

Stepping Motors

- Stepping motors are electromechanical motion devices used primarily to convert information in digital form to mechanical motion.
- Introduction and Motivation
 - Stepping Motor Applications
 - Inkjet Printer Application and Testbed
- Stepper Motor Basics

Main References

- Stepping Motors: A Guide to Modern Theory and Practice, 3rd Edition
 - P. P. Acarnley, IEE, 1992
- Stepping Motors and Their Microprocessor Controls, 2nd Edition
 - T. Kenjo and A. Sugawara, Oxford, 1995
- Step Motor System Design Handbook, 2nd Edition
 - A. Leenhouts, Litchfield Engineering Co., 1997

Stepping Motor Applications

- Computer Peripherals
 - Main area for stepping motor applications
 - Printers
 - Carriage transport
 - Paper feed
 - Rotation of the photosensitive drum
 - Toner stirring unit
 - Graph (X-Y) plotters
 - Paper sheet is driven in the forward or backward direction with a stepping motor
 - Pen is driven by another stepping motor in the horizontal direction

- Stepping motor is used to drive the mechanism for replacing ink holders
- Disk drives
 - Head positioning in disk drives
- Numerical Control
 - XY-tables and index tables
 - Milling machines
 - Sewing machines
- Office Machines
 - Copiers
 - Facsimile machines

- Applications in Semiconductor Technology
 - Stepping motors used in high vacuums
 - Goniometer – instrument used to determine crystalline structure
 - Electron-beam microfabricator
- Space Vehicles and Satellites
- Other Applications
 - Time pieces
 - Cameras
 - Heavy industry applications
 - Medical equipment

- Whenever stepping from one position to another is required, whether the application is industrial, military, or medical, the stepper motor is generally used.

Inkjet Printer Application & Testbed

- **Printer Description**
 - **Problem Statement**
 - Potential Causes
 - Potential Countermeasures
 - Goal
 - Typical Nominal Motion Trajectory

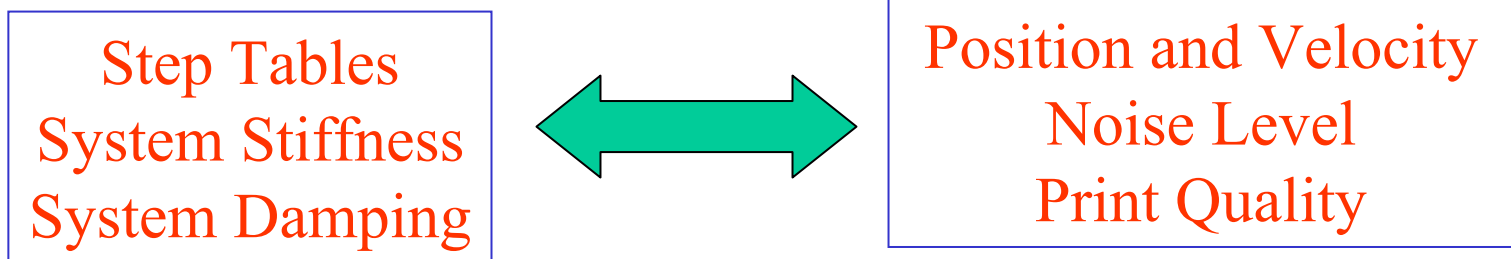
Printer Description

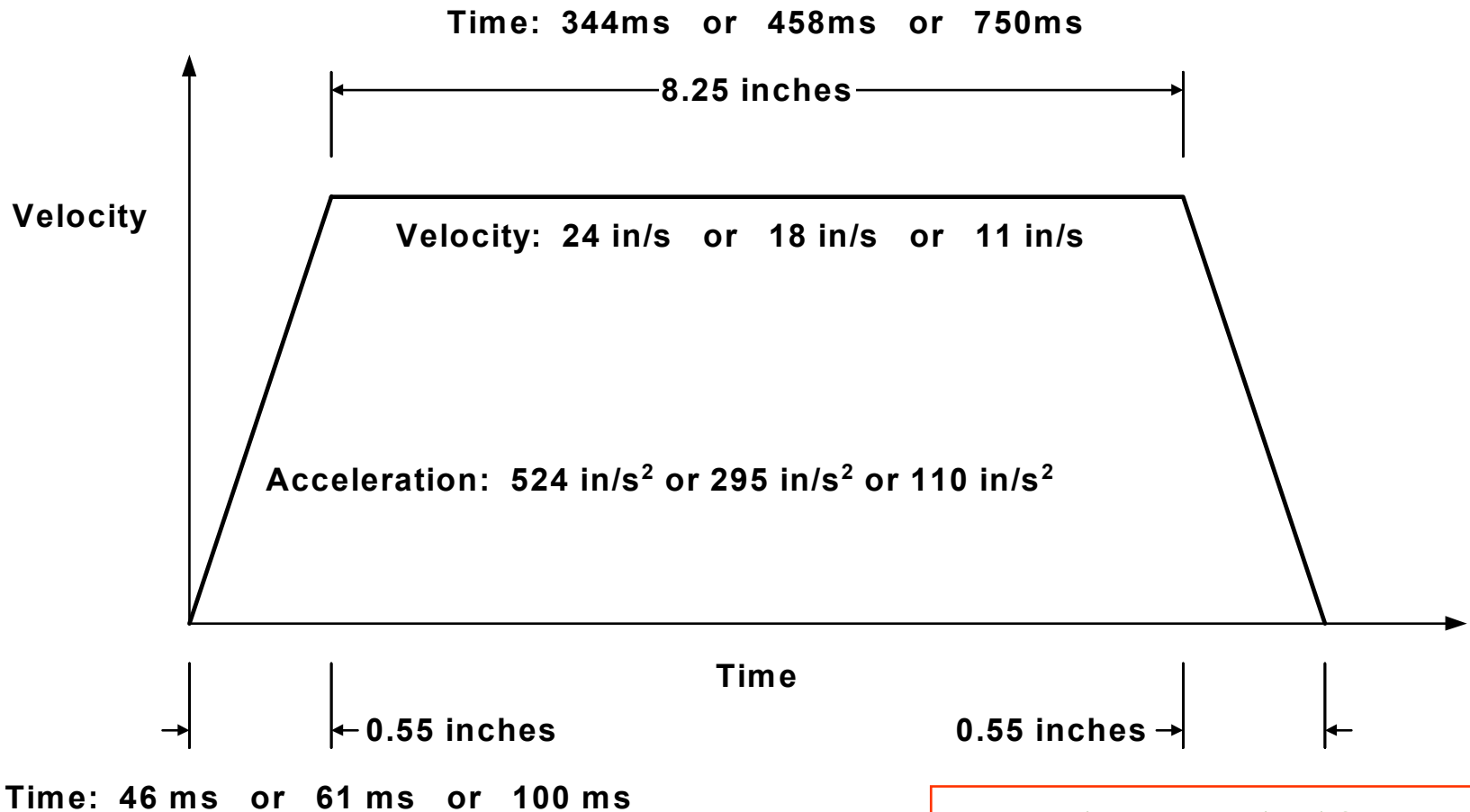


Problem Statement

- Current inkjet printer scan system exhibits undesirable noise and motion quality variations at certain velocities or scan positions.
- Potential Causes:
 - Step tables
 - Carriage vibration
 - Carriage-to-rail interface

- Potential Countermeasures:
 - Optimize scan motor step tables
 - Optimize for cost and performance the system stiffness
 - Optimize rail-to-carriage interface
- Goal
 - Develop an analytical and empirical understanding of the relationship between input parameters and output responses





