EE 4323 – Industrial Control Systems
Module 4b: Sensing for Industrial Controls

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Sensing for Industrial Controls – Overview

- Motivation
- Basic concepts and considerations
- A sampling of sensing techniques
- Position, velocity, acceleration and pressure sensing

References:

- C. L. Nachtigal, *Instrumentation & Control - Fundamentals and Applications*, John Wiley & Sons, 1990 (practical / encyclopedic)
- C. D. Johnson, *Process Control Instrumentation Technology*, Prentice Hall, Fifth Edition, 1997 (very good, emphasis on process control)

Motivation

- Deciding **what to sense** and **how to sense it** may be a large factor in designing an industrial control system
- Sensor characteristics (static, dynamic) may be a major factor in determining (limiting) a control system's performance
- Assuming a sensor is simply modelled as K_{sen} may be totally unrealistic
- Determining a realistic sensor model (the best way to deal with limitations imposed by the sensor) isn't trivial – it takes engineering judgement plus mathematical modelling techniques:
  - physical modelling
  - model identification methods (Module 5)

Basic Concepts

Terminology:

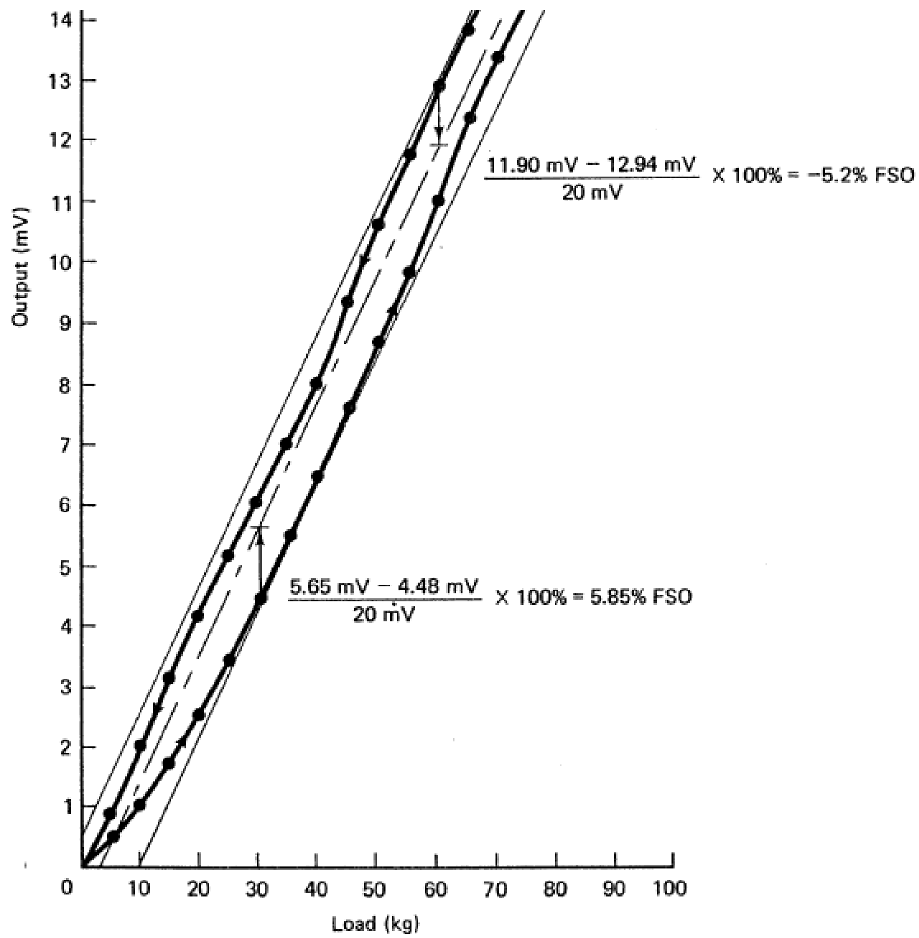
- Transducers / sensors / instrumentation
- Measurands (variables being sensed), signals
- Static and dynamic characteristics - sensitivity, accuracy, resolution, nonlinearity, repeatability, noise sensitivity, delay, lag …
- Environmental effects (e.g., temperature effects on an accelerometer), drift, calibration
- Signal conditioning, "de-glitching", filtering, estimation / indirect sensing (observers)

