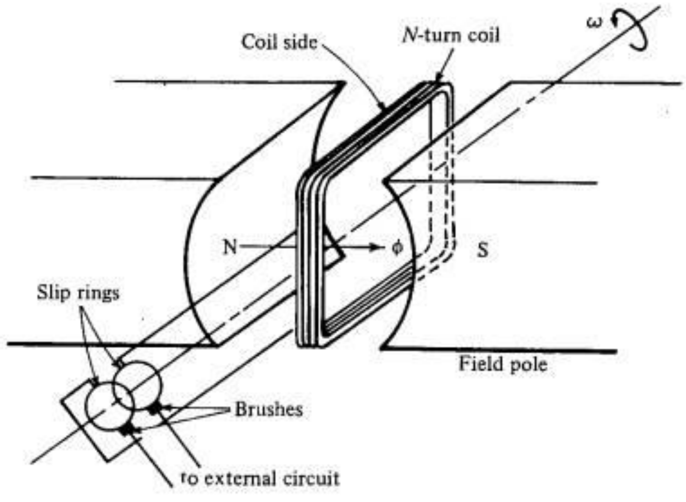
- Motion Actuators is the driving force behind a motion control system. For small/medium power output, actuators are predominantly electrical devices
- For high power with slower response, hydraulic servo systems are used. For simple on/off type motions, pneumatic drives are used.
- This topic is mainly focused on high motion dynamics and high precision electrical motion actuators.
- The motion actuators can be classified as follows:

  - Electrically driven or non-electrically driven
  - For <u>non electrically driven</u> devices:
    + Hydraulic servo system (incompressible fluid)
    + Pneumatic on/off actuators (compressible fluid)
  - For <u>electrical drives</u>:
    + Direct drive versus indirect drive
    + Driving principle: DC verses AC motors
    + Coil construction: single phase versus multi-phase
    + Motion: linear versus rotary
    + Driving technique: DC, induction, variable reluctance, synchronous
    + Open loop drives versus closed loop drives

2. Review on some types of Electric Motor

Brush Type DC Motor Drive Principle

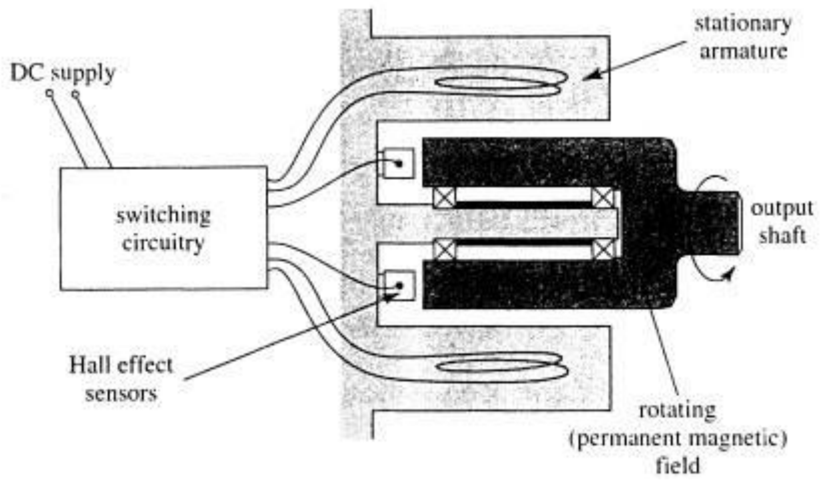
- Almost a linear device, flux produced by magnet is constant
- Relies on commutator. Needs a powerful permanent magnet
- Inertia of coil is low, but the inertia of the rotor iron is high
- The heating problem forbids overdriving of the motor



(a)

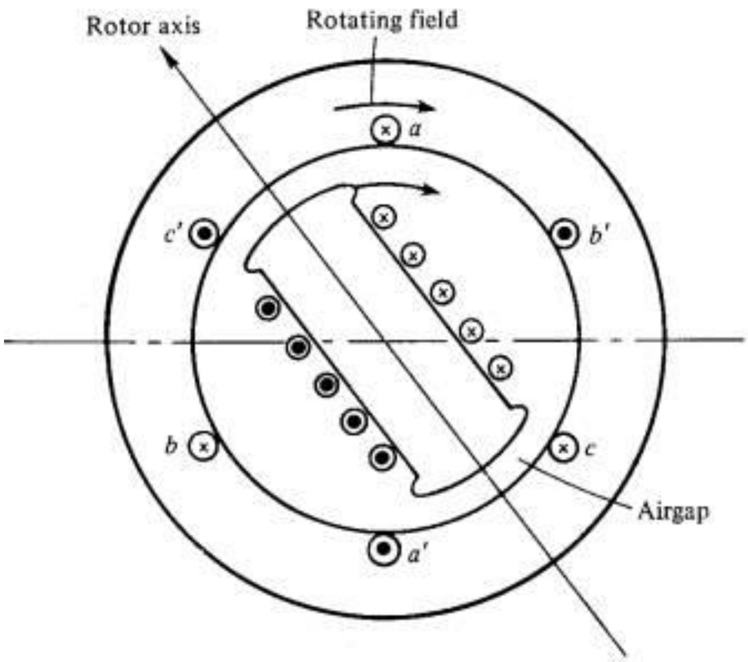
Brushless DC Motor Drive Principle

- Commutated electronically, sensed by Hall effect element
- Coil and the magnet swapped places, when compared to DC motor.
- Trapezoidal current drive, multi-phase
- Much higher power than brush type.



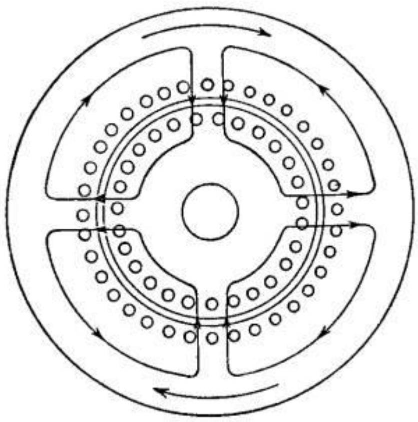
Synchronous Motor Drive Principle

- A rotating field is produced by the stator and the rotor follows the rotating field
- Very similar to brushless DC motor, but it is driven by sinusoidal waveforms
- Needs variable frequency drive, and there is heat dissipation problem
- Basically the drive exhibits linear control characteristics
- Amount of torque is determined by the lead-lag angle
- Torque is produced by the magnetic angle difference between the rotor and stator.
- In most cases, the rotating core is a magnet



The Induction Motor driving Principle

- Torque produced by the motor is based on the "slip velocity"
- Torque control for this type of motor is more complicated than the previous two types
- The power-house of modern electric apparatus
- Not suitable for high precision control

