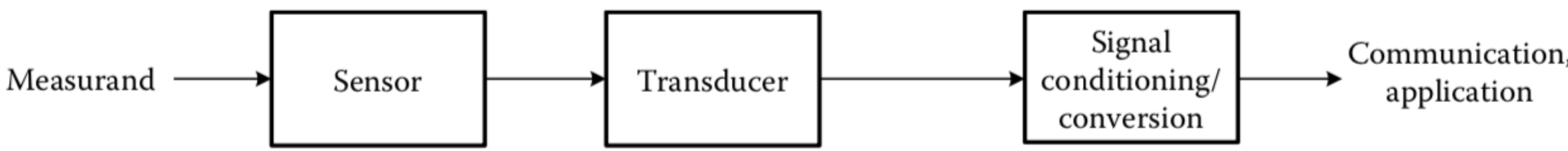
Analog Sensors and Transducers

Chapter 5

ME 473

Professor Sawyer B. Fuller

typical sensing process

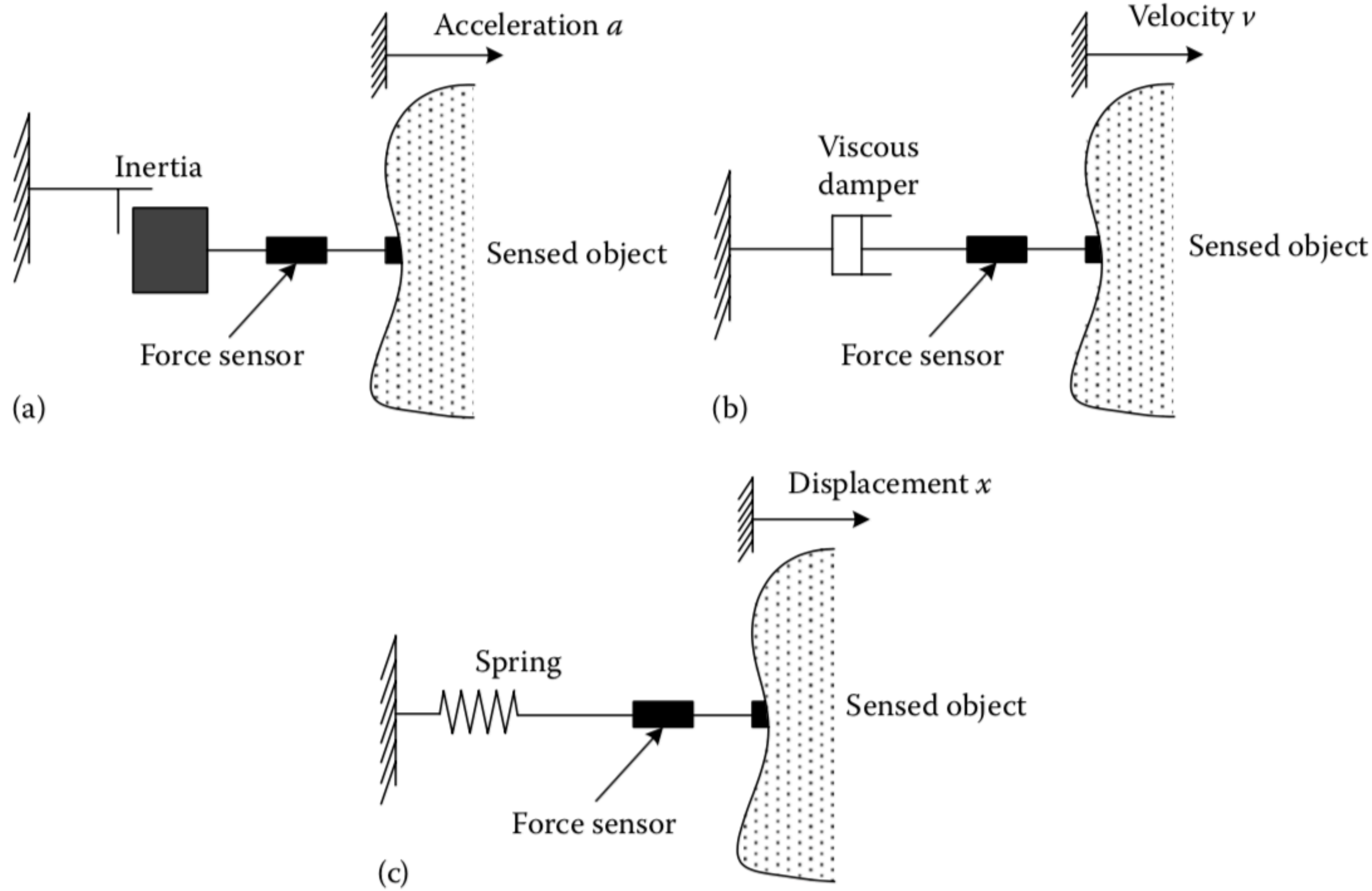


senses measurand

converts into useful form

e.g., low-pass filter

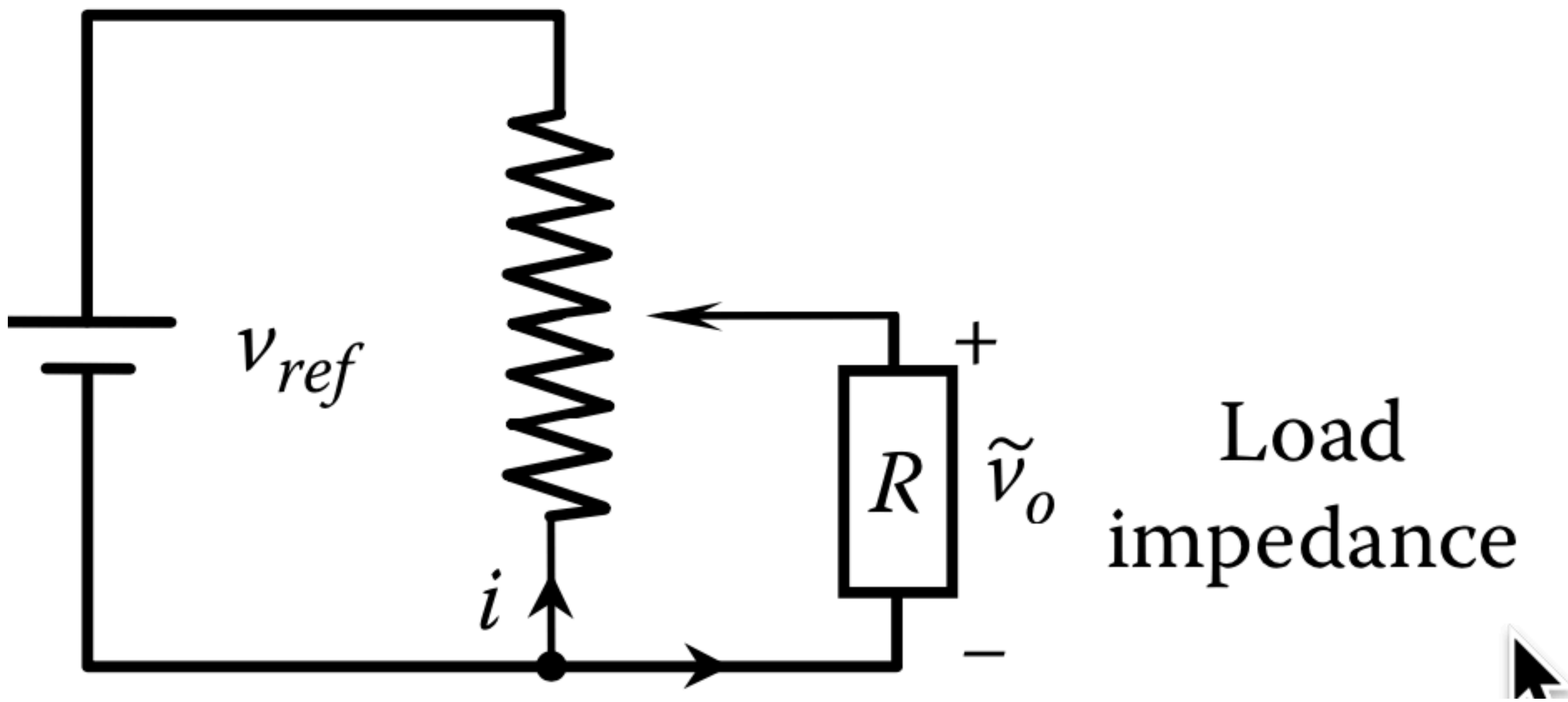
Different types of motion transduction



Resistive transducers

potentiometer

(a)