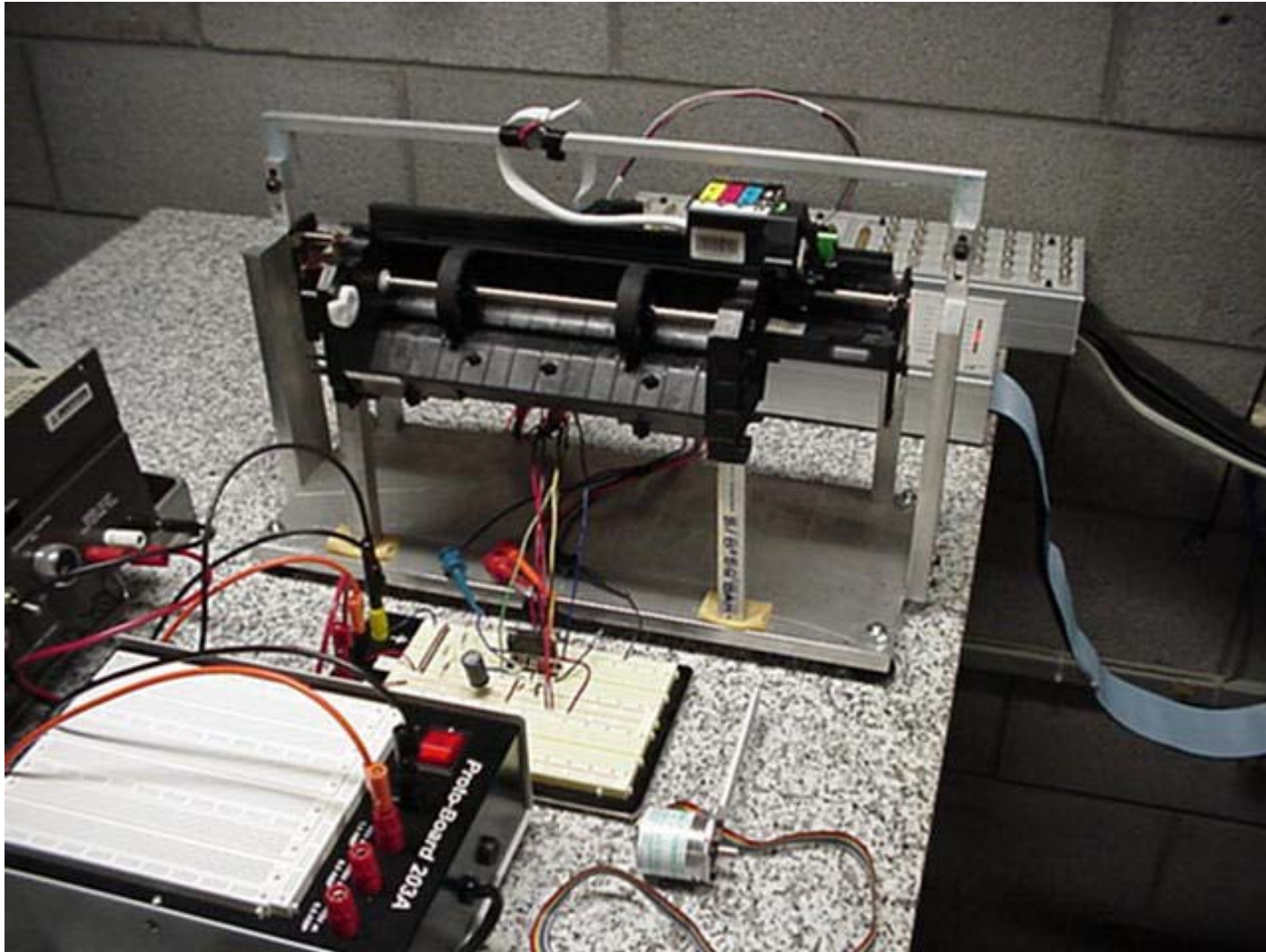
**Typical Nominal Motion Trajectory:
Velocity vs. Time**

0.55 in = 33 half steps
 8.25 in = 495 half steps
 96 half steps / rev
 0.25 in/rad

Inkjet Printer Testbed

- Physical System Description
 - Printer-Carriage, Belt-Drive System
 - Motors: Bipolar and Unipolar
 - Encoders: Linear and Rotary
 - Driver Chips: Bipolar PWM and Unipolar PWM
 - dSpace / MatLab / Simulink Implementation
- System Capabilities
 - Inkjet Printer Applications
 - General Stepper Motor System Design Studies