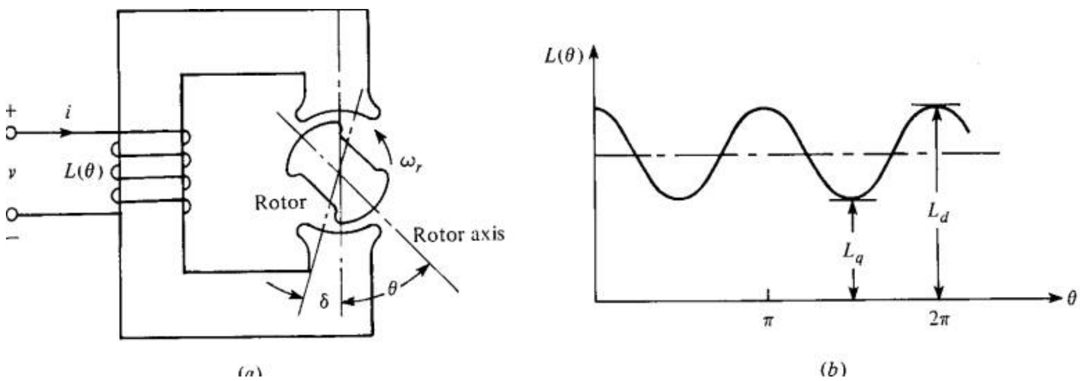


4-pole Stator and Rotor

Fig. 6.1

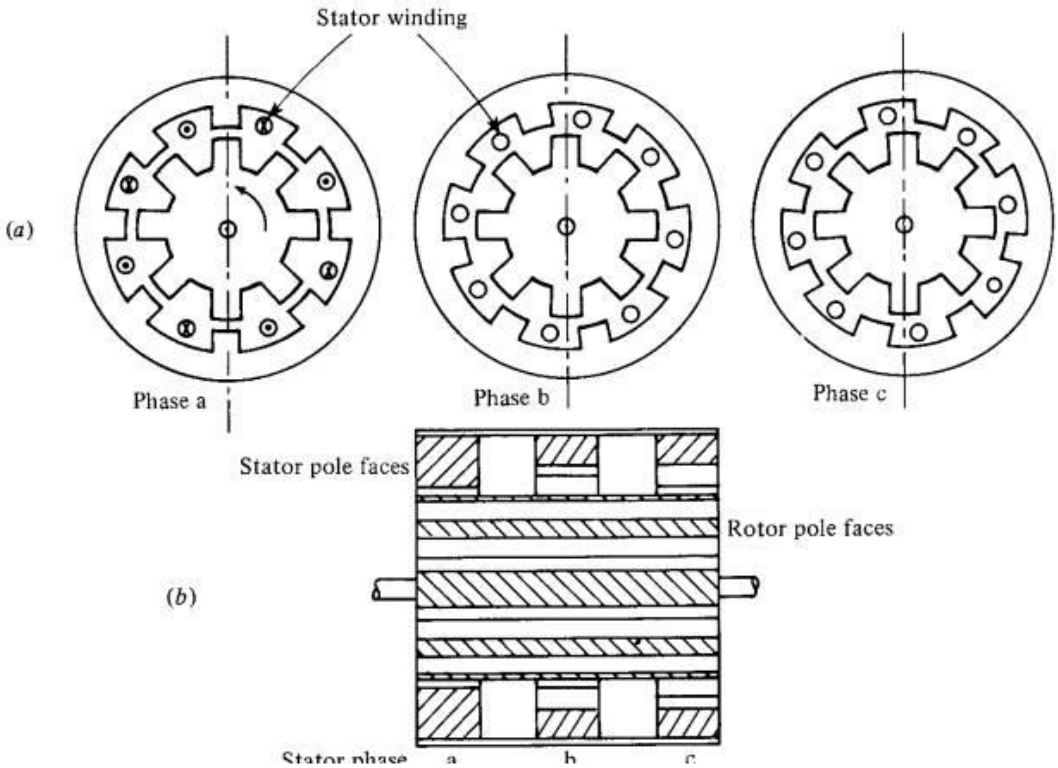
The Variable Reluctance Motor

- Very simple and robust structure
- No copper cage, no magnet, no commutators
- Force depends on the change of reluctance (i.e. on magnetic flux)
- Magnetic flux displays nonlinear characteristics



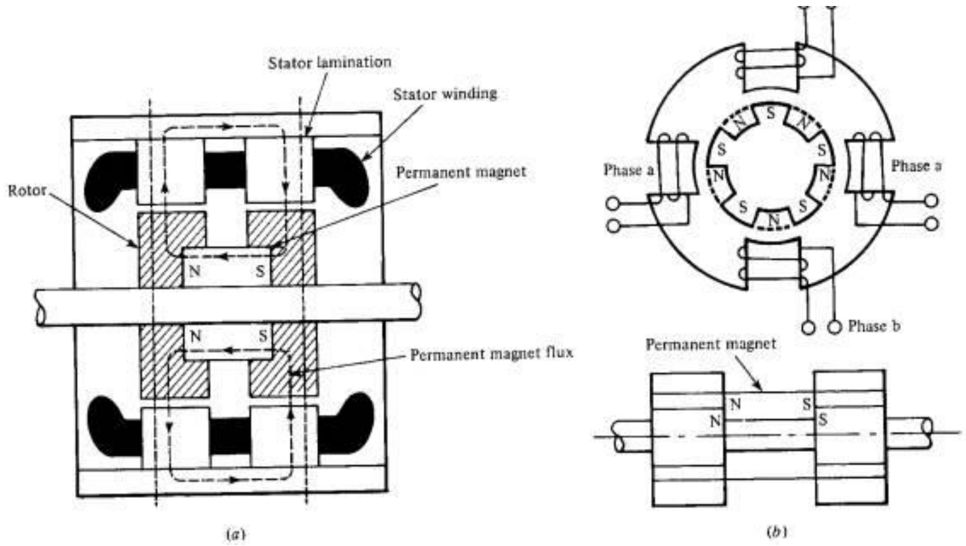
The Variable Reluctance Stepping Motor

- Very similar to VR motor, low cost, robust
- Step angle is usually 7.5 degrees or 15 degrees



The Hybrid Variable Reluctance Stepping Motor

- Similar to VR motor, but a permanent magnet is added
- Step angle is usually 1.5 degrees, cost is higher than VR step motor



2. Specification Requirements of Motion Control Actuators

- High precision
- Accurate repeatability
- Minimize mechanical coupling
- Zero backlash
- Low inertia
- High acceleration/deceleration
- Low cost, low maintenance
- Harsh operating environment
- Easily controllable

Load characteristics, performance requirements, and coupling techniques need to be understood before the designer can select the best motor/drive for the job. While not a difficult process, several factors need to be considered for an optimum solution. A good designer will adjust the characteristics of the elements under his control –including the motor/drive and the mechanical transmission type (gears, lead screws, etc.) – to meet the performance requirements. Some important parameters are listed below.

Torque

Rotational force (ounce-inches or pound-inches) defined as a linear force (ounces) multiplied by a radius (inches). When selecting a motor/drive, the torque capacity of the motor must exceed the load. The torque a motor can provide may vary with its speed. Individual speed/torque curves should be consulted by the designer for each application.

Inertia

An object's inertia is a measure of its resistance to change in velocity. The larger the inertial load, the longer it takes a motor to accelerate or decelerate that load. However, the speed at which a motor rotates is independent of inertia. For rotary motion, inertia is proportional to the mass of the object being moved times the square of its distance from the axis of rotation.

Friction

All mechanical systems exhibit some frictional force, and this should be taken into account when sizing the motor, as the motor must provide torque to overcome any system friction. A small amount of friction is desirable since it can reduce settling time and improve performance.

Torque-to-Inertia Ratio

This number is defined as a motor's rated torque divided by its rotor inertia. This ratio is a measure of how quickly a motor can accelerate and decelerate its own mass. Motors with similar ratings can have different torque-to-inertia ratios as a result of varying construction.

Load Inertia-to-Rotor Inertia Ratio

For a high performance, relatively fast system, load inertia reflected to the motor should generally not exceed the motor inertia by more than 10 times. Load inertias in excess of 10 times the rotor inertia can cause unstable system behavior and inefficent power usage.

Torque Margin

Whenever possible, a motor/drive that can provide more motor torque than the application requires should be specified. This torque margin accommodates mechanical wear, lubricant hardening, and other unexpected friction. Resonance effects, while dramatically reduced with Compumotor's microstepping systems, can cause a stepper motor's torque to be slightly reduced at some speeds. Selecting a motor/drive that provides at least 50% margin for steppers, and 20% for servos, above the minimum needed torque is good practice.

Velocity

Because available torque varies with velocity, motor/drives must be selected with the required torque at the velocities needed by the application. In some cases, a change in the type of mechanical transmission used is needed to achieve the required performance.

Resolution

The positioning resolution required by the application will have an effect on the type of transmission used and the motor resolution. For instance, a leadscrew with 4 revolutions per inch and a 25,000-step-per-revolution motor/drive would give 100,000 steps per inch. Each step would then be 0.00001 inches.

Duty Cycle

Servo motors can produce peak torque for *short* time intervals as long as the RMS or average torque is within the motor's continuous duty rating. To take advantage of this feature, the application torque requirements over various time intervals need to be examined so RMS torque can be calculated.

Solving Duty Cycle Limitation Problems

Operating a motor beyond its recommended duty cycle results in excessive heat in the motor and drive. This can destroy the motor and drive package. The duty cycle may be increased by providing active cooling to the drive and the motor. A fan directed across the motor and another directed across the drive's heatsink will result in increased duty cycle capability.