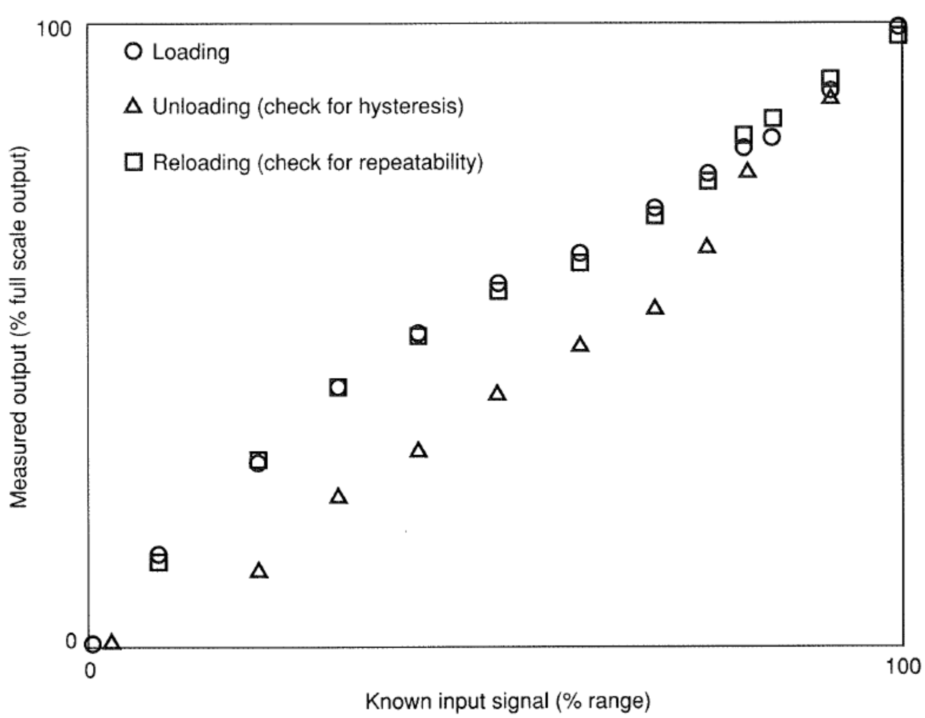
We will look at some of these terms and issues generically or as we deal with a sampling of specific sensing techniques.

Basic Considerations

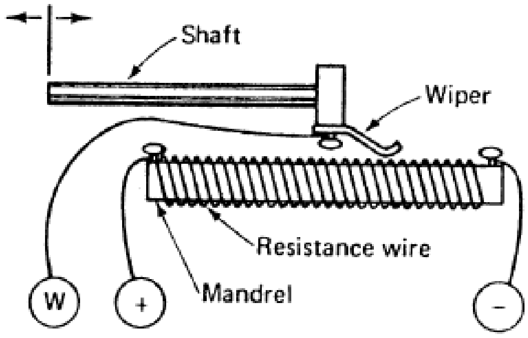
- Most fundamentally: **what variable do you need to sense, over what range**; then factor in "imperfections" such as nonlinearity, loading, dynamic effects (lag), frequency response (related to lag), drift, calibration, environmental effects, cost, ruggedness, reliability, . . .
- The most basic limitations (imperfections) are **static nonlinearity** and **dynamic response**; we will focus more closely on those issues and techniques for modelling them. In this context, the most important considerations are:
  - What type of model to use – **nonlinear**: polynomial, piece-wise linear, exponential, log, . . . ; **dynamic**: usually continuous-time, the question is: what order?
  - In either case **overfitting** is a major concern (high-order polynomials, high-order transfer-functions); in the case of static nonlinearity there is also the issue of model "**safety**" (e.g., high-order polynomials become useless outside the fitting range and may also be in error between fitted points, while piece-wise linear models don't suffer from these problems)
  - The above points should be carefully considered **before** modelling and design