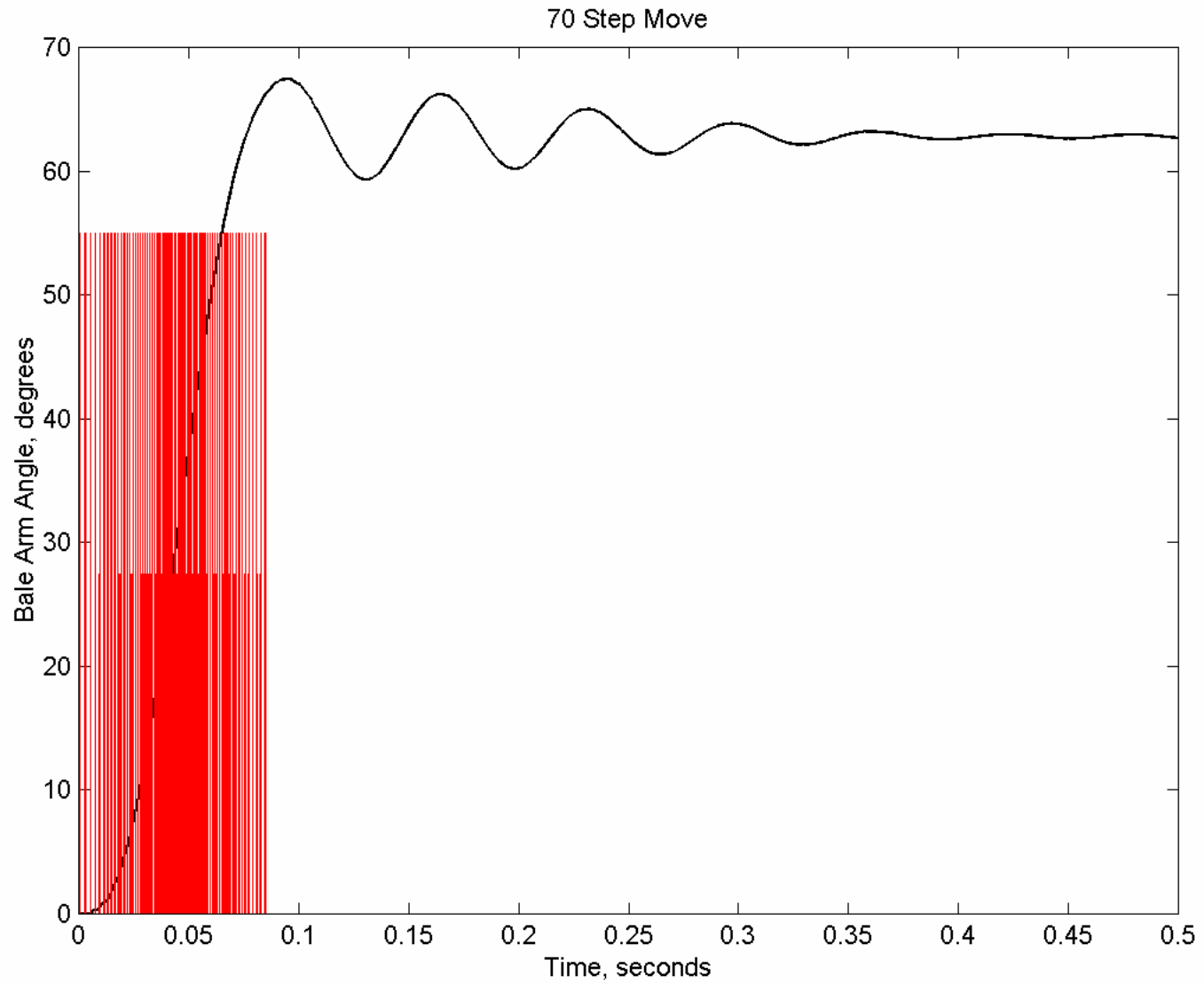
Inkjet Printer Testbed

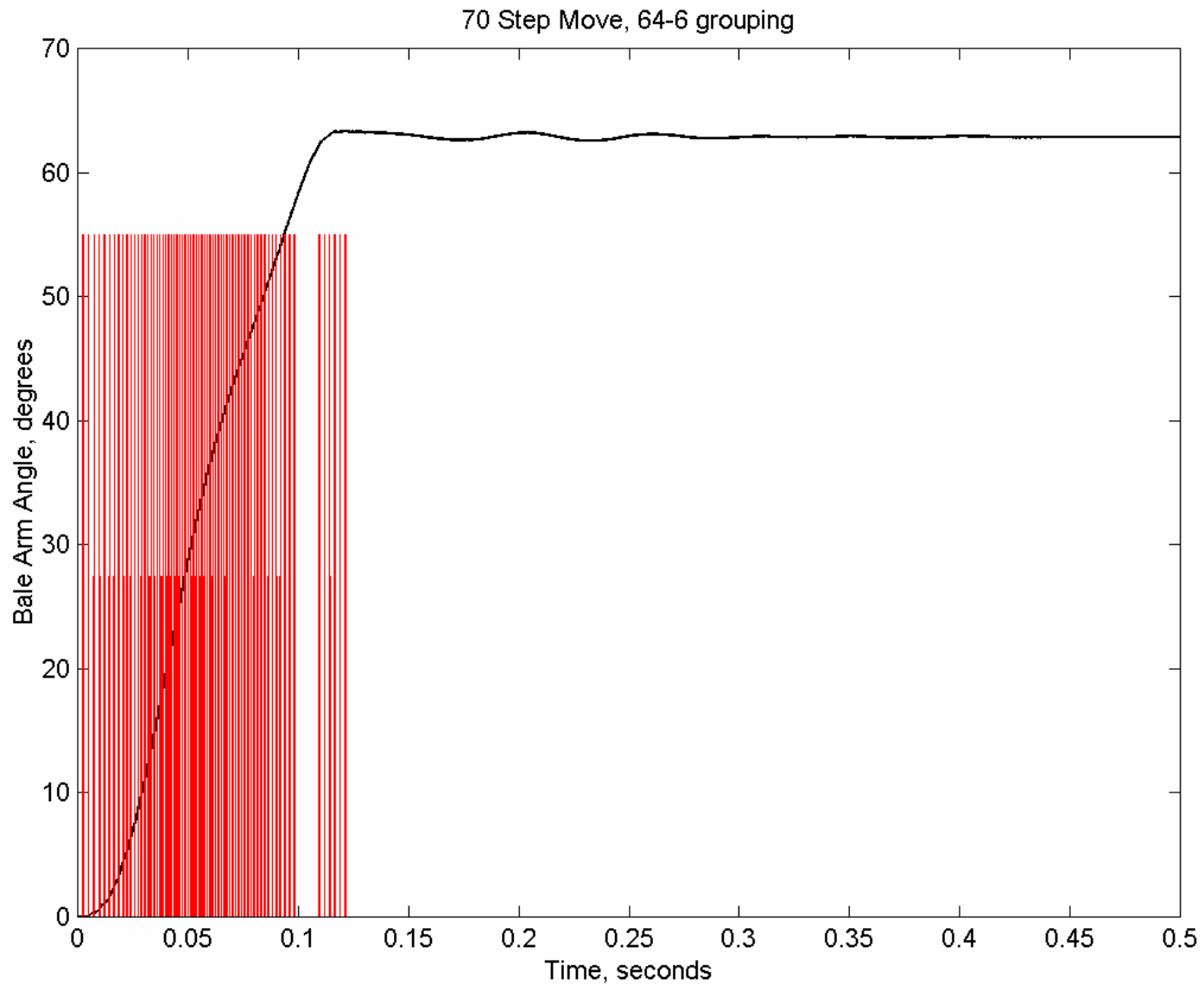


Xerox Application









Stepper Motor Basics

- Introduction
- DC Motors vs. Stepper Motors
- Advantages of Stepper Motors
- Disadvantages of Stepper Motors
- Stepper Motor Basics
 - Variable Reluctance (VR) Stepper Motor
 - Hybrid Stepper Motor
- Bifilar vs. Unifilar Windings

Introduction

- Proper selection of actuators is of *utmost importance* in the design of mechatronic systems.
- Factors such as power, motion resolution, repeatability, and operating bandwidth requirements for an actuator can differ significantly, depending on the particular mechatronic system and the specific function of the actuator within the system.
- AC motors, DC motors and hydraulic/pneumatic actuators are *continuous-drive actuators*.
- A stepper motor is an electromagnetic actuator, like a DC motor, however, it is an *incremental-drive (digital) actuator* and is driven in fixed angular steps.

- Each step of rotation is the response of the motor to an input pulse (or digital command).
- Step-wise rotation of the rotor can be synchronized with pulses in a command-pulse train, assuming that no steps are missed, thereby making the motor respond faithfully to the pulse signal in an open-loop manner.
- Stepper motors have emerged as cost-effective alternatives for DC servomotors in high-speed, motion-control applications (except the high torque-speed range) with the improvements in permanent magnets and the incorporation of solid-state circuitry and logic devices in their drive systems.
- Today stepper motors can be found in computer peripherals, machine tools, medical equipment, automotive devices, and small business machines, to name a few applications.

DC Motors vs. Stepper Motors

- Stepper motors are operated open loop, while most DC motors are operated closed loop.
- Stepper motors are easily controlled with microprocessors, however logic and drive electronics are more complex.
- Stepper motors are brushless and brushes contribute several problems, e.g., wear, sparks, electrical transients.
- DC motors have a continuous displacement and can be accurately positioned, whereas stepper motor motion is incremental and its resolution is limited to the step size.
- Stepper motors can slip if overloaded and the error can go undetected. (A few stepper motors use closed-loop control.)
- Feedback control with DC motors gives a much faster response time compared to stepper motors.

Advantages of Stepper Motors

- Position error is noncumulative. A high accuracy of motion is possible, even under open-loop control.
- Large savings in sensor (measurement system) and controller costs are possible when the open-loop mode is used.
- Because of the incremental nature of command and motion, step motors are easily adaptable to digital control applications.
- No serious stability problems exist, even under open-loop control.
- Torque capacity and power requirements can be optimized and the response can be controlled by electronic switching.
- Brushless construction has obvious advantages.

Disadvantages of Stepper Motors

- They have low torque capacity (typically less than 2,000 oz-in) compared to DC motors.
- They have limited speed (limited by torque capacity and by pulse-missing problems due to faulty switching systems and drive circuits).
- They have high vibration levels due to stepwise motion.
- Large errors and oscillations can result when a pulse is missed under open-loop control.