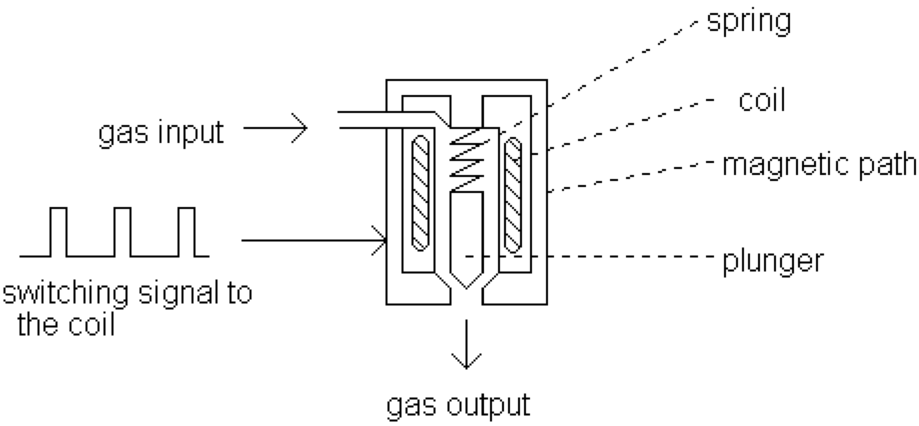
Note: Motors will run at case temperatures up to 100°C (212°F)—temperatures hot enough to burn individuals who touch the motors.

To Improve Duty Cycle:

- Use a motor large enough for the application
- Mount the drive with heatsink fins running vertically
- Fan cool the motor
- Fan cool the drive
- Put the drive into REMOTE POWER SHUTDOWN when it isn't moving, or reduce current (Steppers Only)
- Reduce the peak current to the motor (if possible)

2. Single Phase Linear Actuators

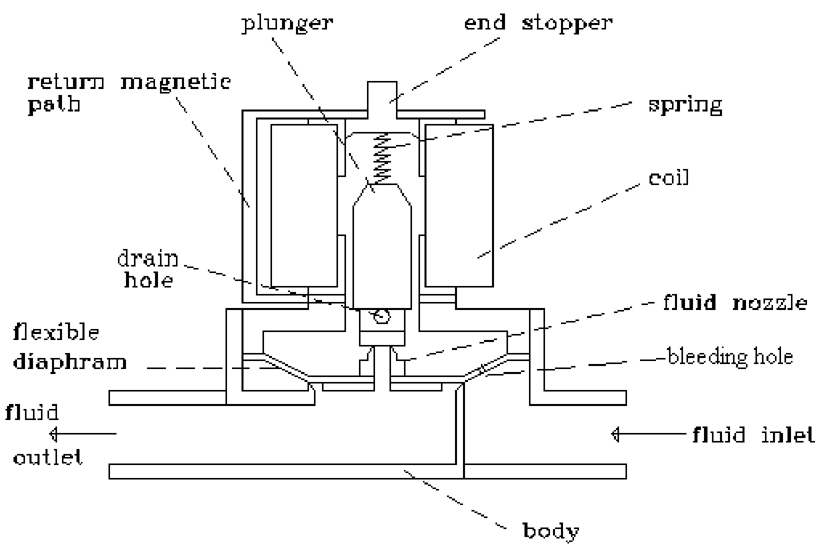
Bang-bang controlled solenoid valves



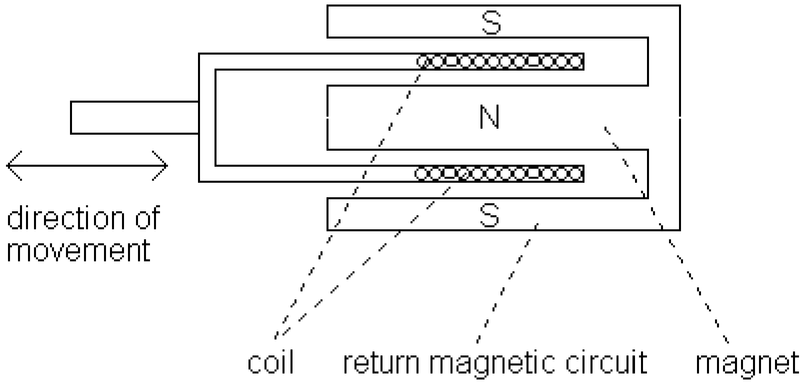
- For pressure control - e.g. fuel injection in cars
- Very high switching rate
- The on-off ratio will determine the amount of gas output
- Only useful for mechanical systems with large time constant

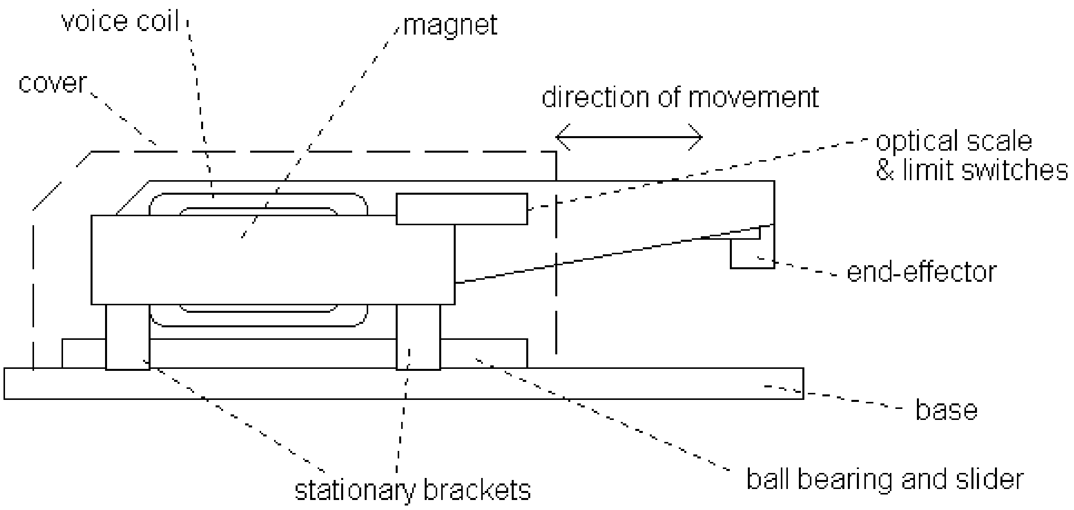
Single phase switching /proportional VR solenoid

- Primary useful for switching purpose
- Can be changed to proportional control, using complex control algorithm
- A two stage fluid valve
- Can be used as a servo valve in hydraulic servo systems



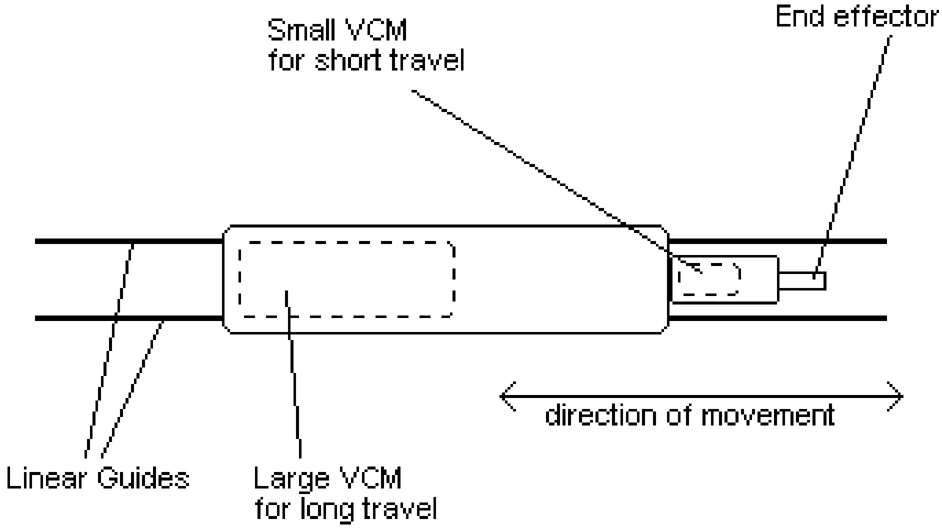
The Permanent Magnet Linear Motor (Voice Coil Motor)