Basic Considerations – Nonlinearity

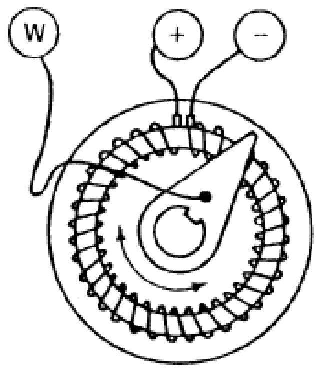


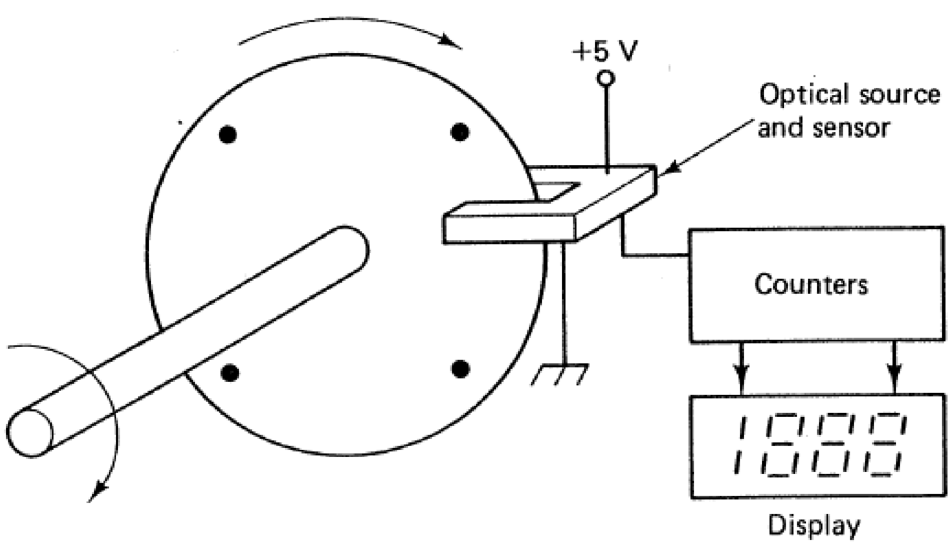


Basic Considerations – Resolution

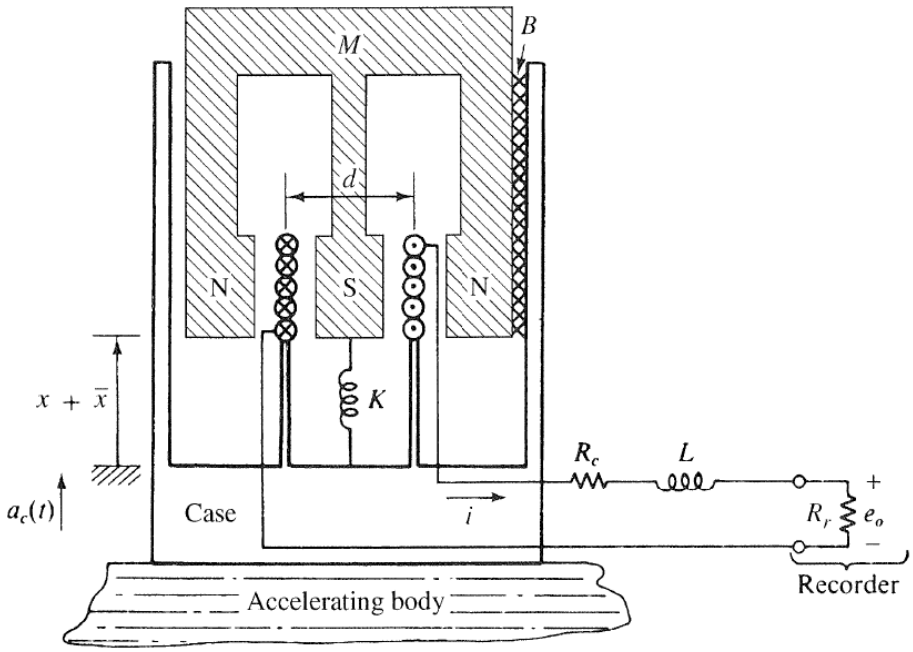


(a)





Basic Considerations – Dynamic Response

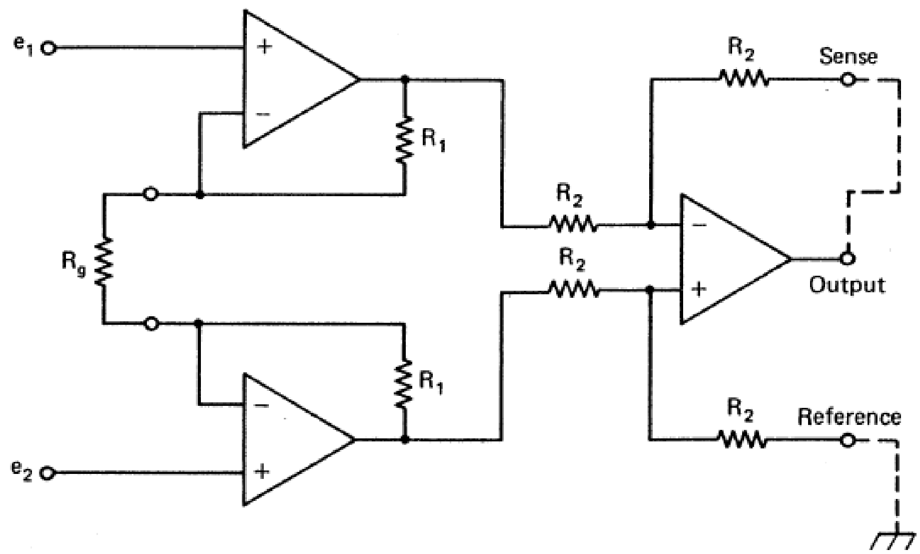


We will see that an accurate model of this mass-spring-damper system (accelerometer) is second-order and usually lightly damped – the dynamics **do** matter