Stepper Motor Basics

- To produce a significant torque from a reasonable volume, both the stationary and rotating components must have large numbers of iron teeth, which must be able to carry a substantial magnetic flux.
- Performance of the stepper motor depends on the strength of the magnetic field. High flux leads to high torque.
- Only two basic types need to be considered:
 - Variable-Reluctance
 - Hybrid

- Essential Property
 - Ability to translate switched excitation changes into precisely defined increments of rotor position (steps).
 - Accurate positioning of the rotor is generally achieved by magnetic alignment of the iron teeth of the stationary and rotating parts of the motor.
- Hybrid Motor
 - Main source of magnetic flux is a permanent magnet; dc currents flowing in one or more windings direct the flux along alternative paths.
- Variable Reluctance (VR)
 - There are two configurations; in both cases the magnetic field is produced solely by the winding currents.

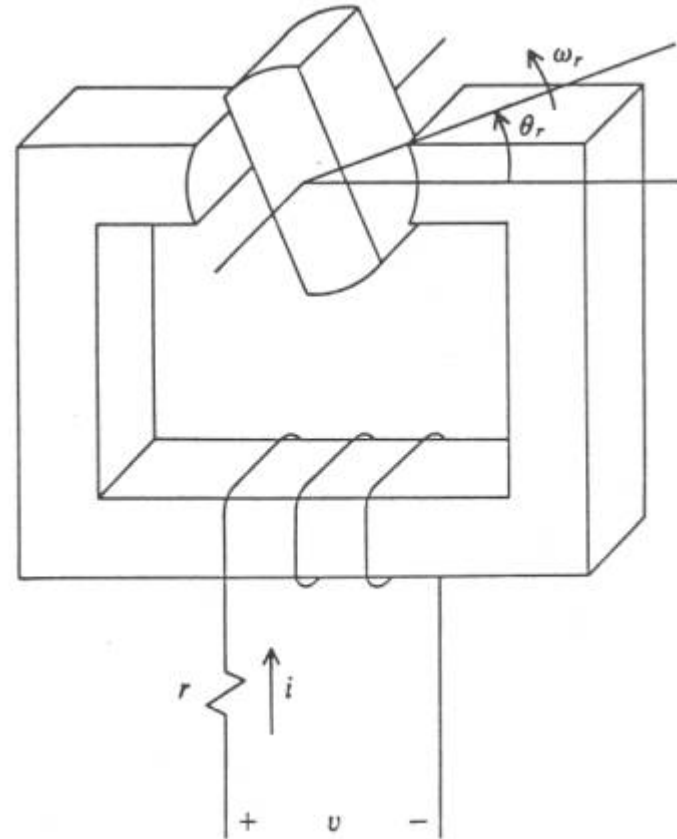
Review: Single-Phase Reluctance Machine

- The machine consists of:
 - stationary core with a winding of N turns
 - moveable member which rotates

θ_r = angular displacement

ω_r = angular velocity

$$\theta_r = \int_0^t \omega_r(\xi) d\xi + \theta_r(0)$$



$$v = ri + \frac{d\lambda}{dt}$$

voltage equation

$$\phi = \phi_\ell + \phi_m$$

ϕ_ℓ = leakage flux

ϕ_m = magnetizing flux

$$\lambda = (L_\ell + L_m)i$$

It is convenient to express the flux linkages as the product of the sum of the leakage inductance and the magnetizing inductance and the current in the winding.

L_ℓ = constant (independent of θ_r)

L_m = periodic function of θ_r

$$L_m = L_m(\theta_r)$$

$$L_m(0) = \frac{N^2}{\mathfrak{R}_m(0)}$$



$\left\{ \begin{array}{l} \mathfrak{R}_m \text{ is maximum} \\ L_m \text{ is minimum} \end{array} \right.$

$$L_m\left(\frac{\pi}{2}\right) = \frac{N^2}{\mathfrak{R}_m\left(\frac{\pi}{2}\right)}$$



$\left\{ \begin{array}{l} \mathfrak{R}_m \text{ is minimum} \\ L_m \text{ is maximum} \end{array} \right.$

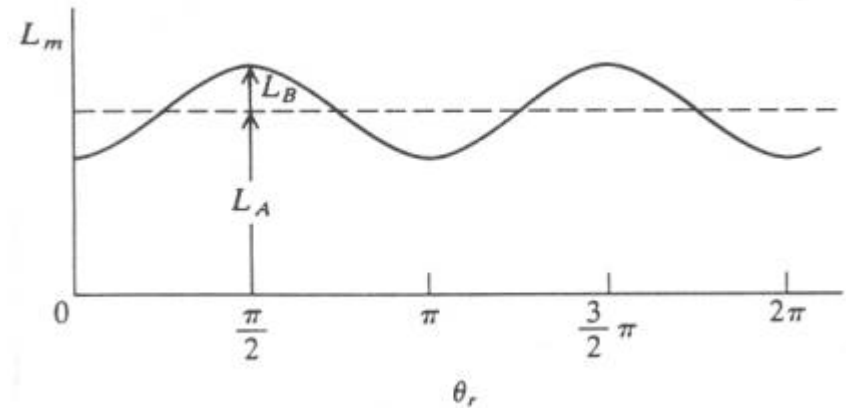
The magnetizing inductance varies between maximum and minimum positive values twice per revolution of the rotating member.

Assume that this variation may be adequately approximated by a sinusoidal function.

$$L_m(\theta_r) = L_A - L_B \cos(2\theta_r)$$

$$\begin{aligned} L(\theta_r) &= L_\ell + L_m(\theta_r) \\ &= L_\ell + L_A - L_B \cos(2\theta_r) \end{aligned}$$

$$v = ri + [L_\ell + L_m(\theta_r)] \frac{di}{dt} + i \frac{dL_m(\theta_r)}{d\theta_r} \frac{d\theta_r}{dt}$$



$$L_m(0) = L_A - L_B$$

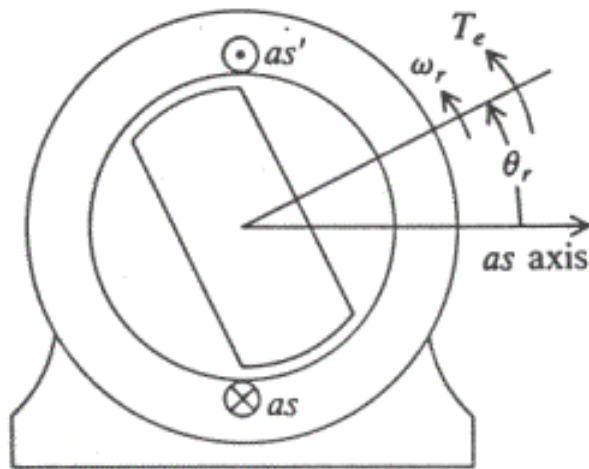
$$L_m\left(\frac{\pi}{2}\right) = L_A + L_B$$

$$L_A > L_B$$

$$L_A = \text{average value}$$

voltage equation

- This elementary two-pole single-phase reluctance machine is shown in a slightly different form. Winding 1 is now winding as and the stator has been changed to depict more accurately the configuration common for this device.



r_s = resistance of as winding
 L_{asas} = self-inductance of as winding

$$v_{as} = r_s i_{as} + \frac{d\lambda_{as}}{dt}$$

$$\lambda_{as} = L_{asas} i_{as}$$

$$L_{asas} = L_{\ell s} + L_A - L_B \cos(2\theta_r)$$

$$\theta_r = \int_0^t \omega_r(\xi) d\xi + \theta_r(0)$$

$L_{\ell s}$ = leakage inductance

- Electromagnetic torque:

- Magnetic system is linear, hence $W_f = W_c$.