- Excellent Linear characteristics
- High force to size ratio
- Expensive, needs a high flux density magnet
- For short travel only

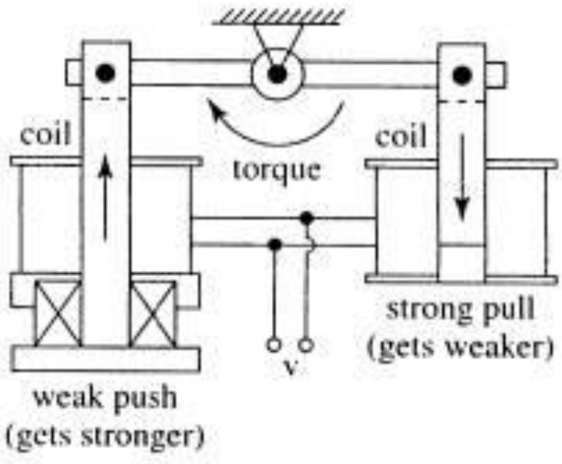
Special single phase actuators - the dual voice coil actuator



- Suitable for both long travel and high speed short stroke movements
- The actuator is arrange in the form of two voice coils motors (VCM)
- The small one responsible for high speed/short travels
- The larger one for lower speed and longer travels

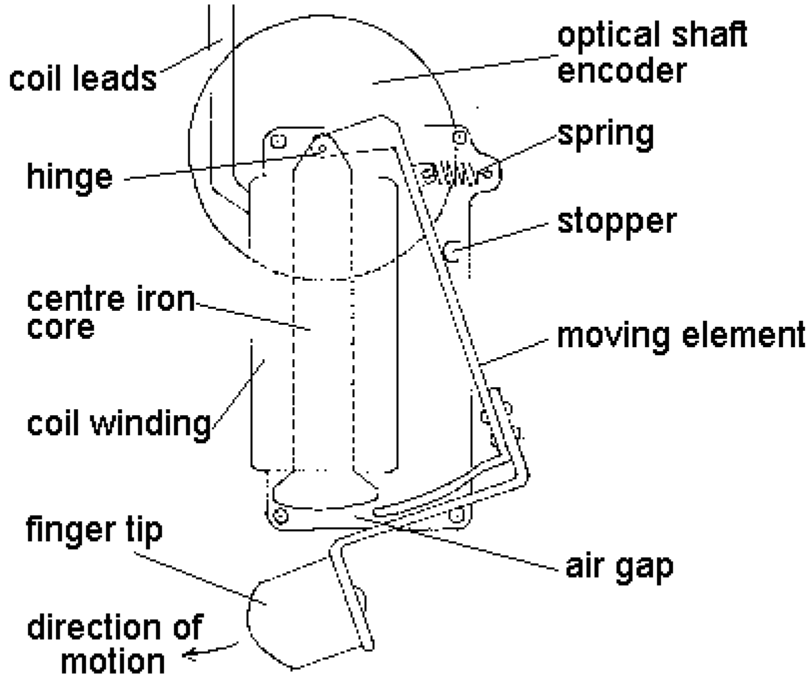
Servo Valves, using VR linear actuators

- The resultant torque is due to the torque difference between the two torque motors
- Used extensively in hydraulic servo valves