Rotary Potentiometer

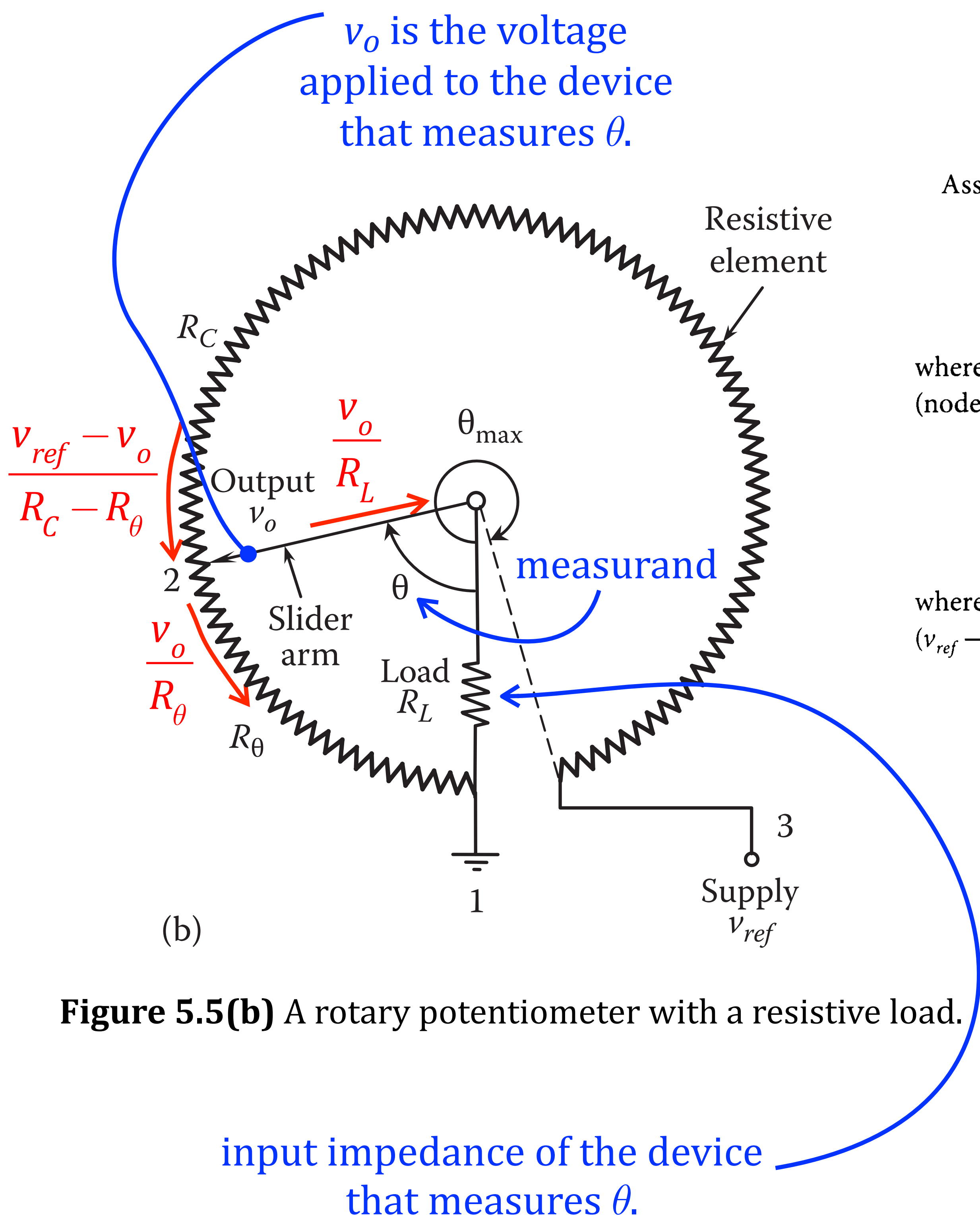


Figure 5.5(b) A rotary potentiometer with a resistive load.

Assuming a uniform coil, one has

$$R_\theta = \frac{\theta}{\theta_{max}} R_C \tag{5.2}$$

where R_C is the total resistance of the potentiometer coil. The current balance at the sliding contact point (node 2) gives

$$\frac{v_{ref} - v_o}{R_c - R_\theta} = \frac{v_o}{R_\theta} + \frac{v_o}{R_L} \tag{5.3}$$

where R_L is the load resistance. Multiply Equation 5.3 throughout by R_C and use Equation 5.2. We get, $(v_{ref} - v_o)/(1 - \theta/\theta_{max}) = (v_o/(\theta/\theta_{max})) + (v_o/(R_L/R_C))$. By using straightforward algebra, we have

$$\frac{v_o}{v_{ref}} = \left[\frac{(\theta/\theta_{max})(R_L/R_C)}{(R_L/R_C + (\theta/\theta_{max}) - (\theta/\theta_{max})^2)}\right] \tag{5.4}$$

Rotary Potentiometer

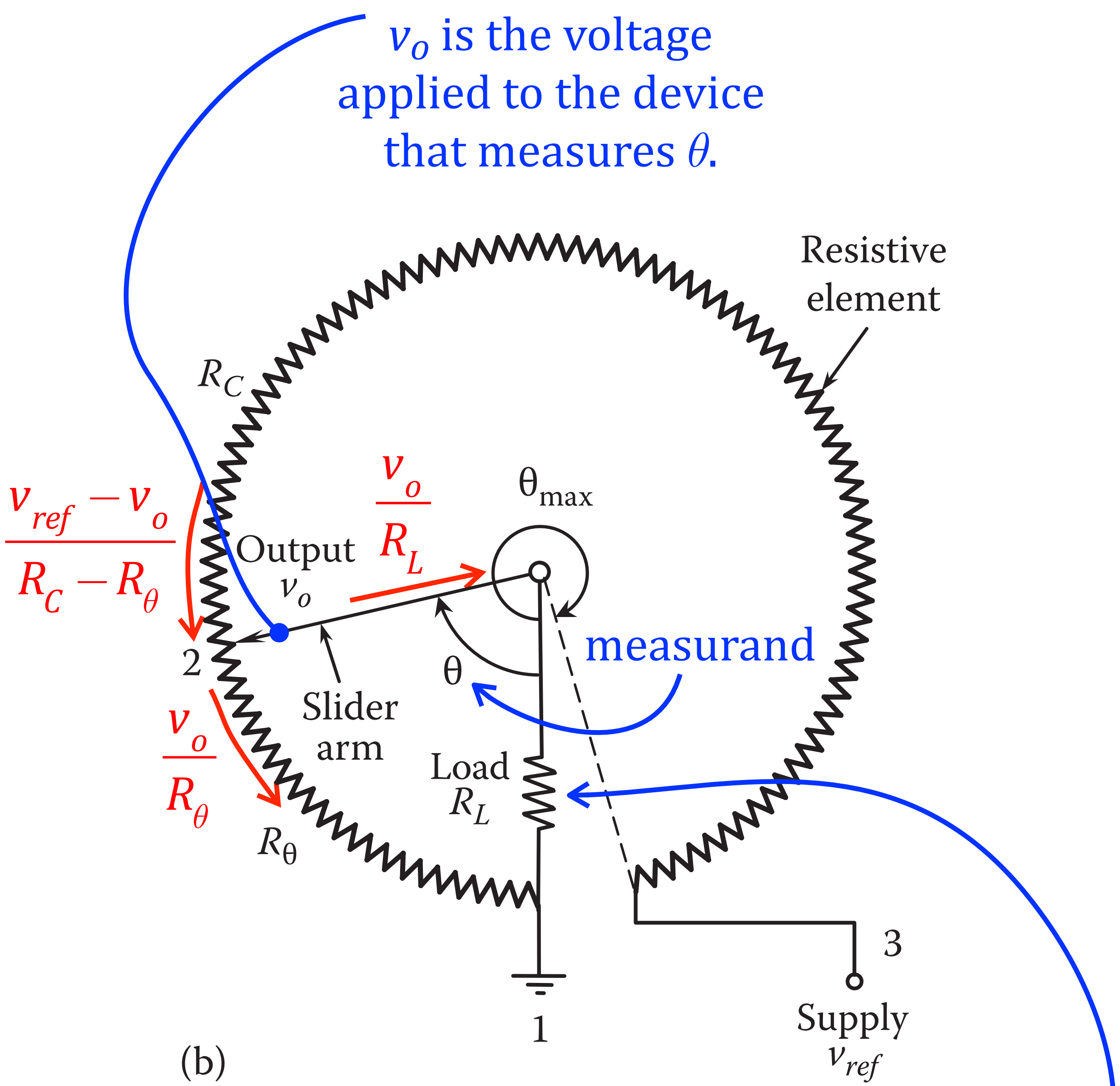


Figure 5.5(b) A rotary potentiometer with a resistive load.