Basic Considerations – Environmental Effects

- Some sensors have a temperature-dependent response, e.g., strain gauges. Either they must be kept at constant temperature or they must be **compensated**
- Some sensors are delicate and must be protected from shock and vibration
- Some sensors require a clean and dry environment and must be encapsulated
- Some optical sensors work only in an appropriate illumination level. Either they must be kept in a controlled environment or encapsulated

Basic Considerations – Electronics



Electronics are required to prevent loading the sensor (usually high-impedance device)

$$v_0 = (1 + \frac{2R_1}{R_2})\,(e_2 - e_1)$$

- Gain is highly accurate (using precision resistors)
- Electronic drift is minimal

Basic Considerations (Cont'd)

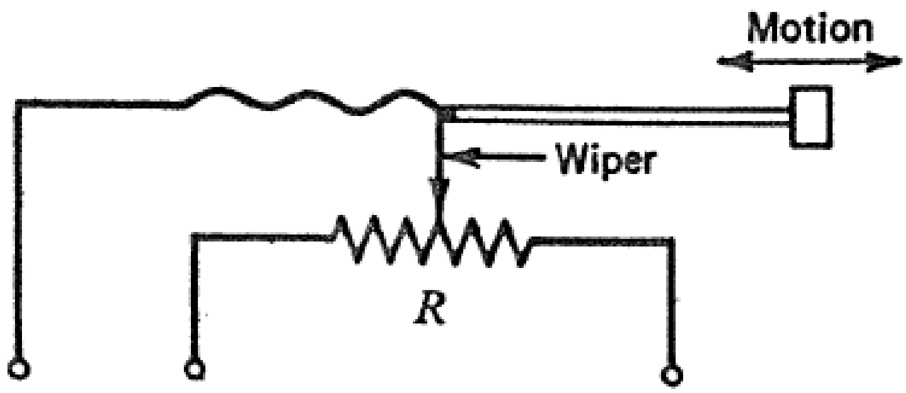
Criteria for picking a sensor - desirable attributes:

- Cheap !
- Rugged !
- Reliable !
- Work in harsh environments !
- Work over required range !
- Loading negligible / acceptable !
- Provide required Sensitivity !
- Provide required resolution !
- Provide required repeatability !
- Provide a clean signal (low noise) !
- Linear over needed range !

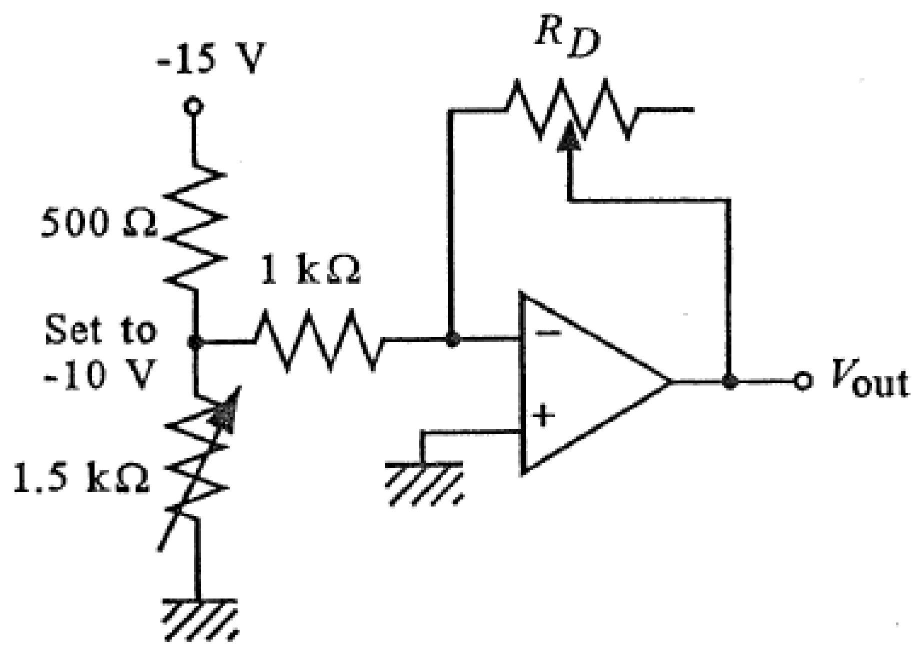
Which criteria apply and with **what priority** depends upon the application and context; some flexibility exists due to design / performance tradeoffs.