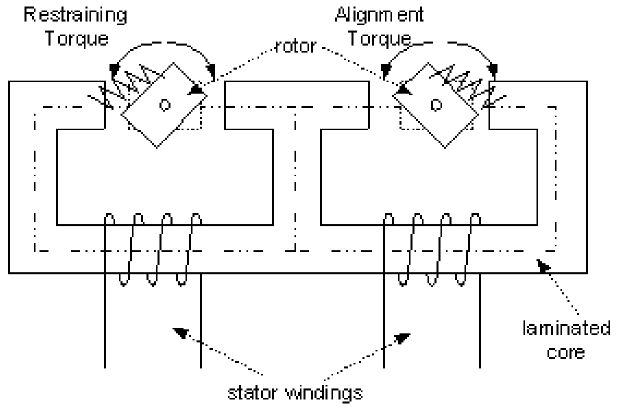


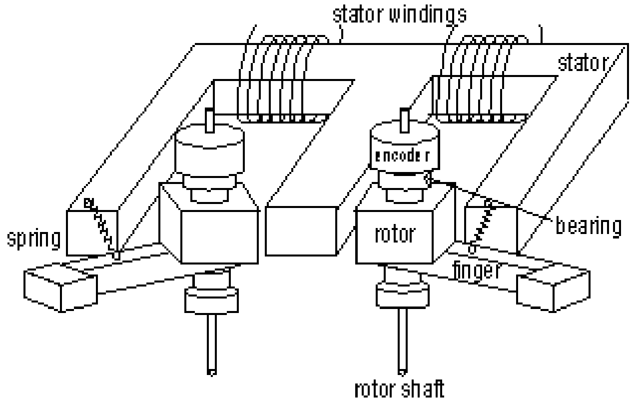
3. Rotary Actuators and Finger Grippers

A rotary finger gripper based on VR principle

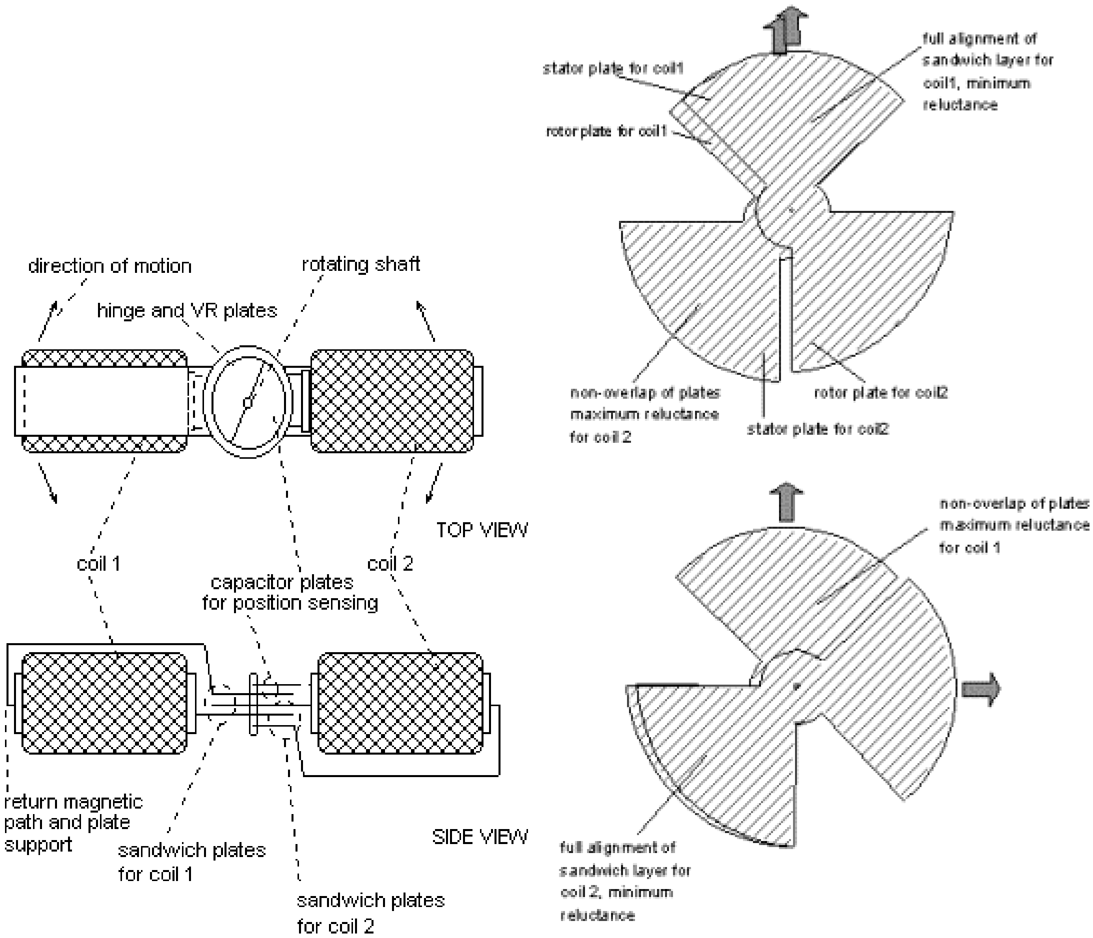


A rotary two-finger gripper

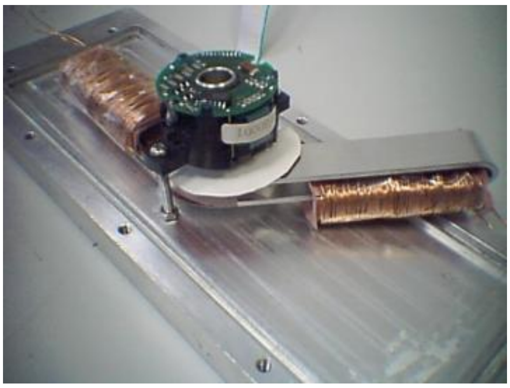


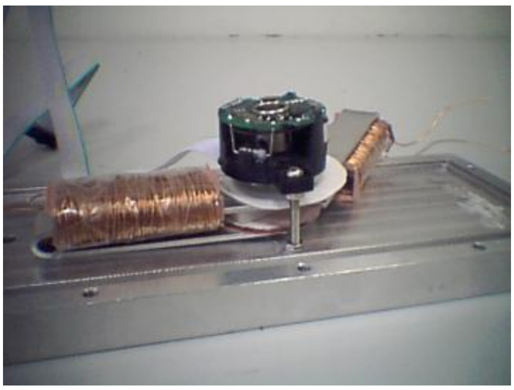


An Artificial Joint for Robotics Applications



The overall construction (left) & the centre circular plates (right)

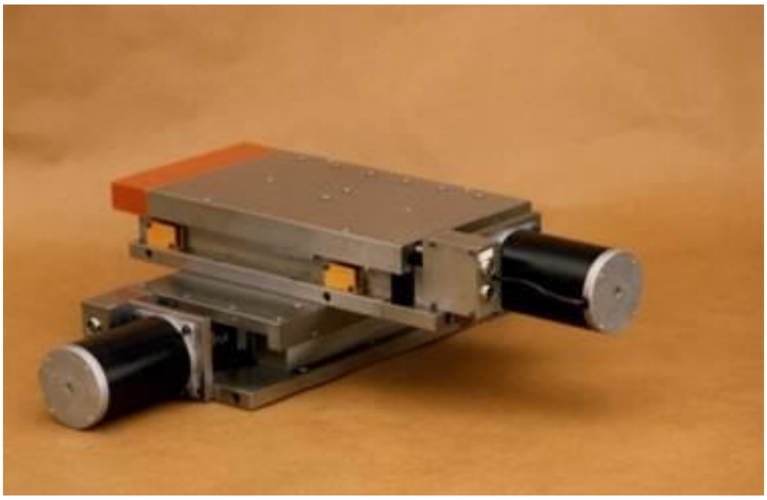


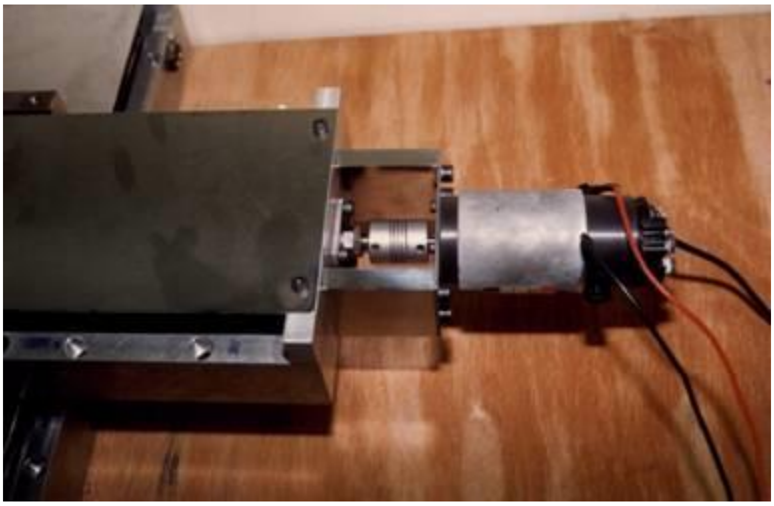


4. The Need for Direct Drive Actuators

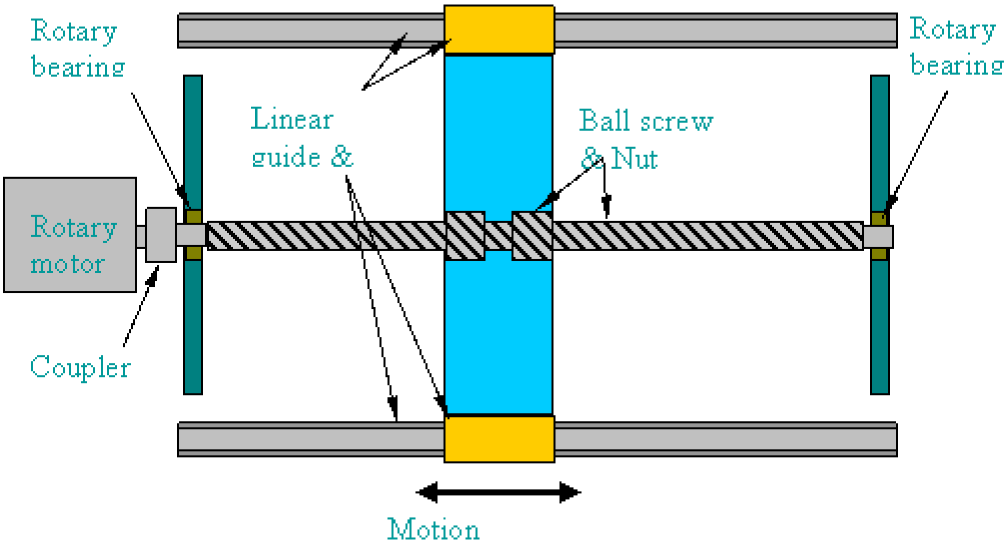
A traditional X-Y table - use extensively in manufacturing automation

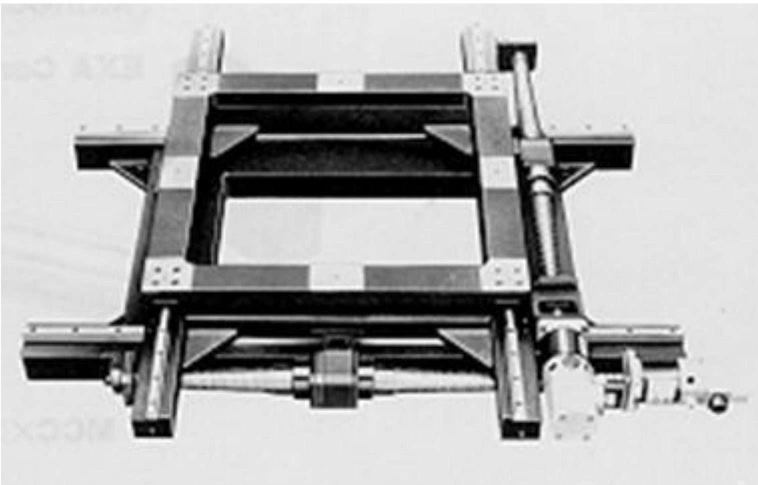
- One mechanical slide is responsible for one axis
- Needs complex couplings, rotary to linear translators (ie ball screws), and linear guide
- Requires complex mechanical alignments, frequent maintenance, and thorough lubrication
- The structure is complex, and the high precision mechanical parts are expensive.