$$W_c(i_{as}, \theta_r) = \frac{1}{2} (L_{ls} + L_A - L_B \cos(2\theta_r)) i_{as}^2$$

$$T_e(\vec{i}, \theta) = \sum_{j=1}^J \left[i_j \frac{\partial \lambda_j(\vec{i}, \theta)}{\partial \theta} \right] - \frac{\partial W_f(\vec{i}, \theta)}{\partial \theta}$$

$$T_e(\vec{i}, \theta) = \frac{\partial W_c(\vec{i}, \theta)}{\partial \theta}$$

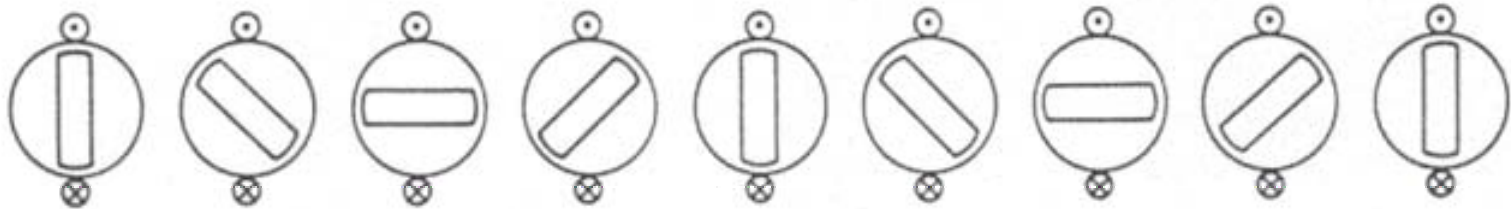
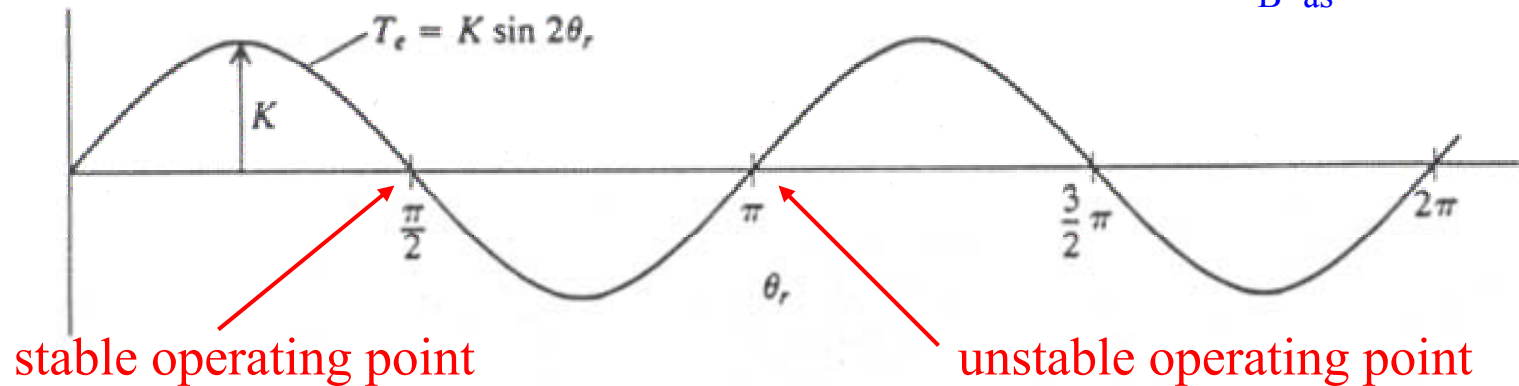
$$T_e(i_{as}, \theta_r) = L_B i_{as}^2 \sin(2\theta_r)$$

Valid for both transient and steady-state operation

- Consider steady-state operation: i_{as} is constant

$$T_e = K \sin(2\theta_r)$$

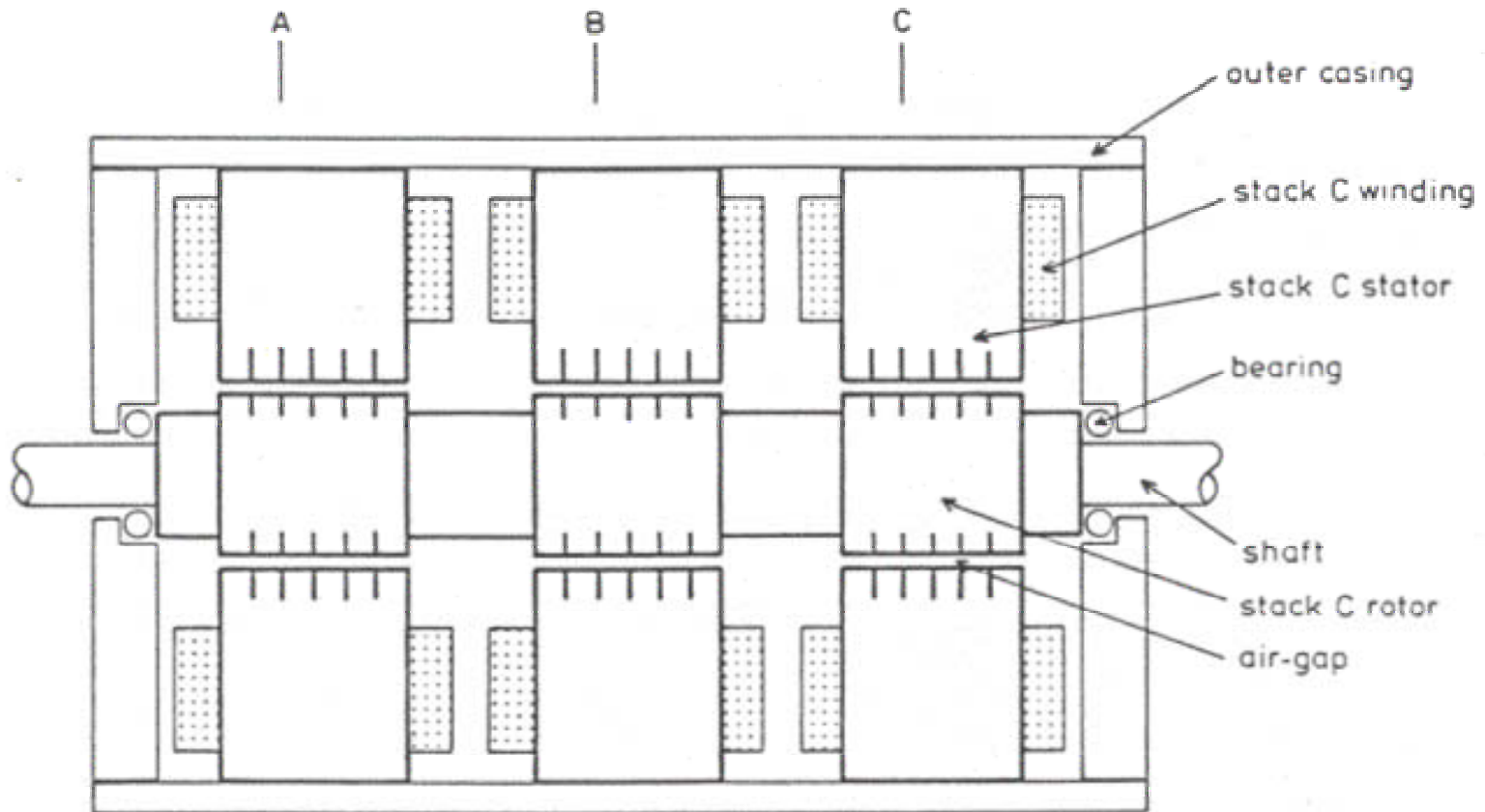
$$K = L_B i_{as}^2$$



Electromagnetic torque versus angular displacement of a single-phase reluctance machine with constant stator current

- Although the operation of a single-phase reluctance machine with a constant current is impracticable, it provides a basic understanding of reluctance torque, which is the operating principle of variable-reluctance stepper motors.
- In its simplest form, a variable-reluctance stepper motor consists of three cascaded, single-phase reluctance motors with rotors on a common shaft and arranged so that their minimum reluctance paths are displaced from each other.