Sensing Position

- With a potentiometer:

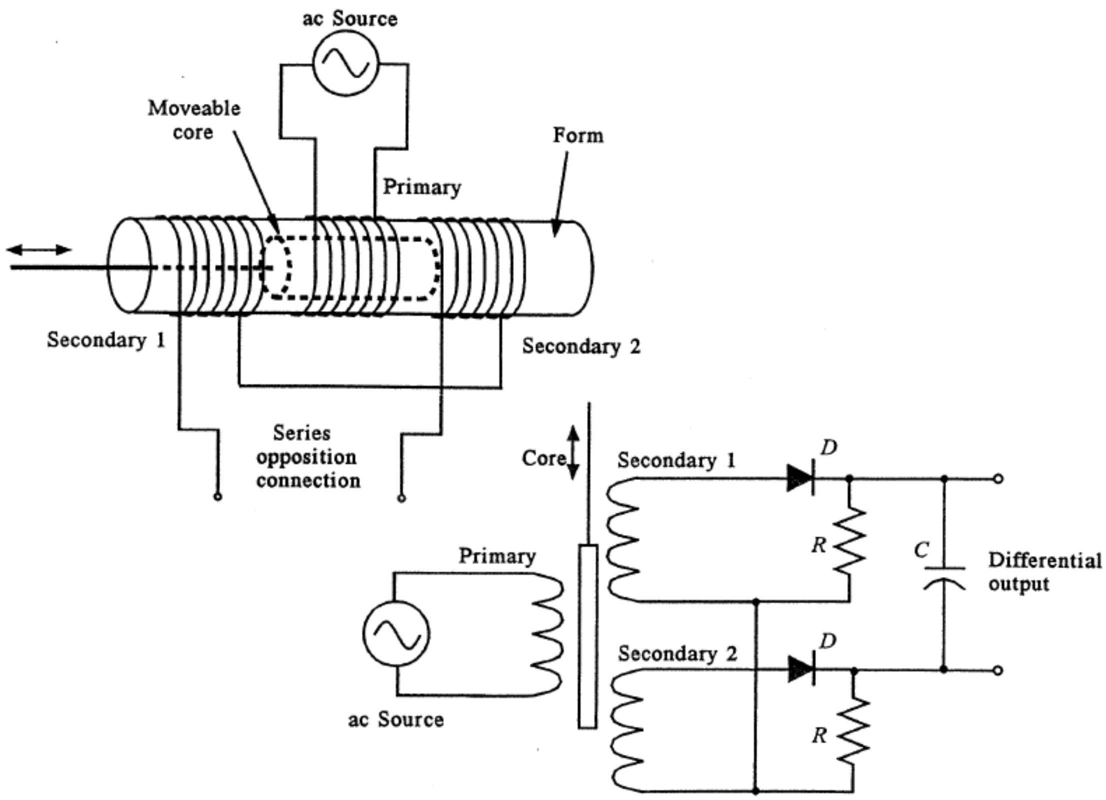


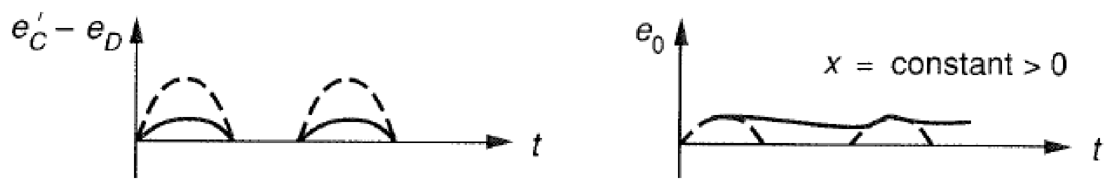
A voltage divider is nonlinear if loaded; using an op-amp circuit will keep it linear



Sensing Position (Cont'd)