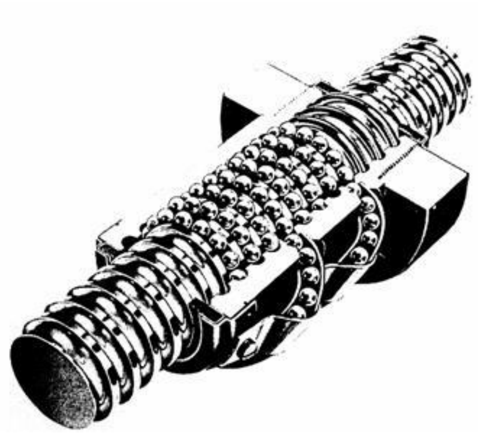


Construction of typical mechanical translation systems (1 dimensional & 2 dimensional)





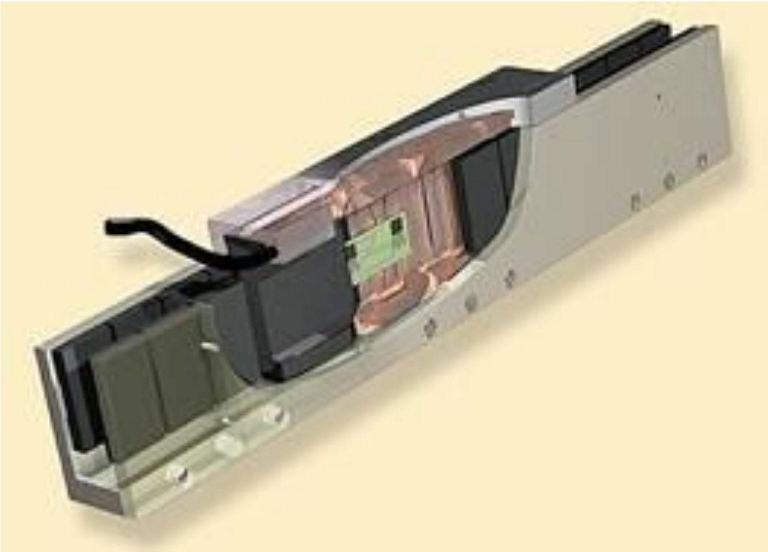
The Roller Ball Screw



The Correct Way to Go.....

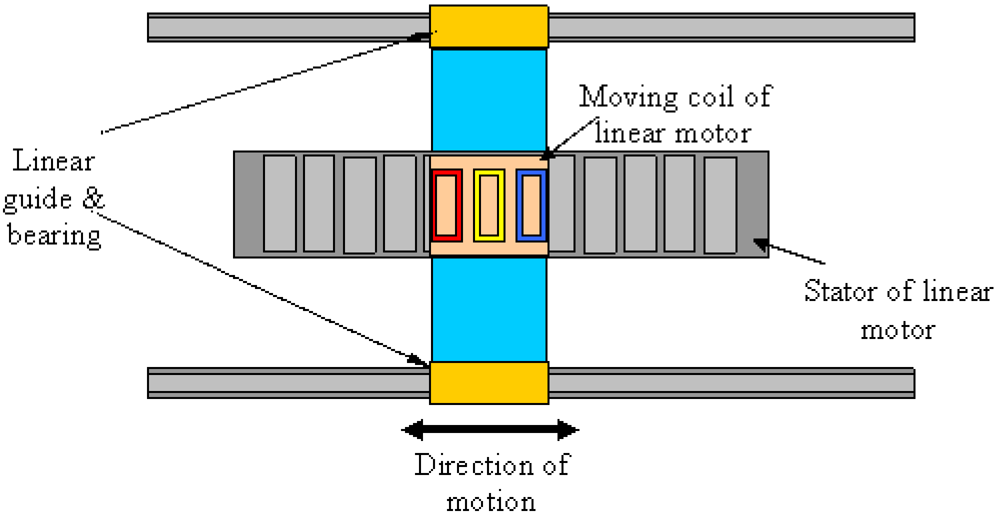
- Design specialized actuators instead of couplers
- Use advanced control algorithm to overcome the non-linearity
- Use complex software, but simple hardware
- Use direct-drive
- Simplify the mechanics through specilized direct drive actuators and advanced control methodologies.

5. Direct Drive Permanent Magnet Linear Motors

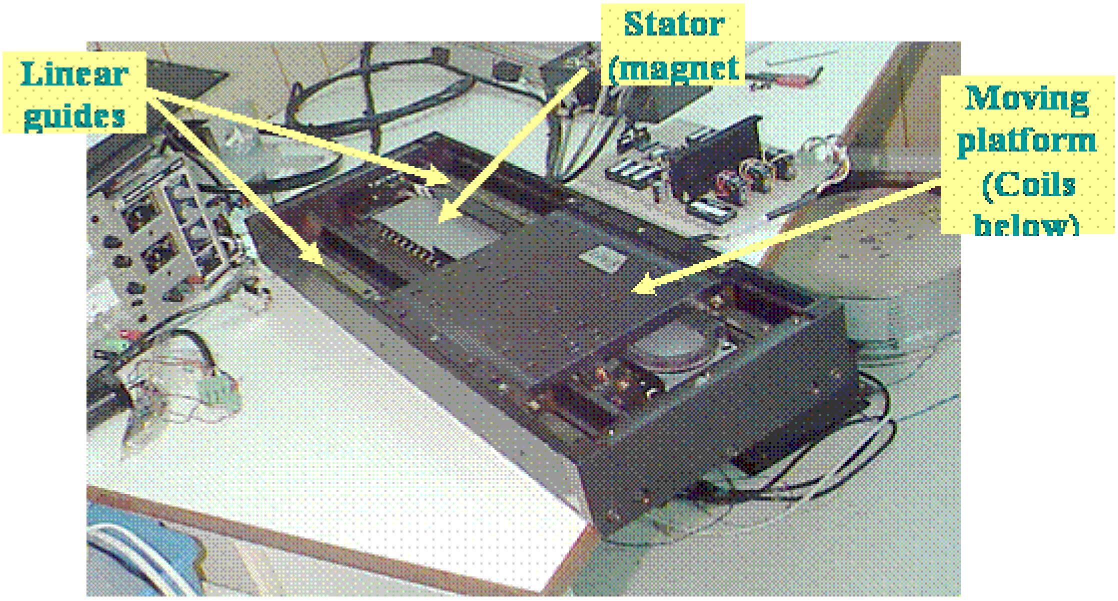


- The design is mostly based on the flattening out of a rotary design
- The left figure is a linear motor based on permanent magnet track and a 3 phase coil winding

- Construction of the PM linear brushless motor



- No mechanical translators and couplings
- Precision can be down to sub-micron level



The Coil Arrangements of the Permanent Magnet Linear Motor

- The beginning of winding A starts at zero reference
- The winding of phase B starts at an angle 2p/3 lagging phase A.
- For separate winding it is shifted a cycle backward at 8p/3
- But the return of the winding is at 5p/6 to minimize the size of the mover.
- The winding of phase C is exactly 4p/3 + 1 cycle lagging the winding of phase A