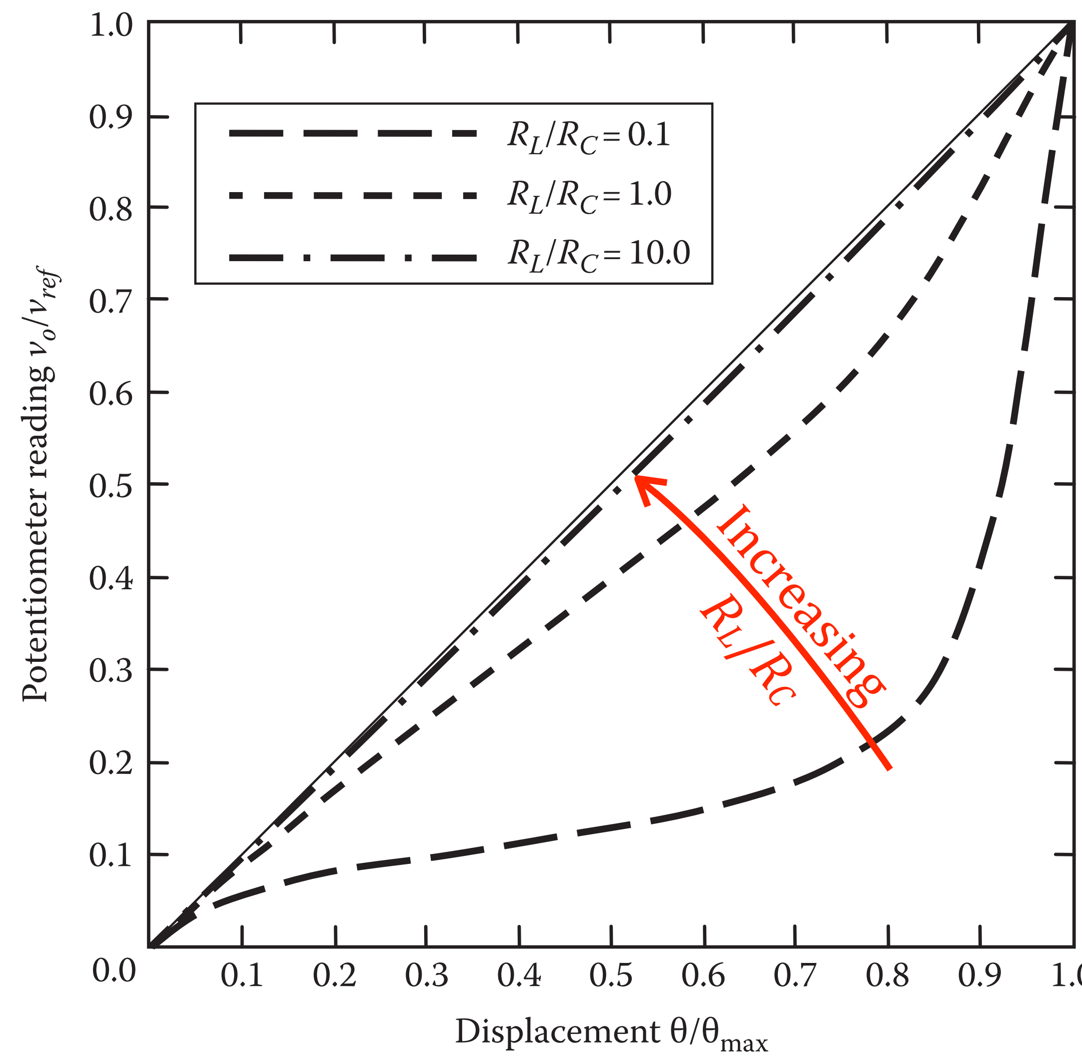


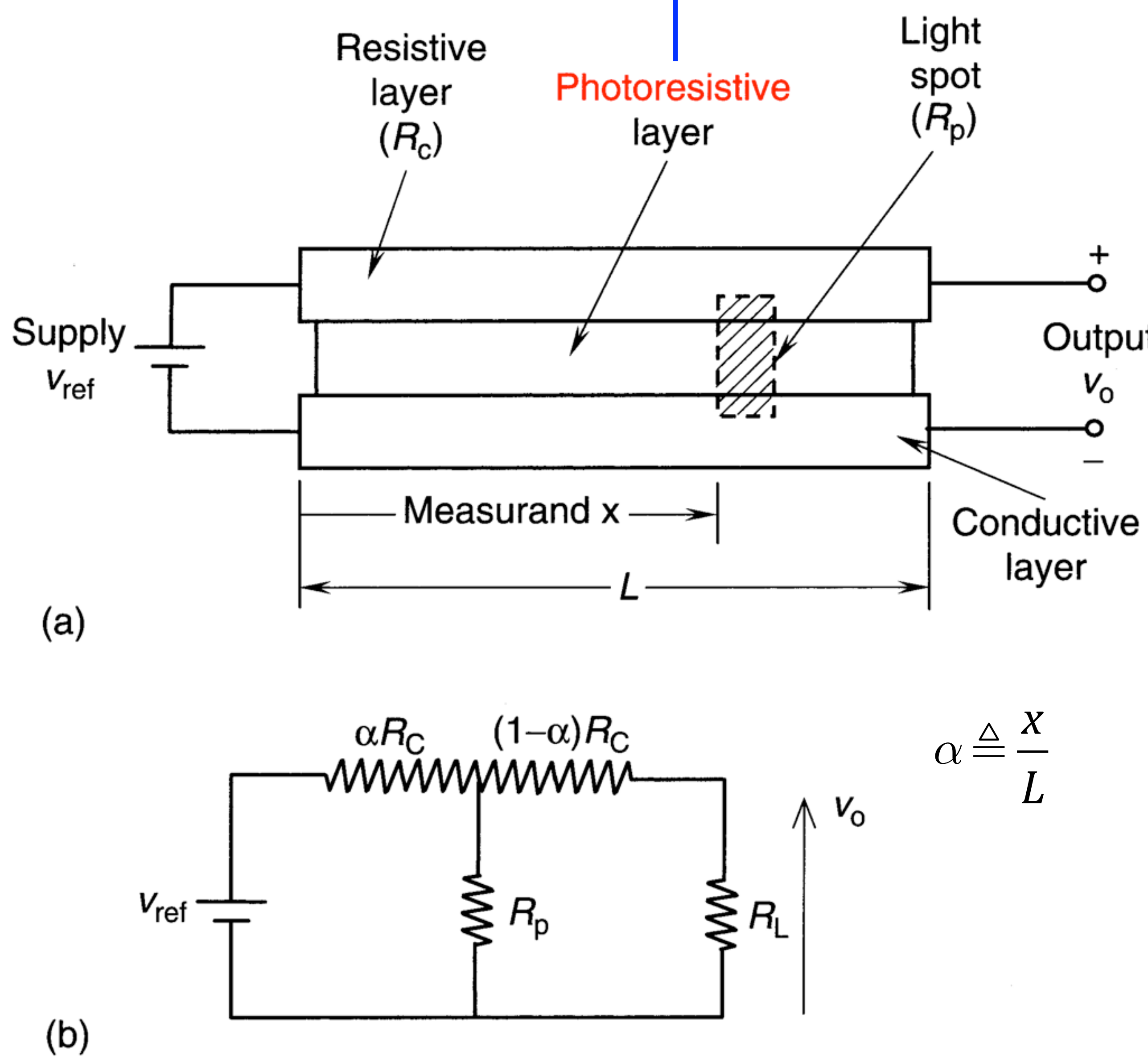
Figure 5.6 Electrical loading nonlinearity in a potentiometer.

$$\frac{v_o}{v_{ref}} = \left[\frac{(\theta/\theta_{max})(R_L/R_C)}{(R_L/R_C + (\theta/\theta_{max}) - (\theta/\theta_{max})^2)}\right]$$

Options for managing the loading nonlinearity:

- Choose a display device with sufficiently high R_L
- Calibrate the display device to account for the nonlinearity

Practically an electrical insulator where no light projects on it.
Develops a resistance R_p where light projects on it.



$$\alpha \triangleq \frac{x}{L}$$

Figure 5.7
(a) An optical potentiometer.
(b) Equivalent circuit ($\alpha = x/L$).

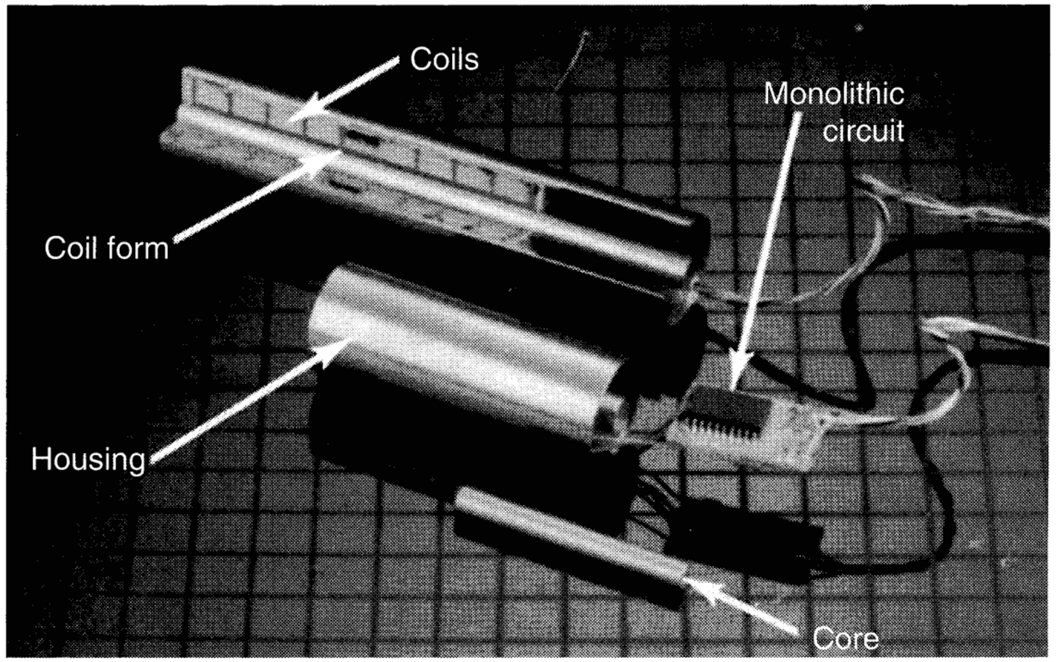
Variable-Inductance Transducers

- Principle of operation: A voltage is produced in response to changes in a magnetic field caused by physical motion
- Benefit: no physical contact
- Examples
  - Linear variable displacement transducers
  - Rotational variable displacement transducers
  - Mutual induction proximity sensors
  - Resolvers
  - Permanent-magnet transducers

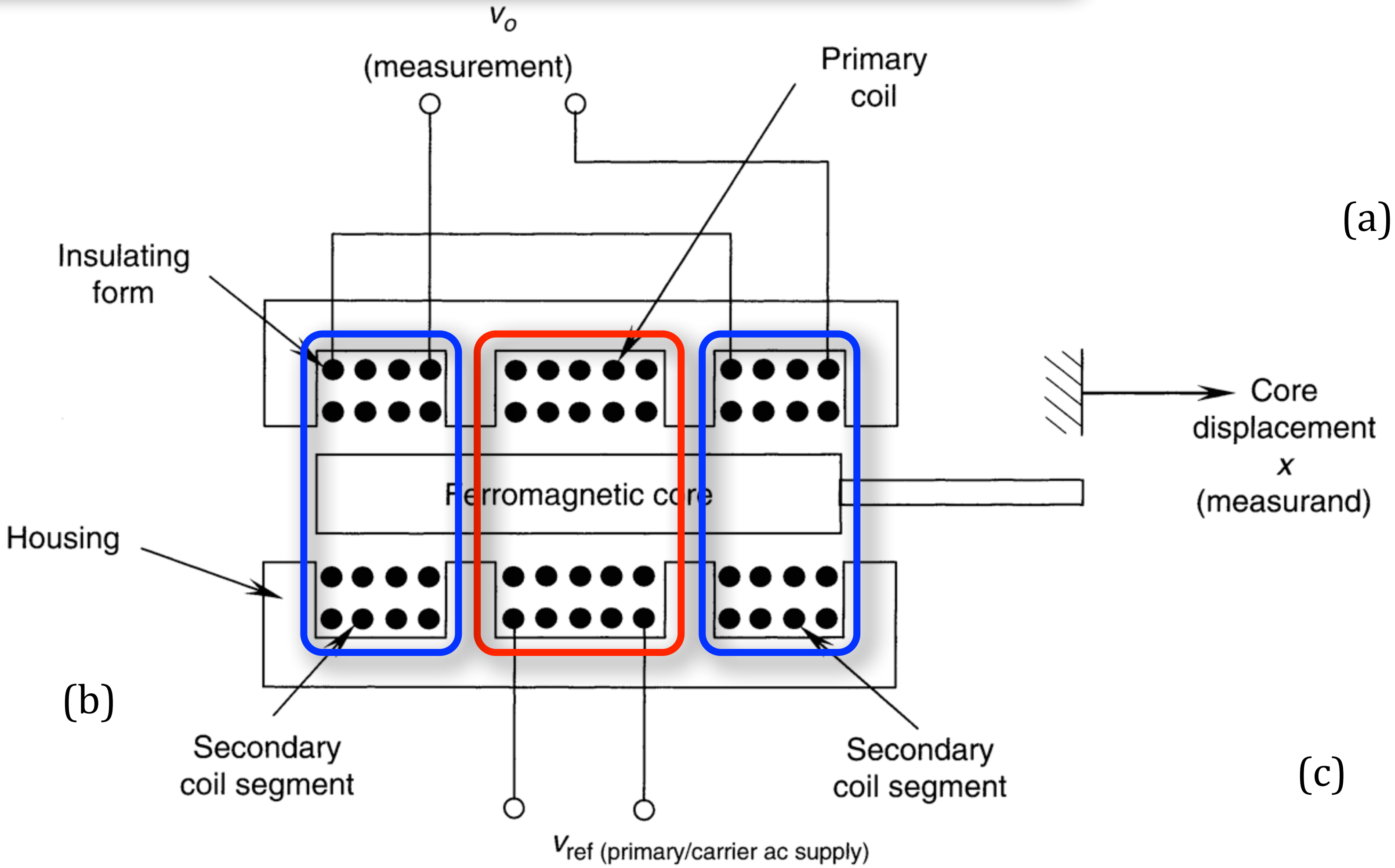
ferromagnetic | ˌferōˌmagˈnetik |

adjective Physics

(of a body or substance) having a high susceptibility to magnetization, the strength of which depends on that of the applied magnetizing field, and that may persist after removal of the applied field. This is the kind of magnetism displayed by iron and is associated with parallel magnetic alignment of neighboring atoms.