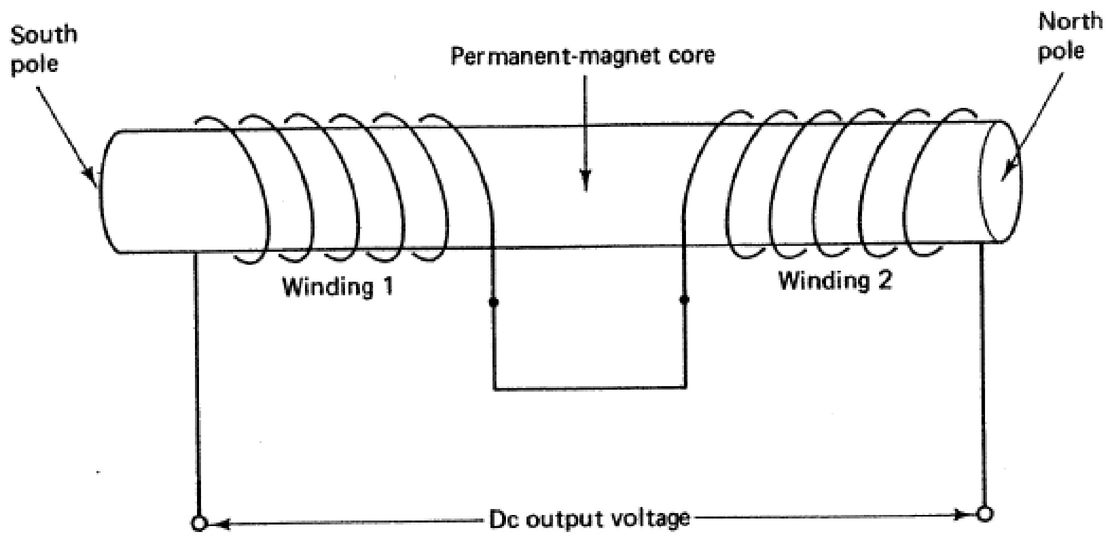
- Linear Variable Differential Transformer (LVDT):

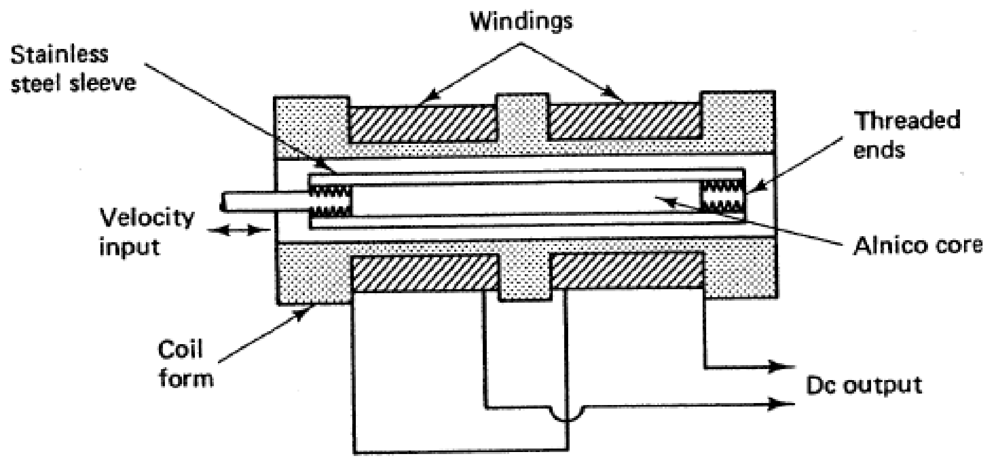




The demodulator provides a half-wave rectified output, which must either be heavily filtered, as shown, or input into a peak-detector. The filtering approach will lead to an output whose dynamics are governed by the excitation frequency, i.e., 60 Hz will lead to a large lag. A peak-detector circuit will provide much less lag.

Sensing Linear Velocity



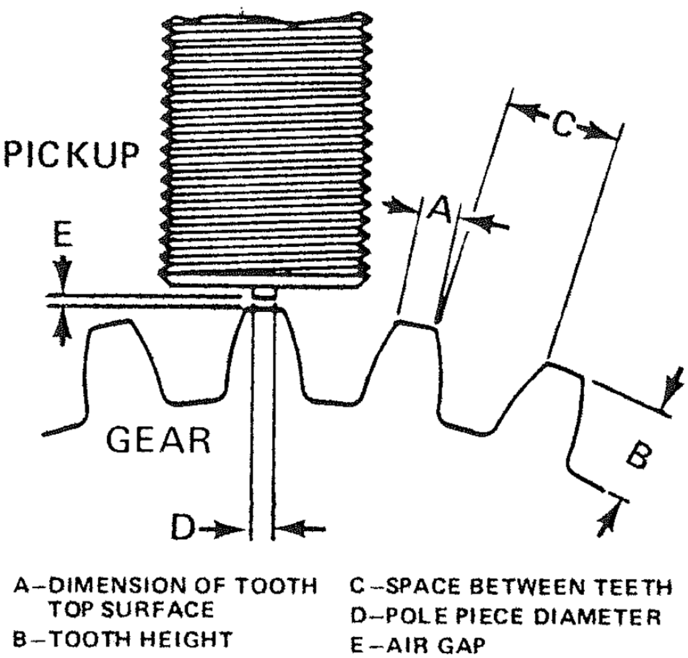


- The output is a DC voltage only as long as the velocity is constant – which cannot be maintained for very long. It will be a **time-varying voltage** related to the velocity of the core