Fig3.2a

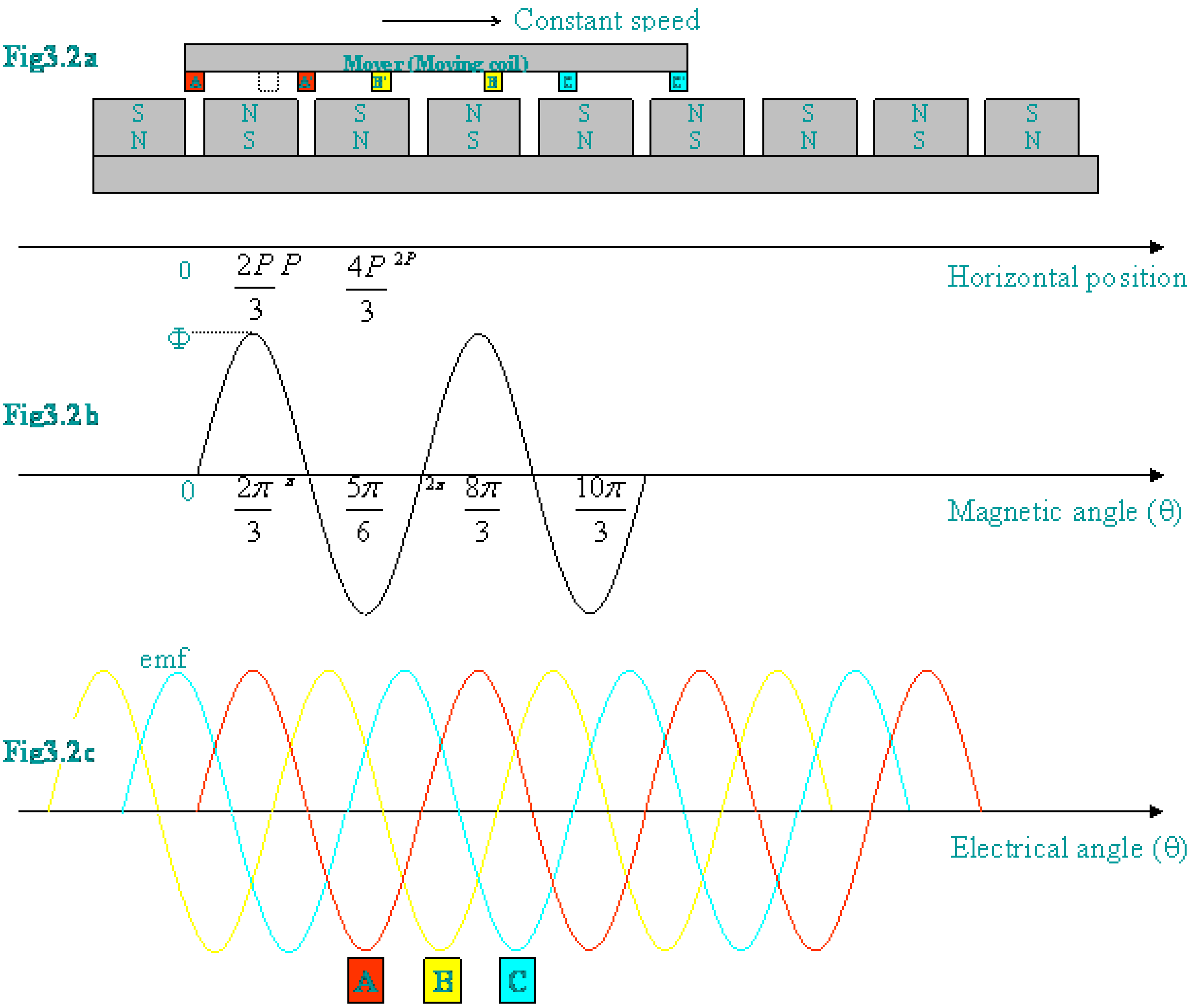


Fig3.2b

Fig3.2c

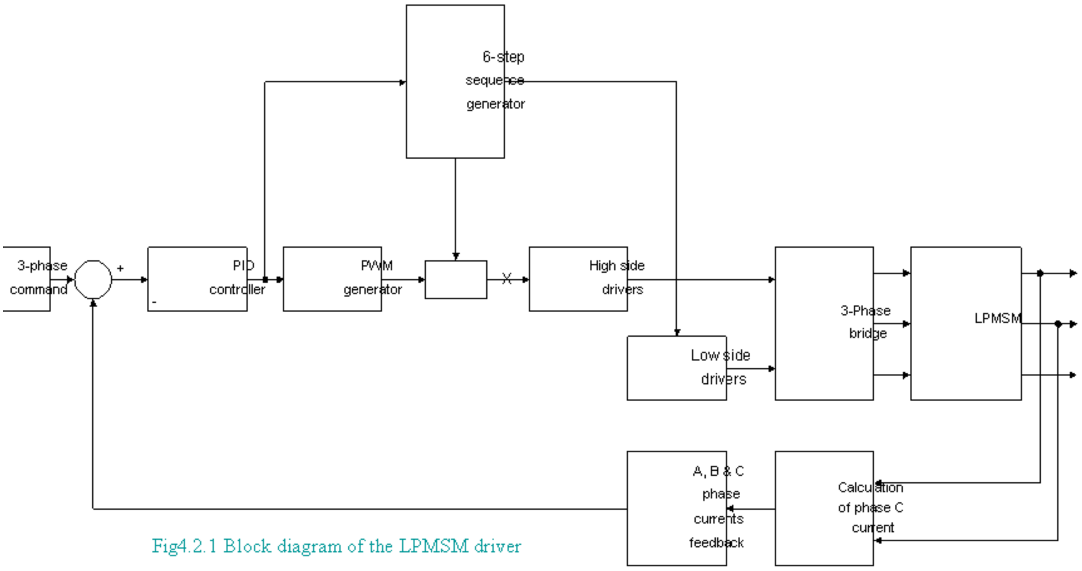


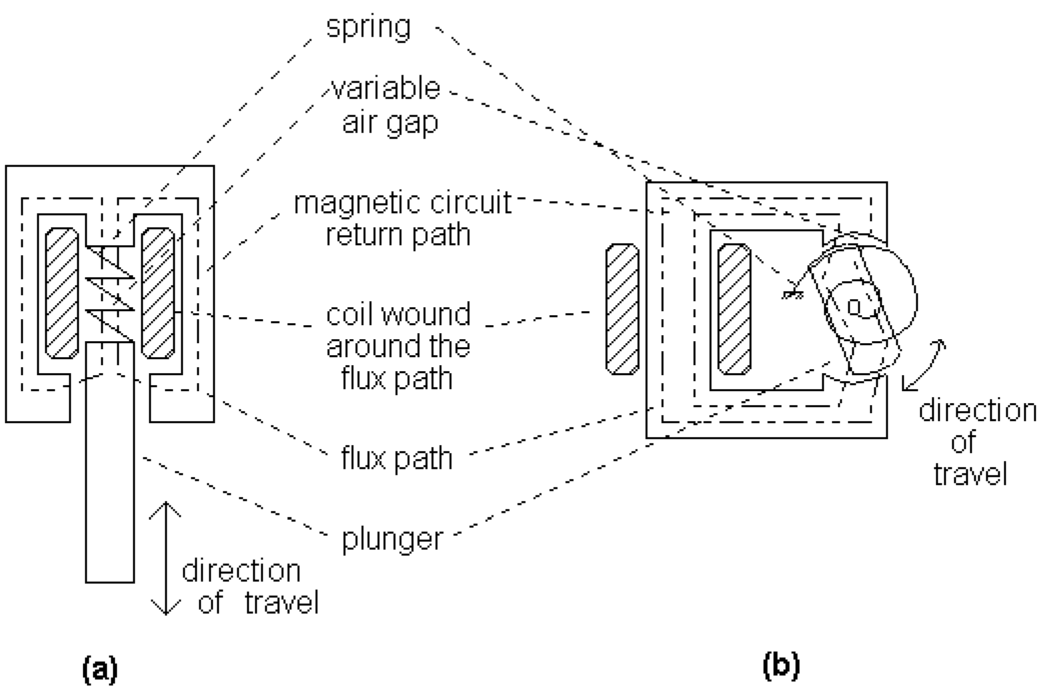
Fig4.2.1 Block diagram of the LPMSM driver

Driving the Permanent Magnet Linear Motor

6. Variable Reluctance Direct Drive Linear Motors

Advantages and Disadvantages of VR actuators

- Robust, can work under harsh environment
- Simple structure
- Maintenance Free
- No magnets – much easier to handle
- Low cost – structure contains coil and iron only
- Flexible structure – embedded into the system
- Easy to manufacture
- No heating problems
- But is has….. Nonlinear characteristics and structure dependent characteristics
- And it is difficult to control



Modelling of the Variable Reluctance Motion Actuator

The variable reluctance linear drive system has a highly non-linear characteristic due its non-linear flux behaviour. The complex dynamics can be described by the following equations:

$$v_j = R_j i_j + \frac{\partial \lambda_j (x, i_j)}{\partial x} \frac{dx}{dt} + \frac{\partial \lambda_j (x, i_j)}{\partial i_j} \frac{di_j}{dt} \bigg|_{j=1,2,3} \quad (1)$$