- **Multi-Stack Variable Reluctance Stepping Motor**

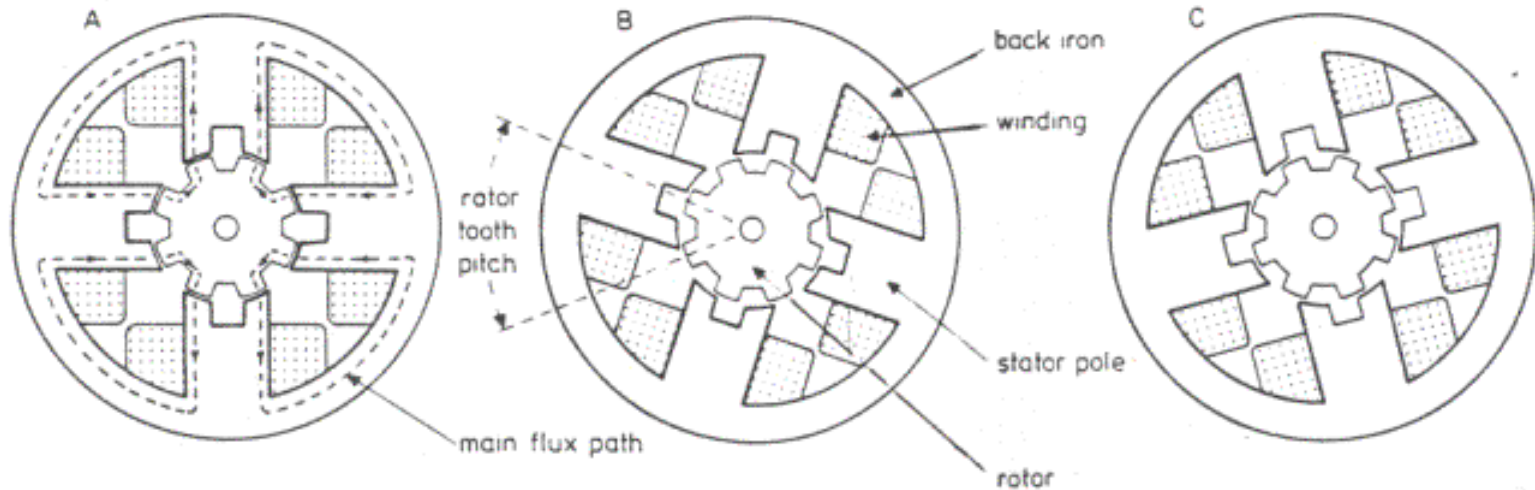


Cross-section of a three-stack variable-reluctance stepping motor parallel to the shaft

Step Length

4 poles, 8 stator / rotor teeth, 3 stacks, 3 phases

$$\frac{360^\circ}{N_p} = \frac{360^\circ}{(3)(8)} = 15^\circ$$



Cross-sections of a three-stack, variable-reluctance stepping motor perpendicular to the shaft

- Magnetically isolated sections (stacks), each of which has a stationary stator and a one-piece rotor, both made of laminated iron.
- Each stator has a number of wound poles, with adjacent poles wound in the opposite sense.
- Magnetic circuit for each pair of adjacent poles is from one stator pole, across the air-gap into the rotor, through the rotor, across the air-gap into an adjacent pole, through this pole, returning to the original pole via the back-iron.
- Rotor and stator have equal numbers of teeth.

- When stator and rotor teeth are fully aligned, the circuit reluctance is minimized and the magnetic flux is at its maximum value.
- Rotor teeth in each stack are aligned; stator teeth have different relative orientations between stacks.
- One tooth pitch is $360/p$ where p is the number of rotor teeth. If N is the number of stacks (and phases), then the step length = $360/Np$. Typical step lengths are 2 to 15 degrees.
- Motors with higher stack numbers have no real performance advantages over a 3-stack motor.

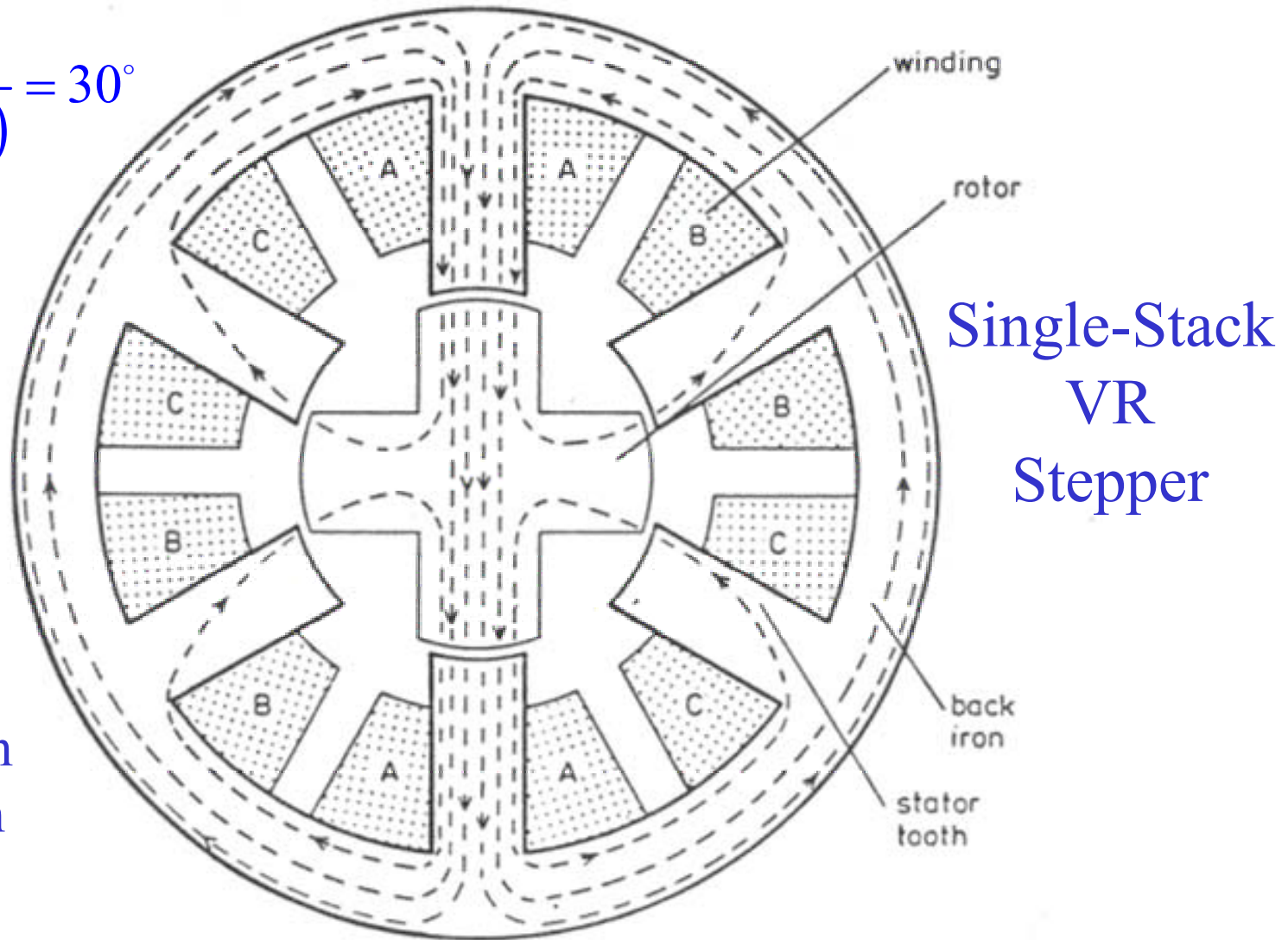
- Continuous CW rotation can be produced by repeating the sequence: A, B, C, A, B, C, A,
- Continuous CCW rotation can be produced by repeating the sequence: A, C, B, A, C, B, A,
- If bi-directional operation is required from a multi-stack motor, it must have at least three stacks so that two distinct excitation sequences are available.