(a)



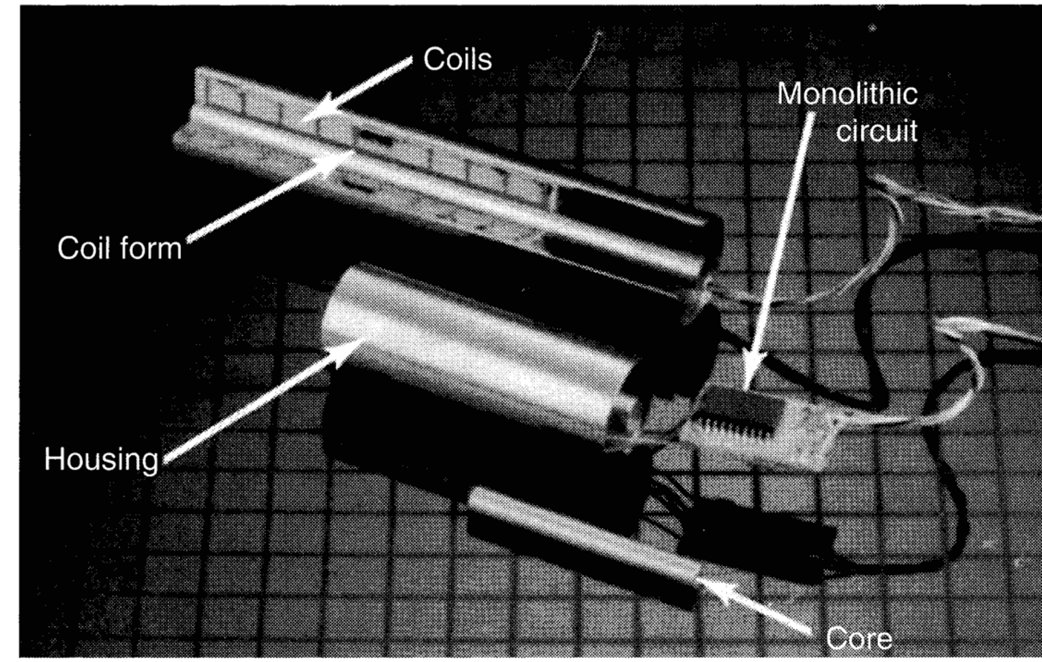
(b)

v_{ref} = AC Voltage

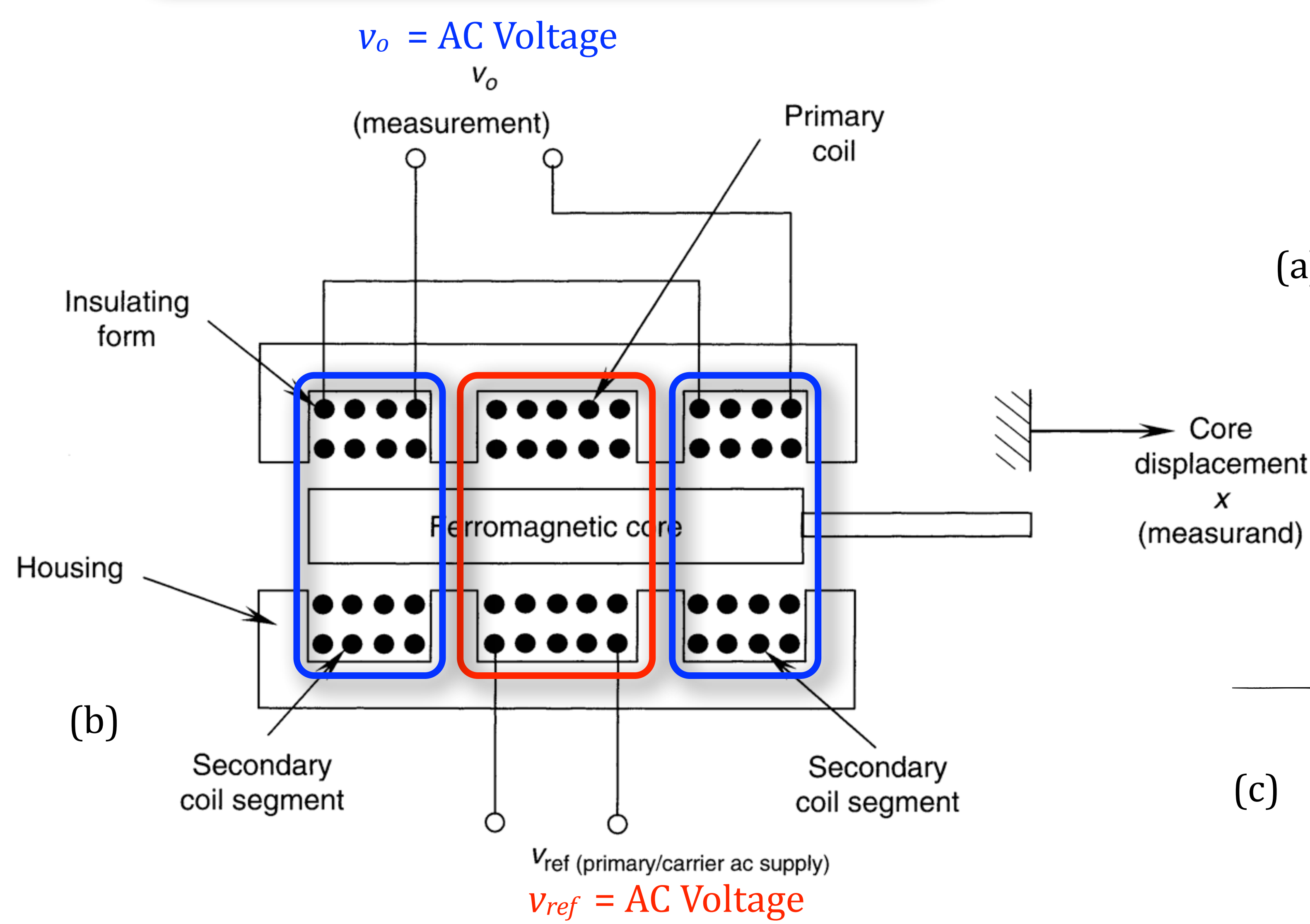
(c)

Figure 5.10
LVDT. (a) A commercial unit (Scheavitz Sensors, Measurement Specialties, Inc. With permission). (b) Schematic diagram. (c) A typical operating curve.

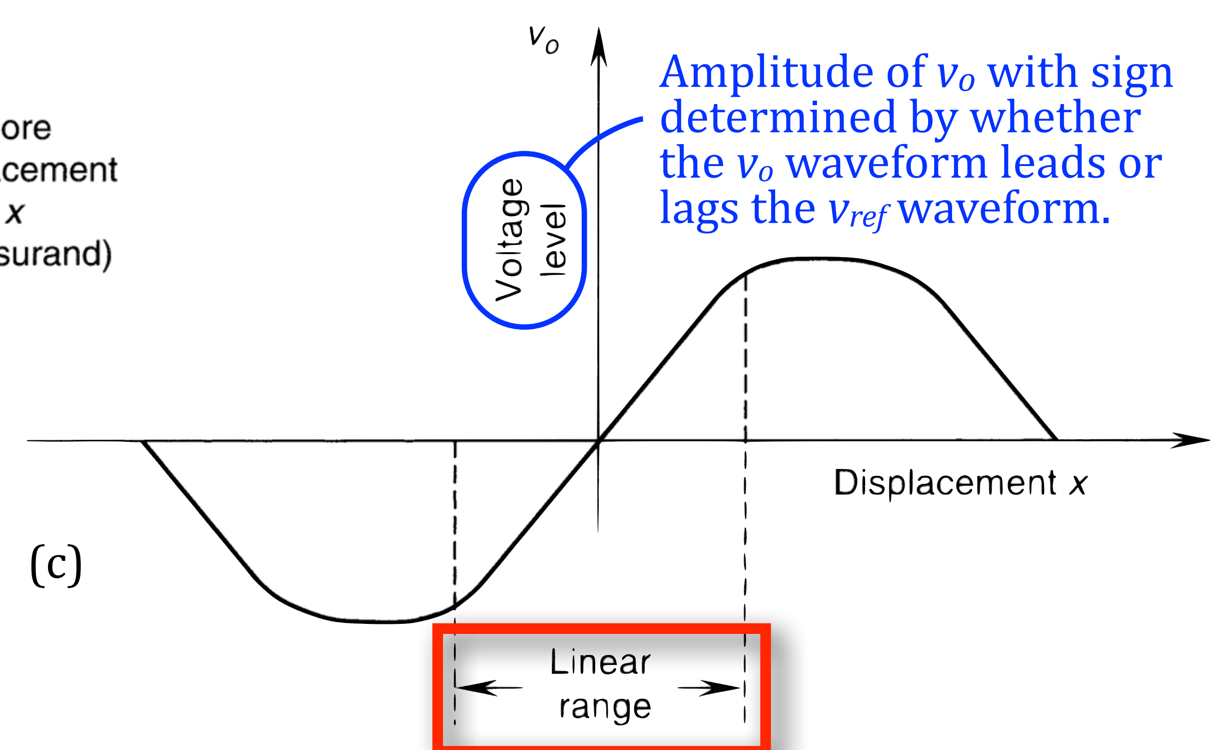
Operating Principal
AC voltage in primary coil generates, by mutual induction, an ac voltage of same frequency in secondary coil.



(a)



(b)



(c)

Figure 5.10
LVDT. (a) A commercial unit (Scheavitz Sensors, Measurement Specialties, Inc. With permission). (b) Schematic diagram. (c) A typical operating curve.