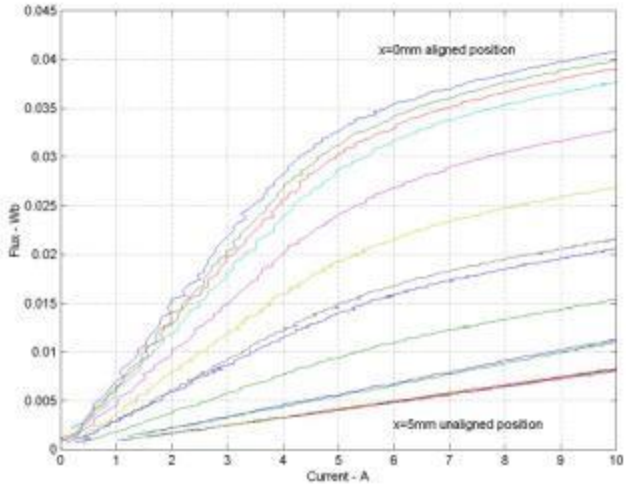
$$f_e = \sum_{j=1}^{3} \frac{\partial \int_0^{i_j} \lambda_j (x, i_j) di_j}{\partial x} = M \frac{d^2 x}{dt^2} + B \frac{dx}{dt} + f_l \quad (2)$$

where v_j, i_j, R_j and λ_j are the phase voltage, phase current, phase resistance and phase flux linkage respectively. x is the travel distance. f_e is the generated electromechanical force and f_l is the load force. M and B are the mass and the friction constant respectively. The most difficult part in modelling a variable reluctance motor is to model the flux linkage function $\lambda_j(x,i_j)$. In this paper, a family of flux-current curves under different distances is first established by measuring the phase voltage and current [6]. Figure 3 (a) shows the measurement results. Then a least square nonlinear two-dimensional surface fitting method [7] is applied to the flux-current chart so that the non-linear function $\lambda_j(x,i_j)$ can be represented by the following equation:

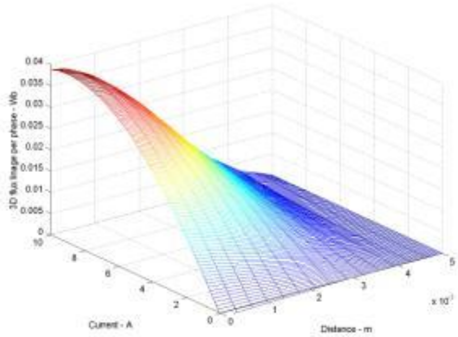
$$\lambda_j(x,i_j) = \sum_{m=0}^{4}\sum_{n=1}^{4} B_{(2n-1),m}\, i^{(2n-1)} \cos\left(\frac{m\pi x}{10^{-2}}\right) \tag{3}$$

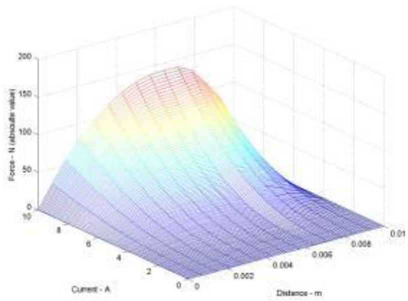
where the coefficient matrix $B_{(2n-1),m}$ is found by minimising the norm of $\sum_{k_1}\sum_{k_2}\left\|\lambda_j(x_{k_1}, i_{j,k_2}) - z_{k_1,k_2}\right\|^2$ where z_{k_1,k_2} is the measured flux at the point (x_{k_1}, i_{j,k_2}) and $k_1 \times k_2$ is the total number of the measurement data. Figure 3 (b) shows the 3D plot of the non-linear flux linkage function for one pole width (5mm), which is generated from Equation (3). To provide a versatile computer-aided design environment, the developed model is embedded in MATLAB/SIMULINK for simplifying the control algorithm design/evaluation at a later stage. The 3D force function per phase is calculated by substituting equation (3) into (2):

$$f_e^{\,j} = \frac{\partial \int_0^{i_j} \lambda_j(x,i_j)\,di_j}{\partial x} = \sum_{m=0}^{4}\sum_{n=1}^{4} \frac{-m\pi}{10^{-2}(2n-1)} B_{(2n-1),m}\, i^{2n} \sin\left(\frac{m\pi x}{10^{-2}}\right) \tag{4}$$



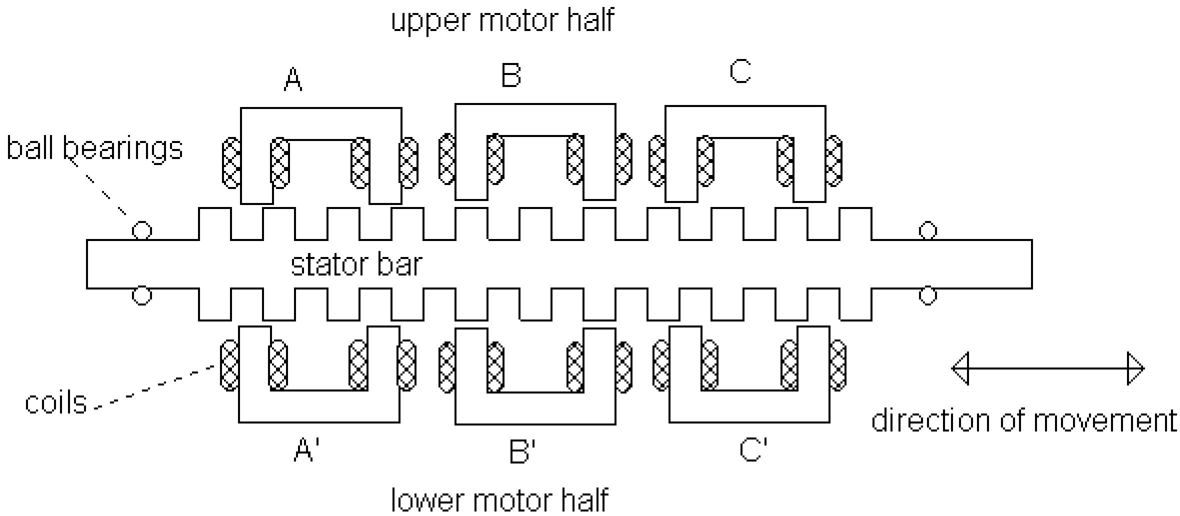
2D flux-current chart



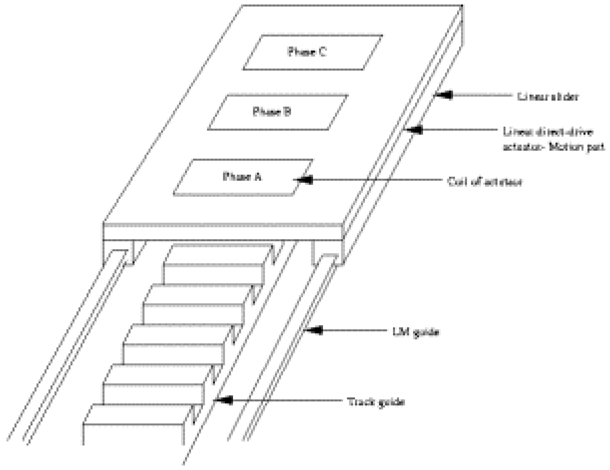


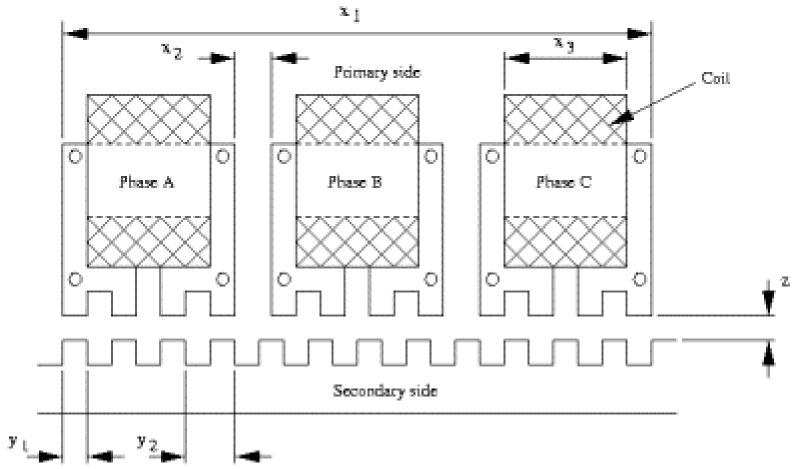
3D flux-current-distance plot 3D force-current-distance plot.

Multi-phase VR linear motor - Moving rod type



Multi-phase VR linear motor - Moving platform type





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