- Design Limitations
 - Pole flux density (magnetic saturation)
 - Winding temperature rise
 - The stator / rotor should reach magnetic saturation at the rated winding current
- Winding Interconnections Vary
 - Low-voltage, high-current drive with parallel winding connection
 - High-voltage, low-current drive with series winding connection
 - In either case, there is no difference in power supplied to the phase

$$\frac{360^\circ}{N_p} = \frac{360^\circ}{(3)(4)} = 30^\circ$$

Step Length

6 stator teeth
4 rotor teeth
3 phases



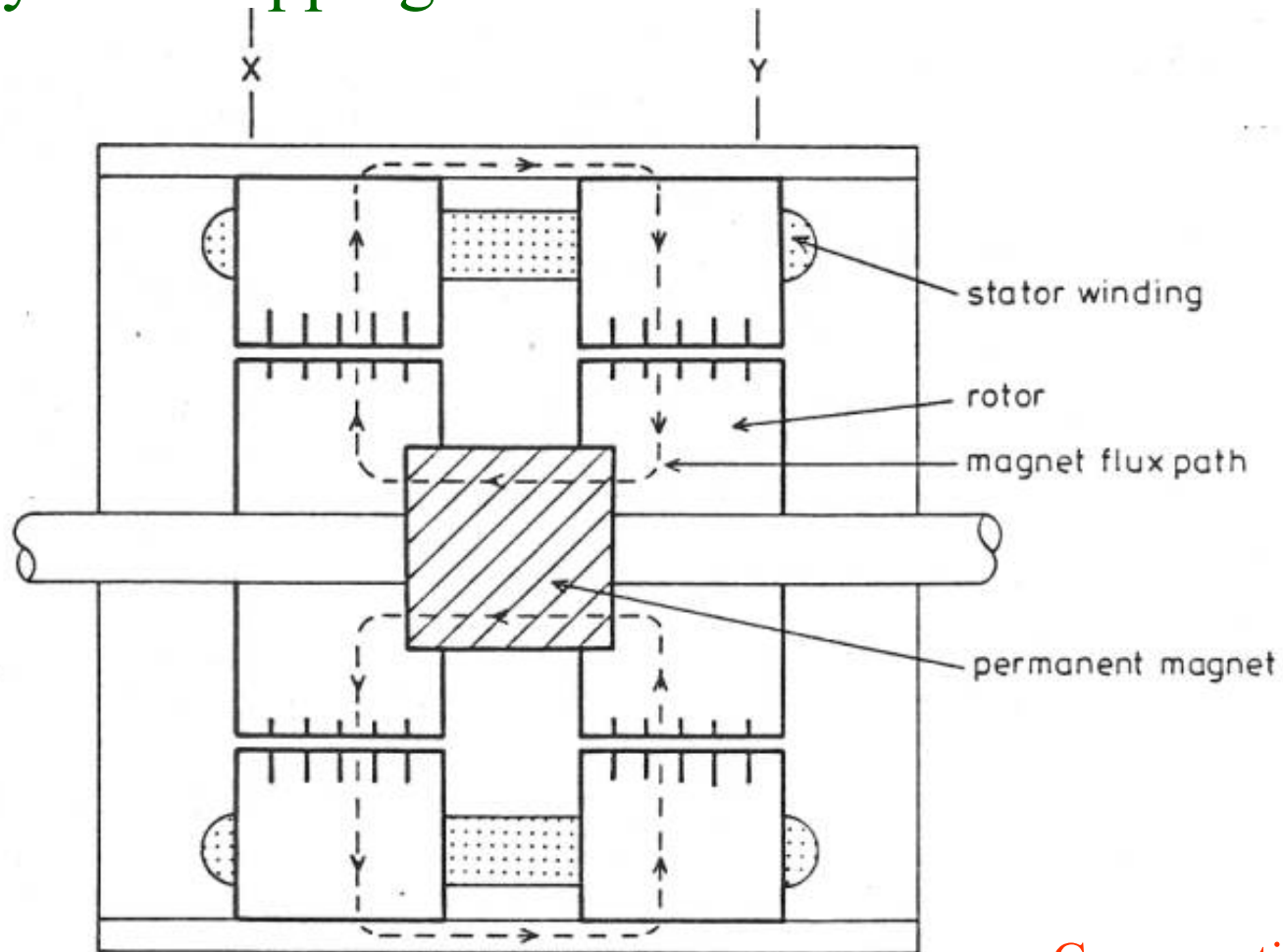
Cross-section of a single-stack variable-reluctance stepping motor perpendicular to the shaft

- There are essential differences between the single- and multi-stack types:
 - Each tooth has a separate winding.
 - Windings on opposite teeth are connected together to form one phase and are in opposing senses.
 - With one phase excited, the main flux path lies from one stator tooth, across the air-gap into a rotor tooth, directly across the rotor to another rotor-tooth / air-gap / stator-tooth combination and returns via the back-iron.
 - Secondary flux paths produce mutual coupling between the phase windings.

- Rotor and stator have different numbers of teeth.
- With one phase excited, only two of the rotor teeth carry the main flux. The rotor moves to a position that minimizes the main flux path reluctance.
- It is interesting to note that the rotor movement is in the opposite direction to the stepped rotation of the stator magnetic field, e.g., for continuous CCW rotation the excitation sequence is: A, B, C, A, B, C, A, ...; similarly, CW rotation can be produced using the excitation sequence: A, C, B, A, C, B, A,

- If N is the number of phases and p is the number of rotor teeth, then the step length = $360^\circ/Np$.
- The number of stator teeth has to be an even multiple of the number of phases.
- For satisfactory stepping action, the number of stator teeth must be near (but not equal) to the number of rotor teeth.