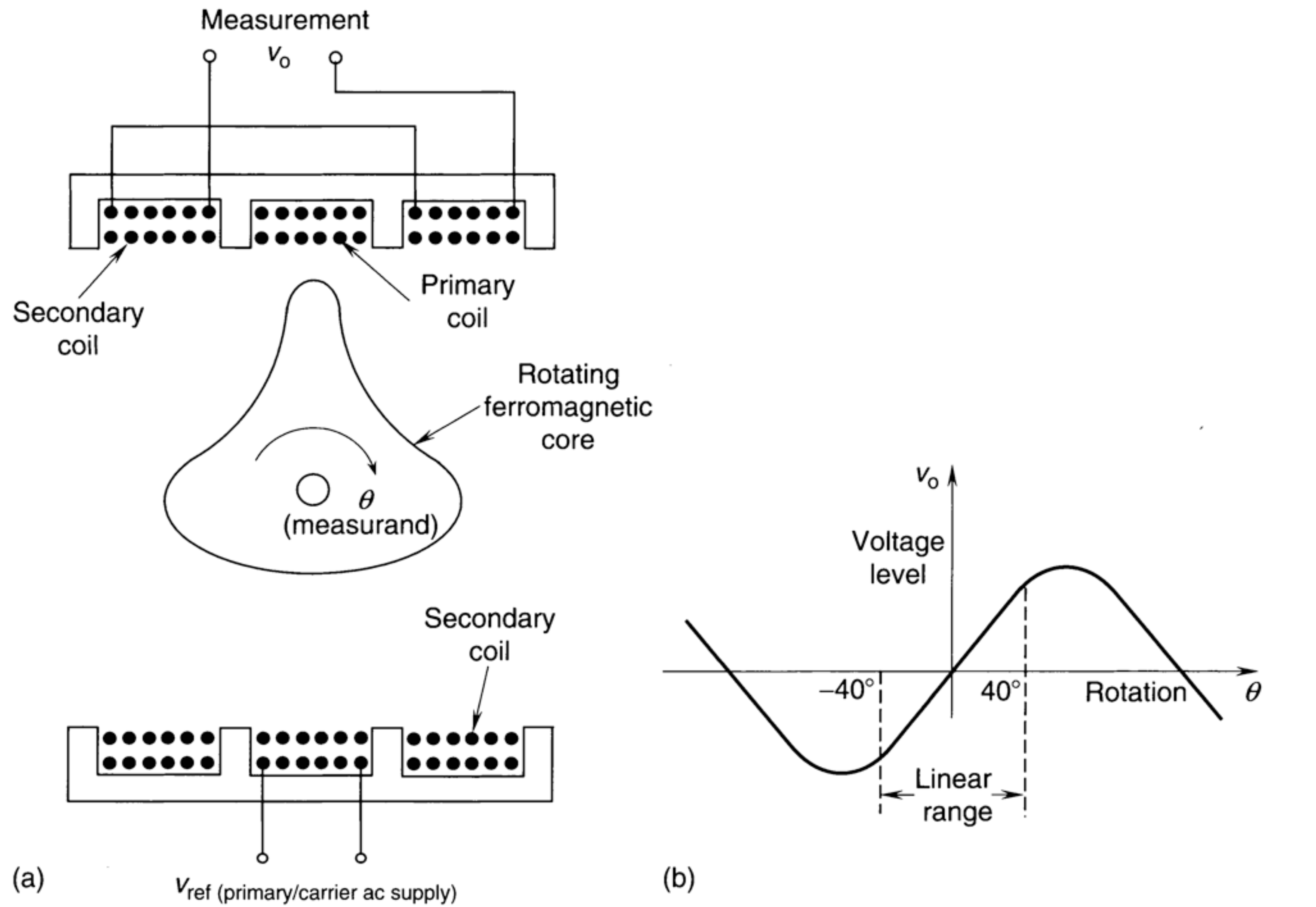


Figure 5.15
(a) Schematic diagram of an RVDT. (b) Operating curve.

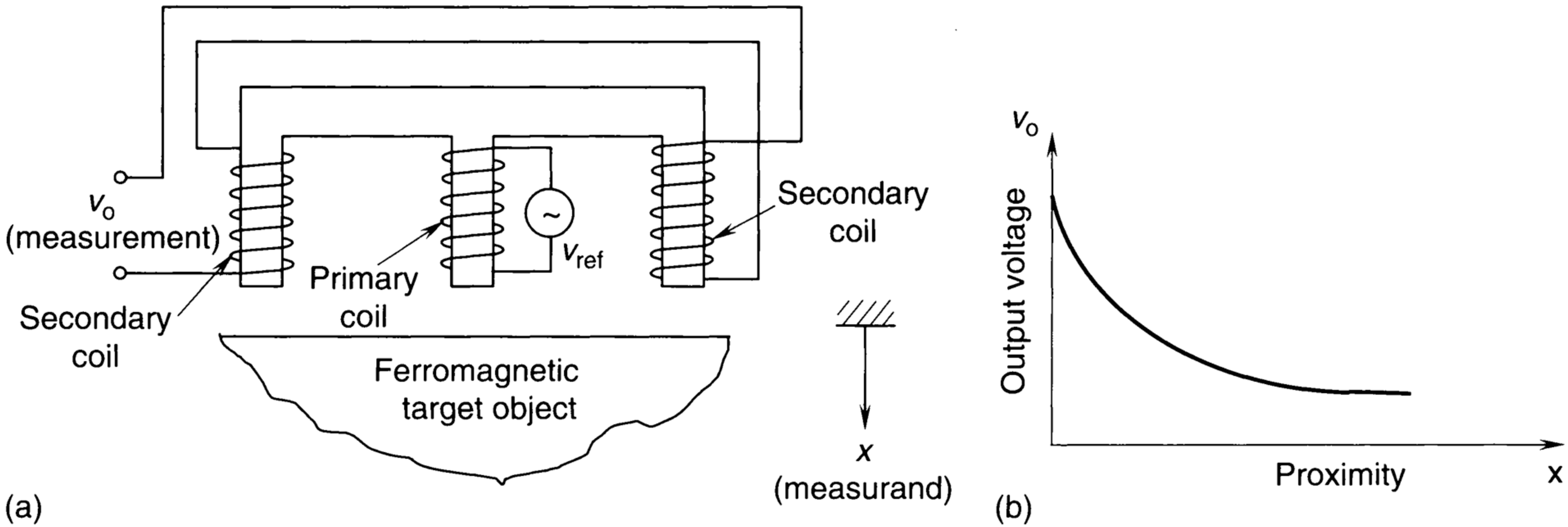


Figure 5.16
(a) Schematic diagram of a mutual-induction proximity sensor. (b) Operating curve.

self-induction proximity sensor

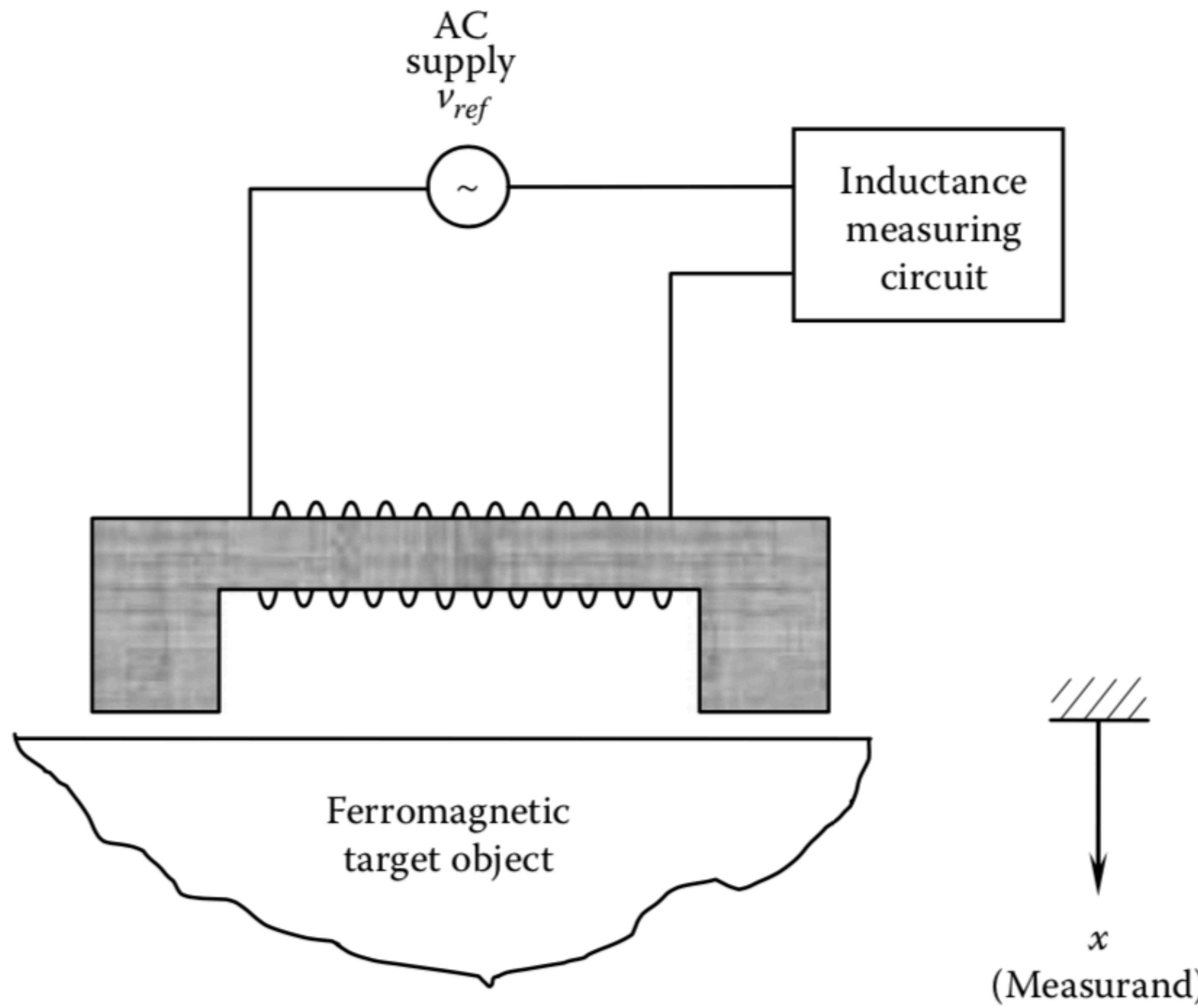
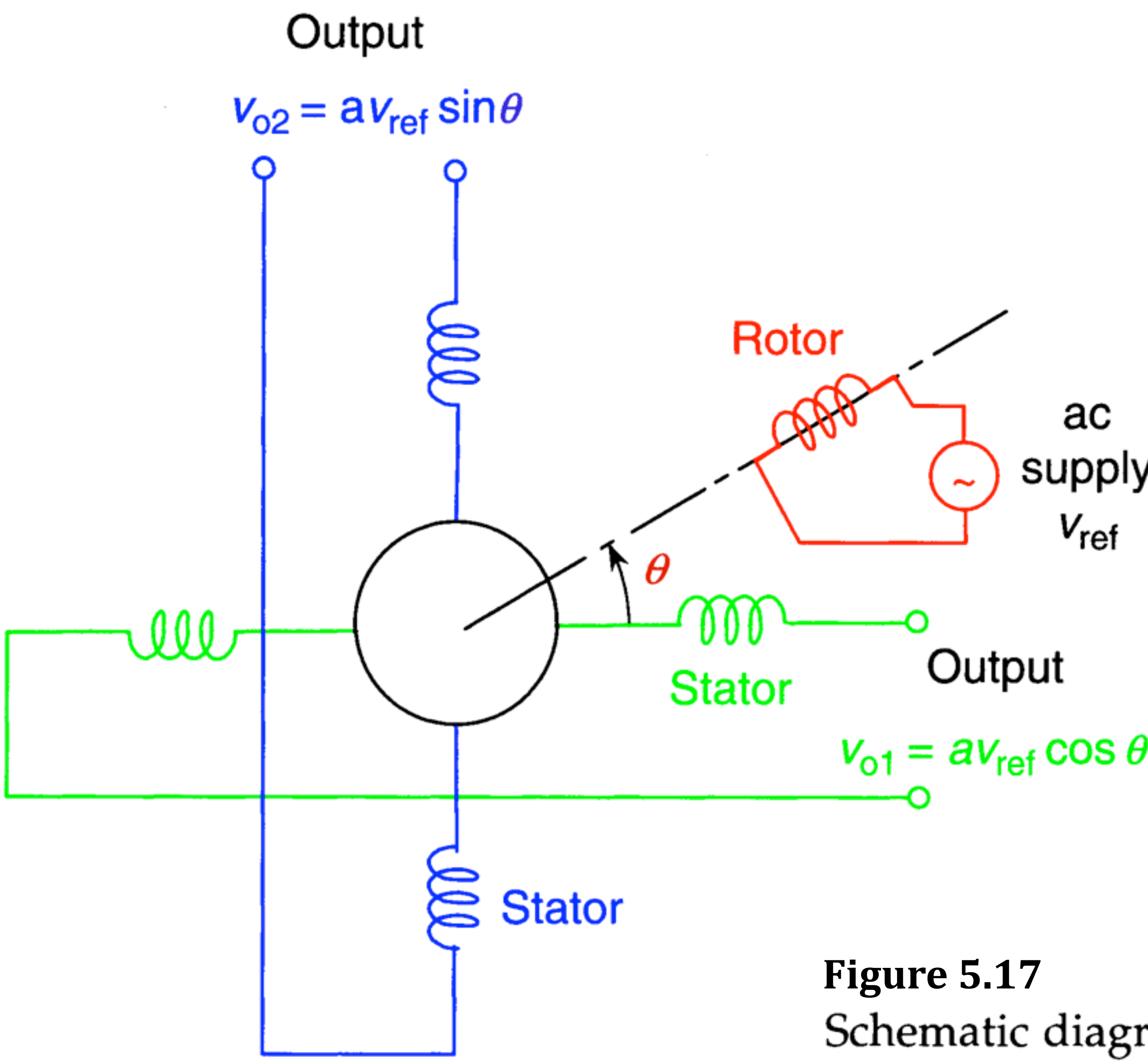


FIGURE 5.18 Schematic diagram of a self-induction proximity sensor.

Resolver

The rotor is attached to the object whose angular position θ is to be measured.

The stator (fixed portion of the sensor) includes two pairs of windings placed 90^{o} apart.



The induced voltage in this pair of windings is

$$v_{o1} = a\, v_{ref} \cos\theta$$

where a is a constant determined by geometric and material properties.

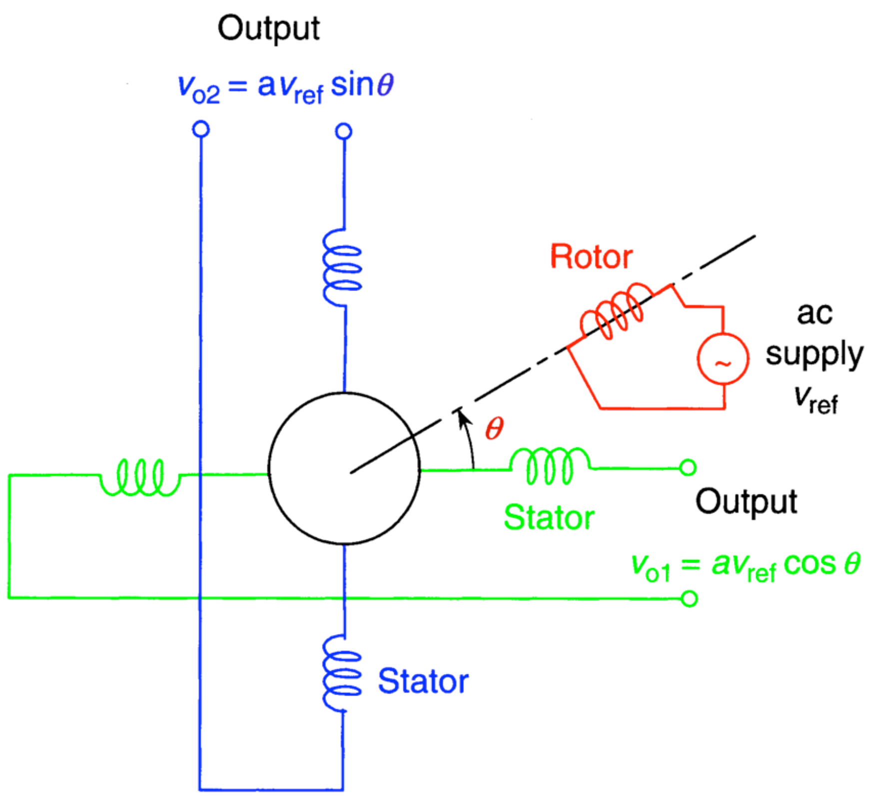
The induced voltage in the other pair of windings is

$$v_{o2} = a\, v_{ref} \sin\theta$$

Figure 5.17
Schematic diagram of a resolver.

5.4.4.1 Demodulation

For differential transformers (i.e., LVDT and RVDT), the displacement signal (transient) from a resolver can be extracted by demodulating its (modulated) outputs. As usual, this is accomplished by filtering out the carrier signal, thereby extracting the modulating signal (which is the displacement signal). The two output signals v_{o1} and v_{o2} of a resolver are termed quadrature signals. Suppose that the carrier (primary) signal is



$$v_{ref} = v_a \sin\omega t \tag{5.21}$$

should be v_{o1}

Then from Equations 5.19 and 5.20, the induced quadrate signals are $v_{o2} = av_a \cos\theta \sin\omega t$ and $v_{o2} = av_a \sin\theta \sin\omega t$. Multiplying these equations by v_{ref}, we get

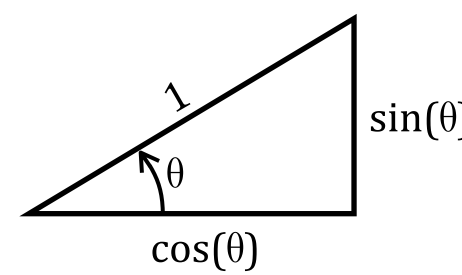
Product is high-frequency compared to cos θ

$$v_{m1} = v_{o1}v_{ref} = av_a^2\cos\theta\sin^2\omega t = \frac{1}{2}av_a^2\cos\theta[1-\cos 2\omega t]$$

$$v_{m2} = v_{o2}v_{ref} = av_a^2\sin\theta\sin^2\omega t = \frac{1}{2}av_a^2\sin\theta[1-\cos 2\omega t]$$

Provided the carrier frequency ω is at least 10 times the maximum frequency of interest in
~~Since the carrier frequency ω should be about 10 times the maximum frequency content of interest in~~
the angular displacement θ, one can use a low-pass filter with a cutoff set at ω/10 to remove the carrier components in v_{m1} and v_{m2}. This gives the demodulated outputs:

$$v_{f1} = \frac{1}{2}av_a^2\cos\theta \tag{5.22}$$

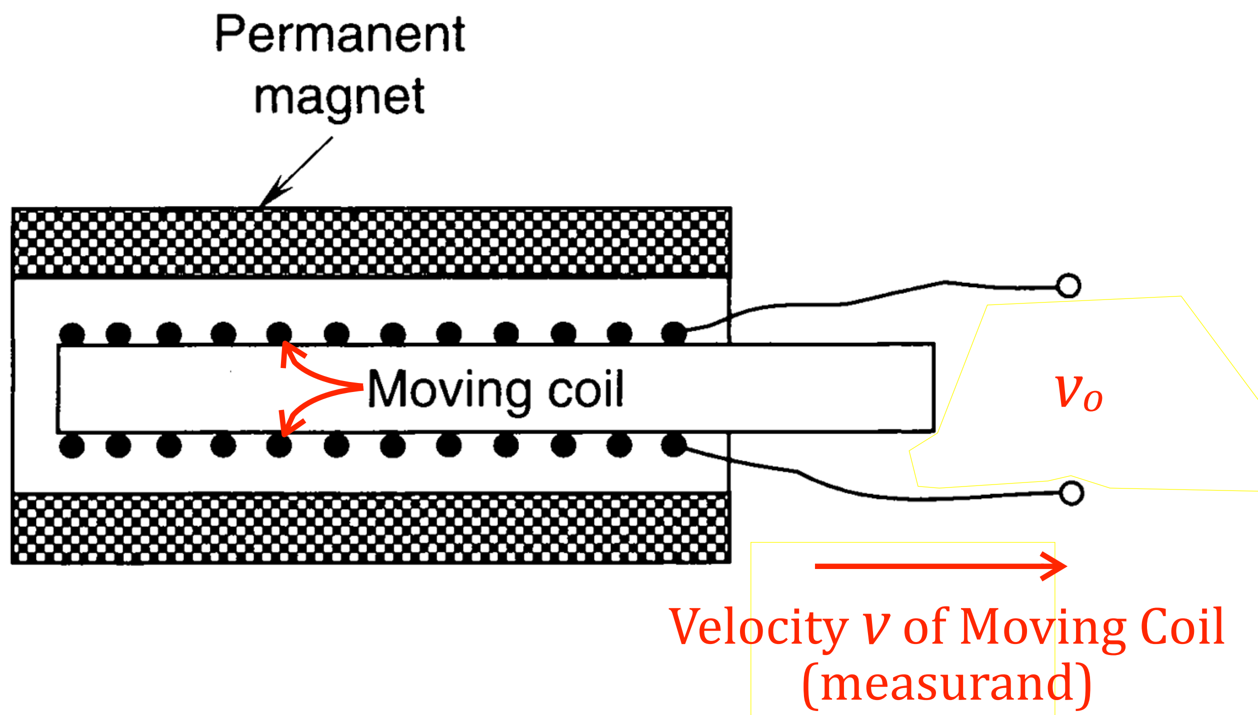


$$v_{f2} = \frac{1}{2}av_a^2\sin\theta \tag{5.23}$$

Note that Equations 5.22 and 5.23 provide both cos θ and sin θ, and hence the magnitude and the sign of θ.