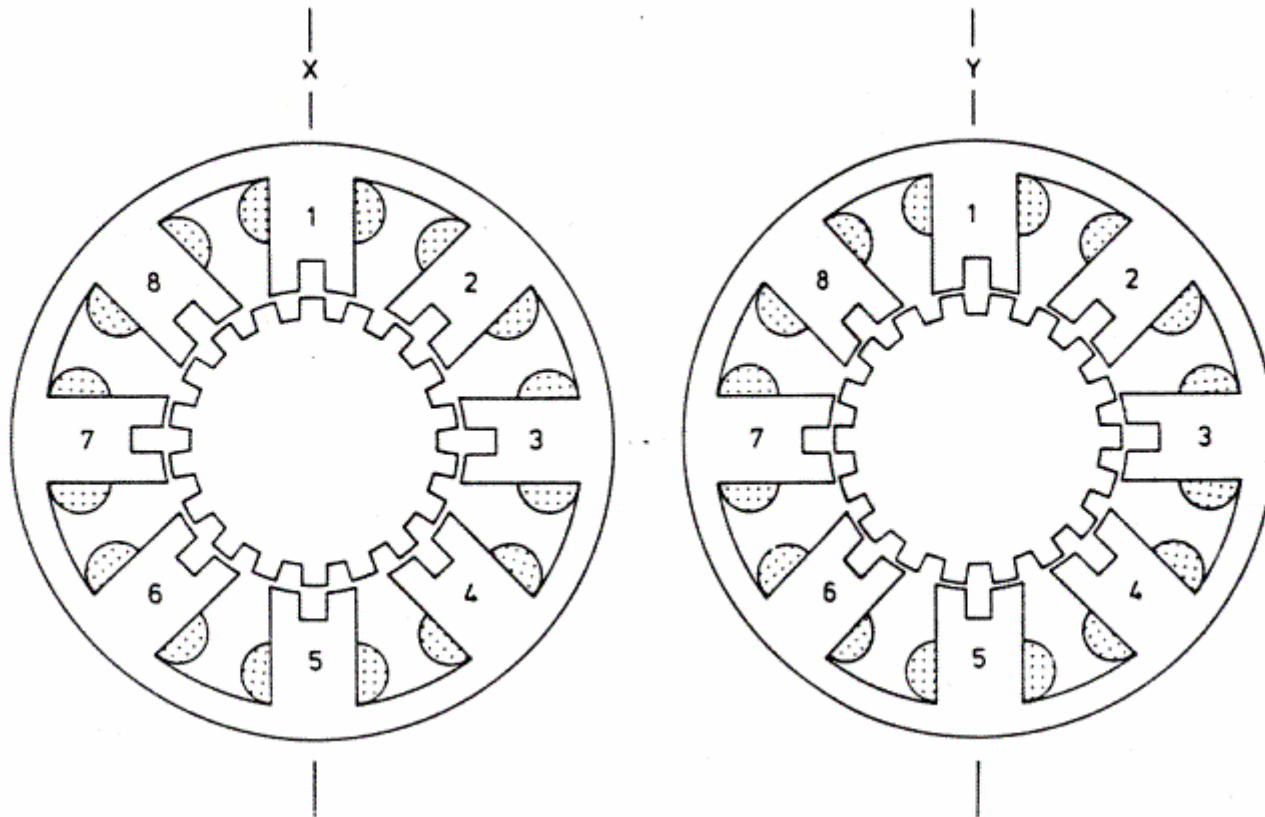
- Hybrid Stepping Motors



Cross-section
parallel to the shaft

Step Length

$$\frac{90^\circ}{p} = \frac{90^\circ}{18} = 5^\circ$$



Cross-section of hybrid motor perpendicular to the shaft

- Permanent magnet is mounted on the rotor.
- Main flux path lies from the magnet N-pole, into a soft-iron end-cap, radially through the end-cap, across the air-gap, through the stator poles of section X, axially along the stator back-iron, through the stator poles of section Y, across the air-gap and back to the magnet S-pole via the end-cap.
- There are typically 8 stator poles and each pole has between 2 and 6 teeth. There are two windings (phases) and each winding is situated on 4 of the 8 stator poles.

- Winding A is placed on poles 1, 3, 5, 7, and winding B is placed on poles 2, 4, 6, 8.
- Successive poles of each phase are wound in the opposite sense.

Winding	Current Direction	Radially Outward	Radially Inward
A	Positive	3, 7	1, 5
A	Negative	1, 5	3, 7
B	Positive	4, 8	2, 6
B	Negative	2, 6	4, 8

- Both stator poles and rotor end-caps are toothed.
- For the motor shown, there are 16 stator teeth and 18 rotor teeth. The stator teeth in sections X and Y are fully aligned; the rotor teeth are completely misaligned between the two sections.
- The rotor tends to align itself so that the air-gap reluctance of the flux path is minimized.
- Continuous CW rotation is produced by sequential excitation of the phase windings: A+, B+, A-, B-, A+, B+, CCW rotation would result from the excitation sequence: A+, B-, A-, B+, A+, B-,

- A complete cycle of excitation consists of 4 states (4 steps) and corresponds to a rotor movement of one tooth pitch ($360^\circ/p$ where p is the number of rotor teeth).
- The step length is therefore $90^\circ/p$.

- Comparison of Motor Types
- Hybrid Motors
 - Small step length (typically 1.8°).
 - Greater torque-producing capability for a given motor volume.
 - Natural choice for applications requiring a small step length and high torque in a restricted working space.
 - Detent torque retains rotor at step position when windings are unexcited.

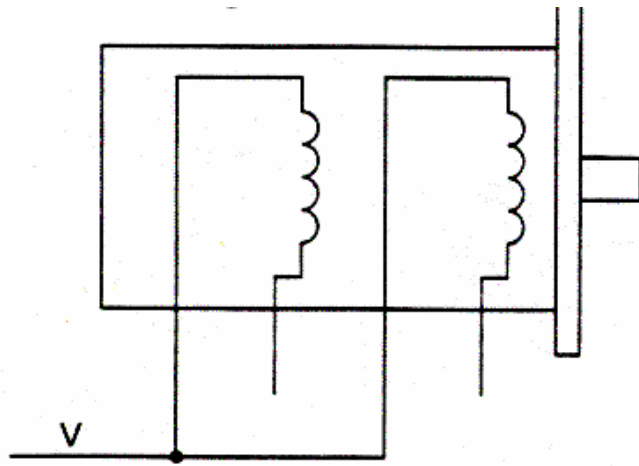
- Variable-Reluctance Motors
 - Typical step lengths (15°) are longer than in the hybrid, so less steps are required to move a given distance.
 - Fewer steps implies less excitation changes and it is the speed with which excitation changes can take place which ultimately limits the time taken to move the required distance.
 - Another advantage is the lower rotor mechanical inertia because of the absence of the permanent magnet.

Bifilar vs. Unifilar Windings

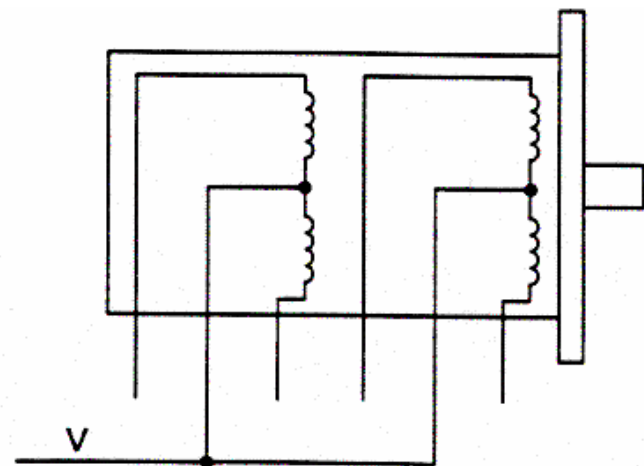
- A common feature in any stepper motor is that the stator of the motor contains several pairs of field windings that can be switched on to produce the electromagnetic pole pairs (N & S).
- The polarities can be reversed in two ways:
 - By reversing the direction of current in the winding (*unifilar windings*).
 - By using two pairs of windings (*bifilar windings*) for each pole pair, one pair giving one set of poles when energized and the other pair giving the opposite polarities.

- Simple on/off switching is adequate for bifilar windings, while current reversal circuitry is needed for unifilar windings.
- Twice the normal number of windings are needed for bifilar windings which increases the motor size for a given torque rating. Decreasing wire diameter helps; this also increases resistance, which increases damping and decreases electrical τ , giving fast but less oscillatory single-step response.

- Because current reversals are absent in bifilar windings, there are smaller levels of induced voltages by self induction and mutual induction. For this reason, the dynamic torque at a given stepping rate is usually larger for bifilar steppers, particularly at high speeds.
- At low speeds, dissipation effects will dominate induced-voltage effects, thereby giving higher torques at low speeds with unifilar windings.



4-Wire Bipolar (unifilar)



6-Wire Unipolar (bifilar)