Permanent Magnet DC Transducers

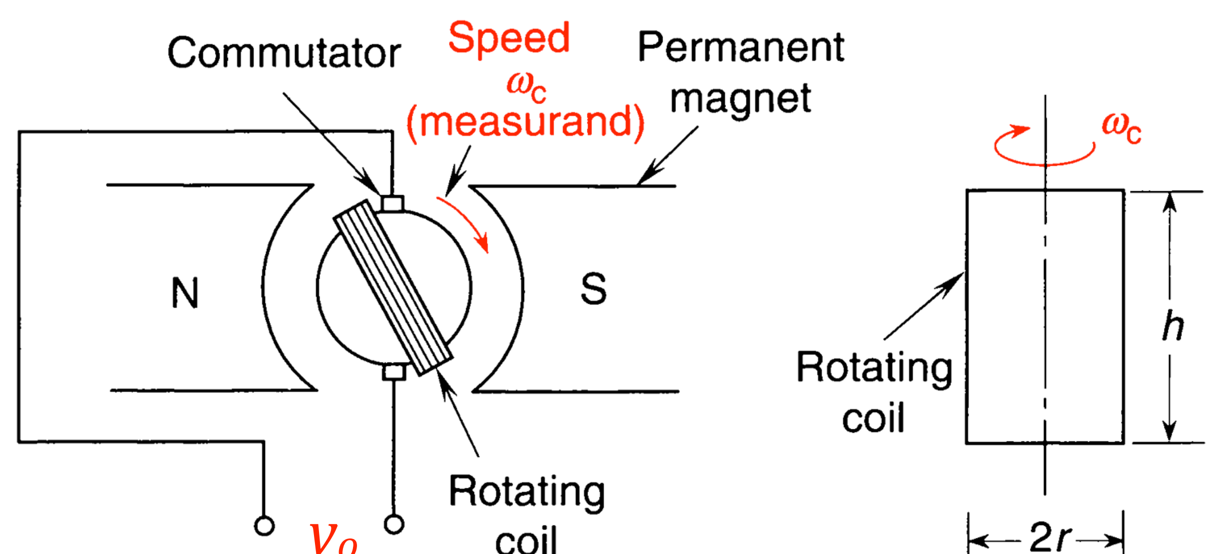
Rectilinear velocity sensor:



From Physics:

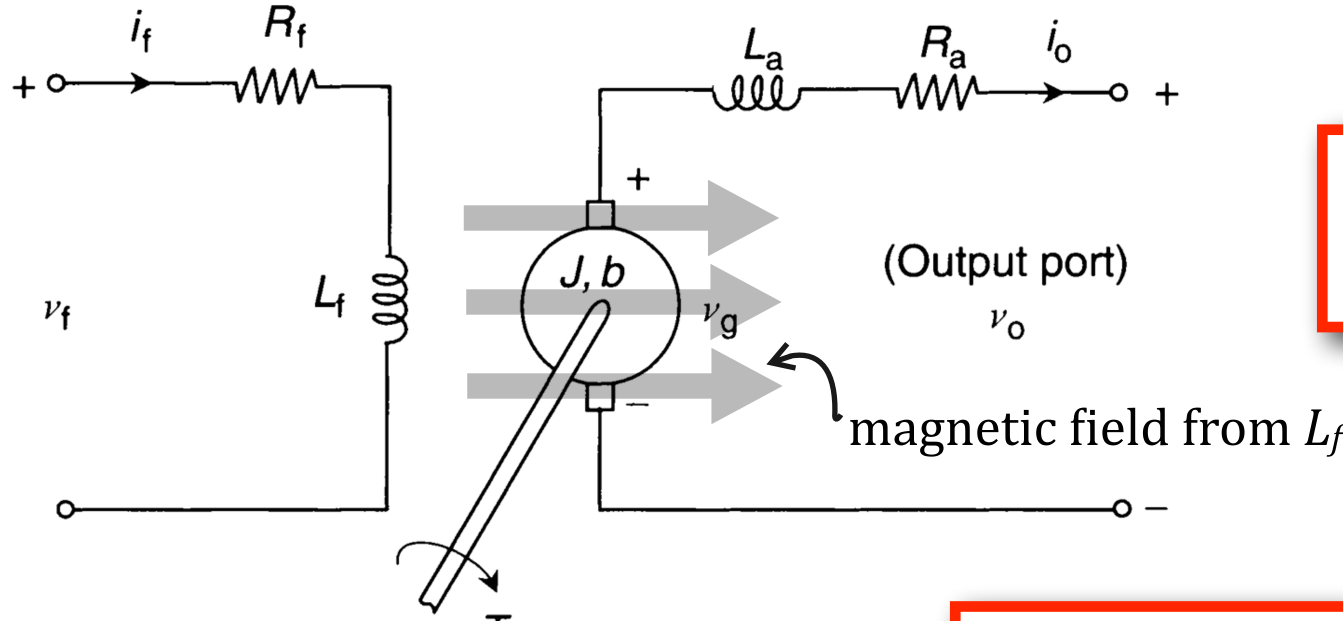
The velocity of a coil of wire in a magnetic field induces a voltage across the coil that is proportional to the velocity.

Angular velocity sensor: (tachometer)



DC Tachometer

DC voltage v_f results in current i_f that, via the field windings (L_f), generates the magnetic field in which the rotor turns.

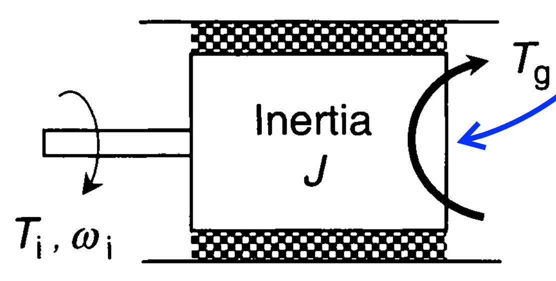


(a)

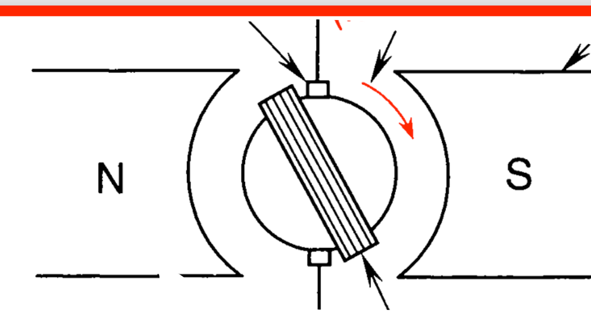
Resulting $v_o(t)$ is used to determine $\omega_i(t)$.

Rotor windings: coil of wire that moves with angular velocity ω_i in a magnetic field

Measurand is the angular velocity, ω_i, at the input port.



(b)

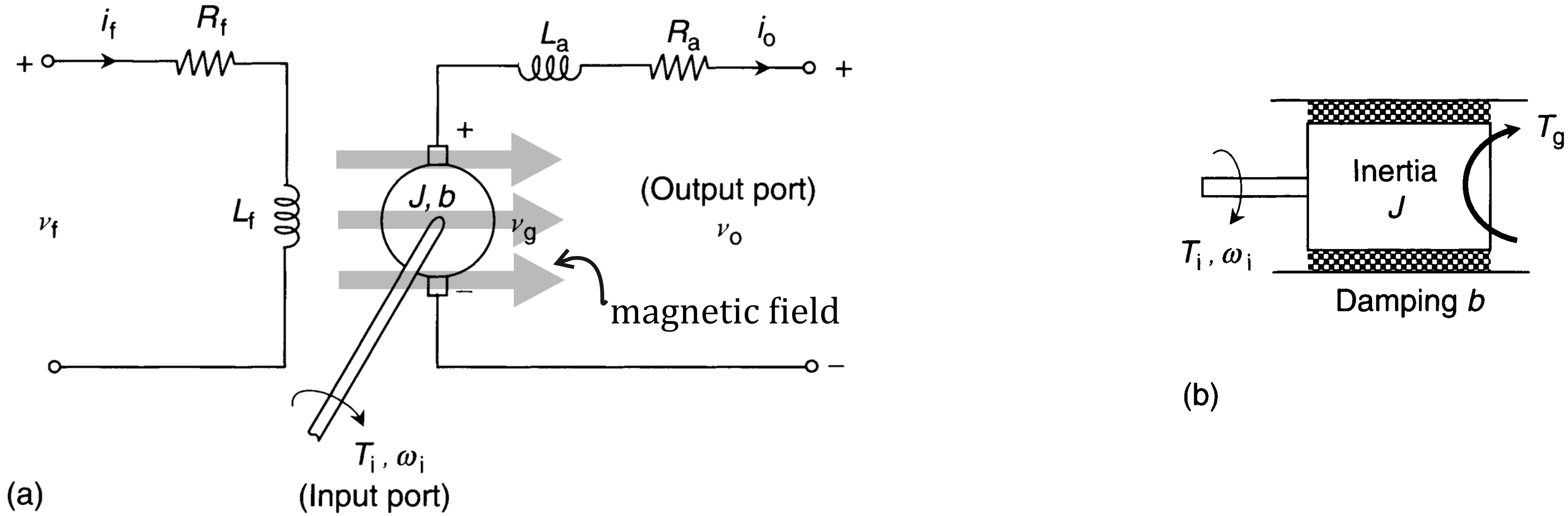


Note: most tachometers consist of more than one coil, "commutated" so that each is connected only at a short interval during which its rotation angle produces maximum voltage

Figure 5.20

A dc tachometer example. (a) Equivalent circuit with an impedance load; (b) Armature free-body diagram.

Under what conditions does this device function as an ideal tachometer: $v_o = K\omega_i$?



Assumption: v_f is constant

Motor transformer equations:

$$v_{rotor} = K\omega_{rotor} \quad \Leftrightarrow \quad v_g = \boxed{K\omega_i}$$

$$i_{rotor} = -\frac{1}{K}T_{rotor} \quad \Leftrightarrow \quad T_g = \boxed{K i_o}$$

ME 374 Notation   Sec. 5.5.1.2 Notation

Loop equation for output side:

$$v_o = v_g - R_a i_o - L_a \frac{di_o}{dt}$$

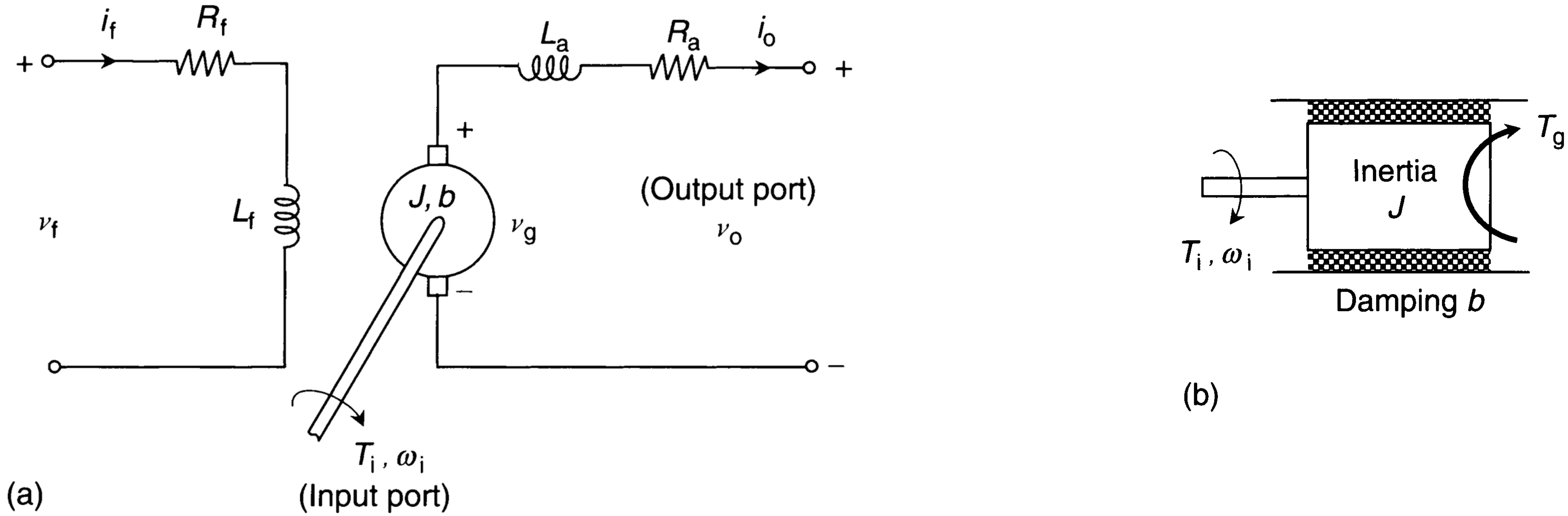
Newton's law applied to rotary inertia:

$$J\frac{d\omega_i}{dt} = T_i - T_g - b\omega_i$$

Substitute $T_g = K\, i_o$, to get $I_o(s)$ equation below.

Then use result to eliminate i_o from above equation to get $V_o(s)$ equation below.

$$\Rightarrow \begin{bmatrix} V_o(s) \\ I_o(s) \end{bmatrix} = \begin{bmatrix} K + (L_a s + R_a)(Js+b)/K & -(L_a s + R_a)/K \\ -(Js+b)/K & 1/K \end{bmatrix} \begin{bmatrix} \Omega_i(s) \\ T_i(s) \end{bmatrix}$$

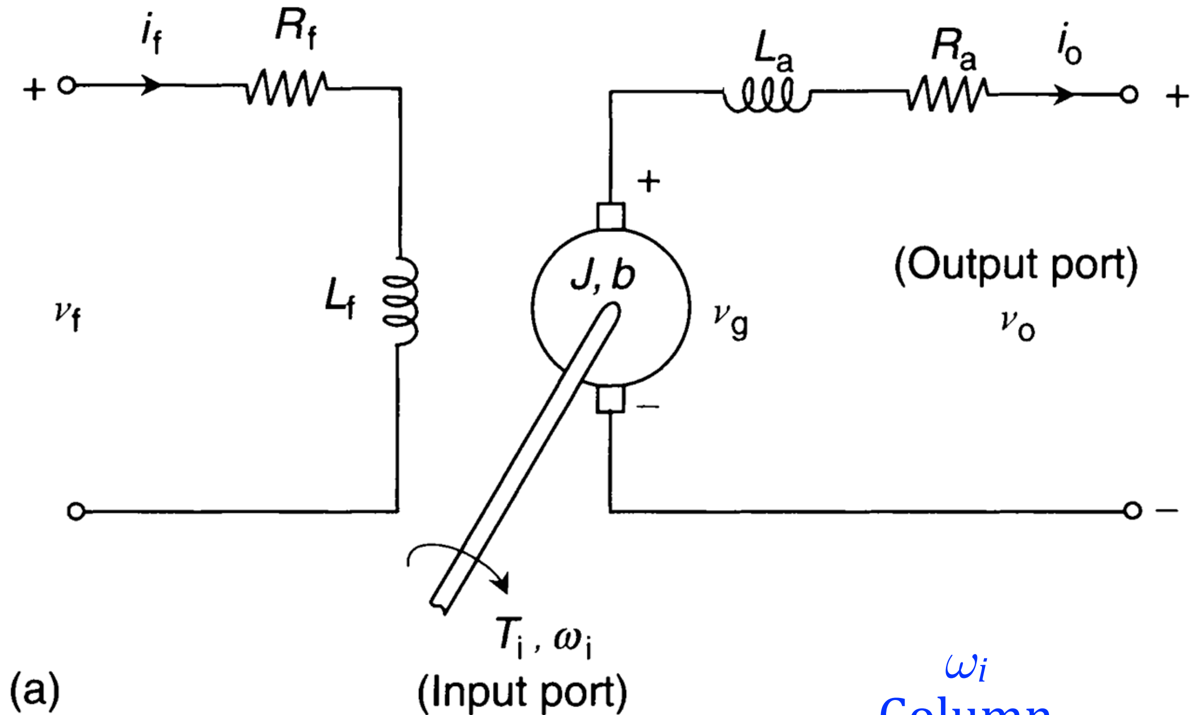


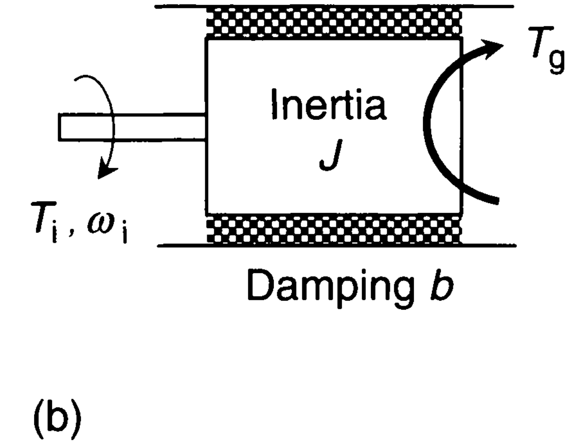
$$\Rightarrow \begin{bmatrix} V_o(s) \\ I_o(s) \end{bmatrix} = \begin{bmatrix} K + (L_a s + R_a)(Js + b)/K & -(L_a s + R_a)/K \\ -(Js+b)/K & 1/K \end{bmatrix} \begin{bmatrix} \Omega_i(s) \\ T_i(s) \end{bmatrix}$$

$$\Leftrightarrow \begin{bmatrix} V_o(s) \\ I_o(s) \end{bmatrix} = \begin{bmatrix} K + \left(\frac{L_a}{R_a}s+1\right)\left(\frac{J}{b}s+1\right)\frac{R_a b}{K} & -\left(\frac{L_a}{R_a}s+1\right)\frac{R_a}{K} \\ -\left(\frac{J}{b}s+1\right)\frac{b}{K} & \frac{1}{K} \end{bmatrix} \begin{bmatrix} \Omega_i(s) \\ T_i(s) \end{bmatrix}$$

$$\Leftrightarrow \begin{bmatrix} V_o(s) \\ I_o(s) \end{bmatrix} = \begin{bmatrix} K + (\tau_e s+1)(\tau_m s+1)\frac{R_a b}{K} & -(\tau_e s+1)\frac{R_a}{K} \\ -(\tau_m s+1)\frac{b}{K} & \frac{1}{K} \end{bmatrix} \begin{bmatrix} \Omega_i(s) \\ T_i(s) \end{bmatrix}$$

$\tau_e = L_a/R_a$ (Electrical time constant) $\qquad$ $\tau_m = J/b$ (Mechanical time constant)





ω_i Column

T_i Column

$\approx \dfrac{R_a b}{K}$ at frequencies $< \min\left(\dfrac{1}{\tau_e}, \dfrac{1}{\tau_m}\right)$

$\approx \dfrac{R_a}{K}$ at frequencies $< \dfrac{1}{\tau_e}$

$$\Leftrightarrow \quad \begin{bmatrix} V_o(s) \\ I_o(s) \end{bmatrix} = \begin{bmatrix} K + \boxed{(\tau_e s + 1)(\tau_m s + 1)\dfrac{R_a b}{K}} & -\boxed{(\tau_e s + 1)\dfrac{R_a}{K}} \\ -(\tau_m s + 1)\dfrac{b}{K} & \dfrac{1}{K} \end{bmatrix} \begin{bmatrix} \Omega_i(s) \\ T_i(s) \end{bmatrix}$$

Typically $K \gg R_a b$ and $K \gg R_a$, in which case

$$v_o \approx K\,\omega_i$$

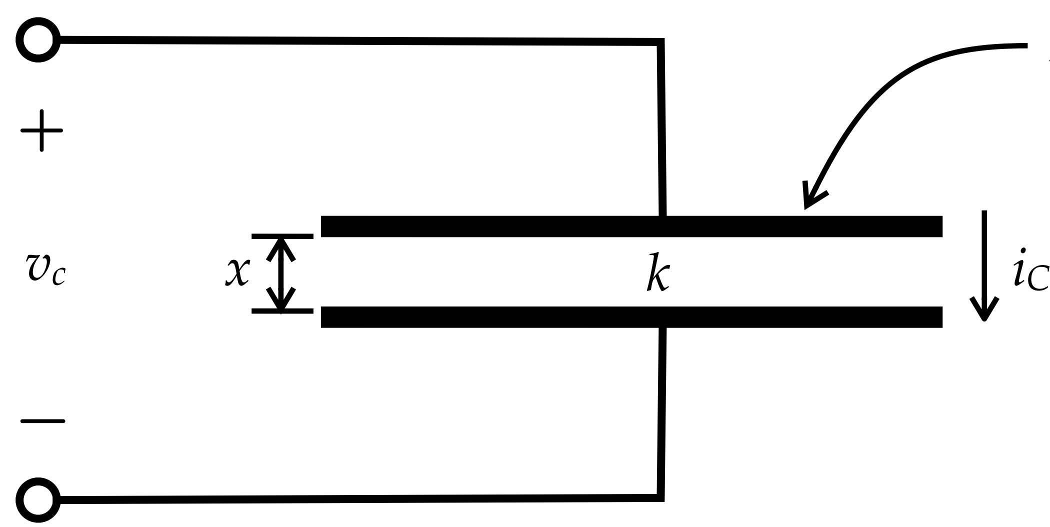
provided the highest frequencies in ω_i and T_i are small compared to $\min(1/\tau_m, 1/\tau_e)$ and $1/\tau_e$, respectively.

A tachometer!

$\tau_e = L_a/R_a$ (Electrical time constant) $\qquad \tau_m = J/b$ (Mechanical time constant)

Variable-Capacitance Transducers

Parallel-plate capacitor:



A = common (overlapping) area of plates

$$C = \frac{kA}{x}$$

Measurand can be any one of these. Fix two of the three, then measure C to deduce the third.

$k =$ dielectric constant (depends upon properties of medium between plates)

$$i_C = \frac{dq_c}{dt} = \frac{d(Cv_c)}{dt} \Leftrightarrow q_c(t) = C(t)v_c(t) = \int_{-\infty}^{t} i_C(\lambda)\,d\lambda$$