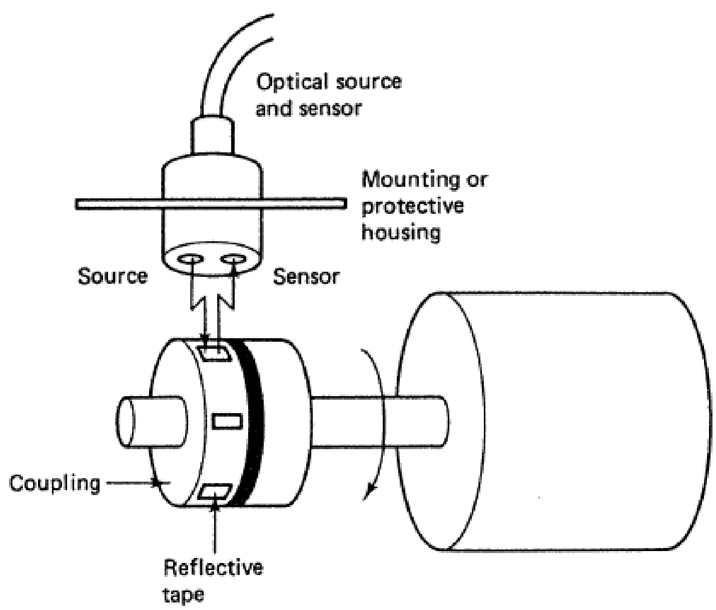
- The response is highly nonlinear unless the motion is very small: $e_{out} = Kv_{core}$ for small core motions but $e_{out} = f(v_{core})$ generally; the nonlinear relation $f(v_{core})$ would be most easily obtained by experiment and least-squares curve fitting.

Sensing Angular Velocity

- An old-fashioned mechanical sensor (more rugged, more tolerent of ambient conditions)



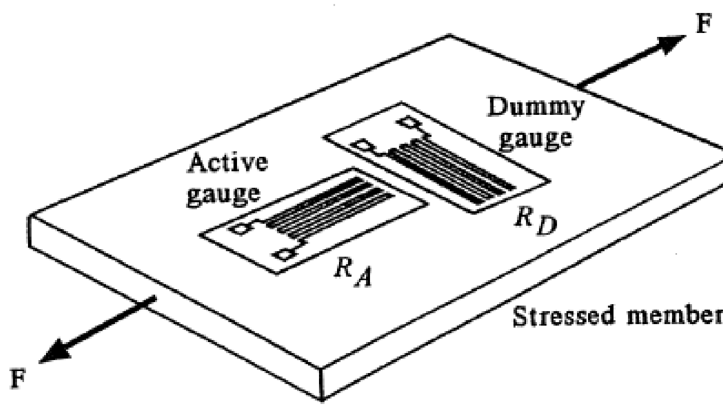
- An optical sensor (less rugged, less tolerent of ambient conditions, potentially better resolution)



Strain Gauge Sensors

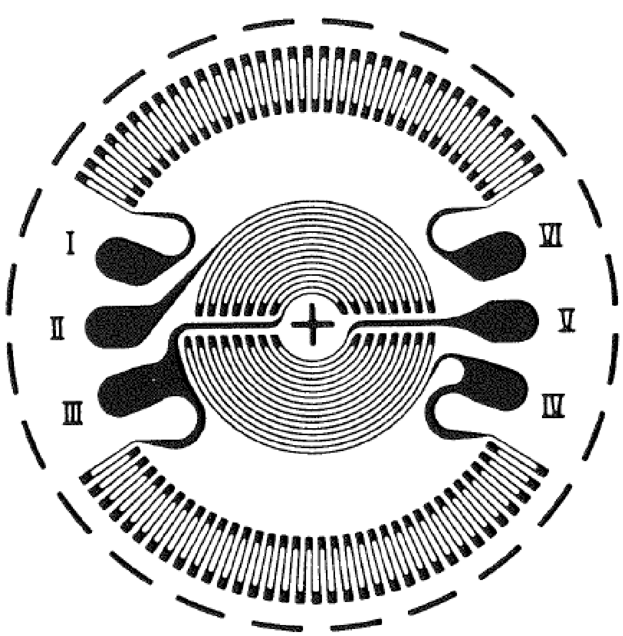
Strain gauges are manufactured in a variety of forms:

- Uni-directional configurations



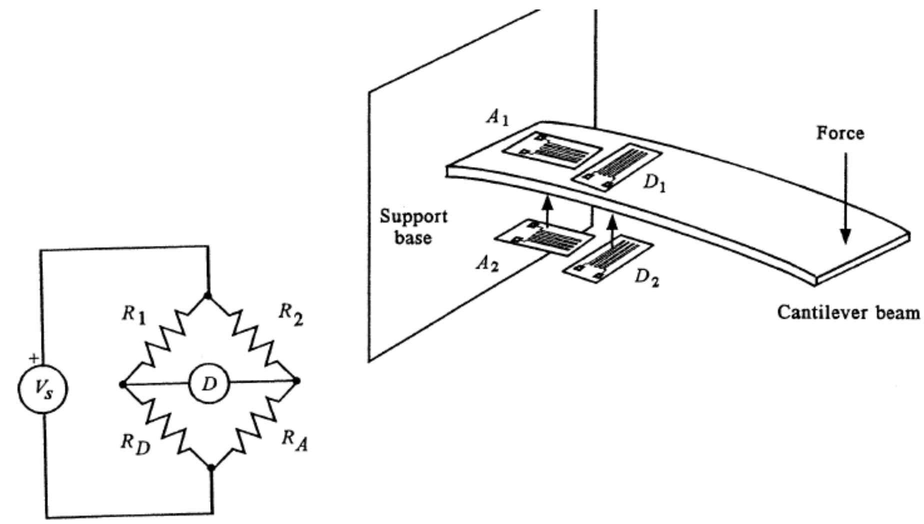
The "dummy gauge" provides temperature compensation when both are used in a bridge circuit

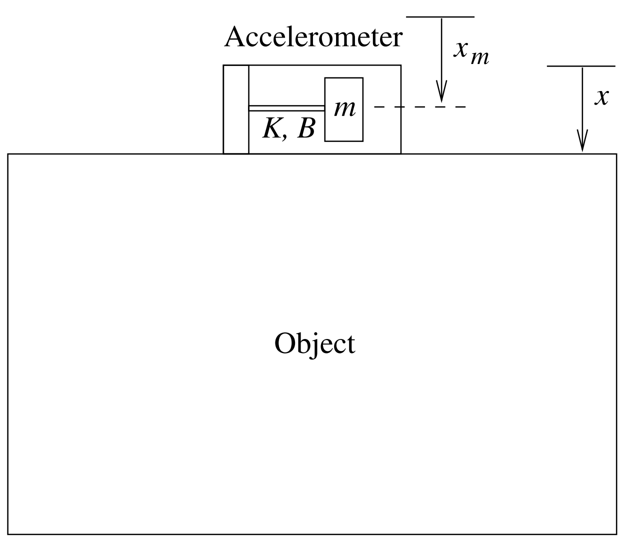
- Radial configurations



We will consider applications for both types.

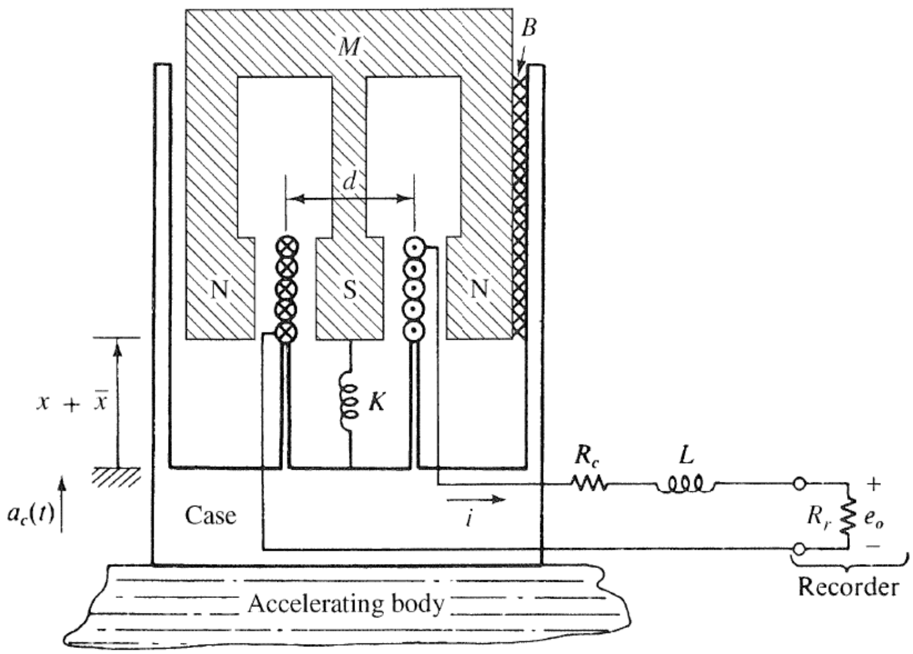
Sensing Acceleration with Strain Gauges

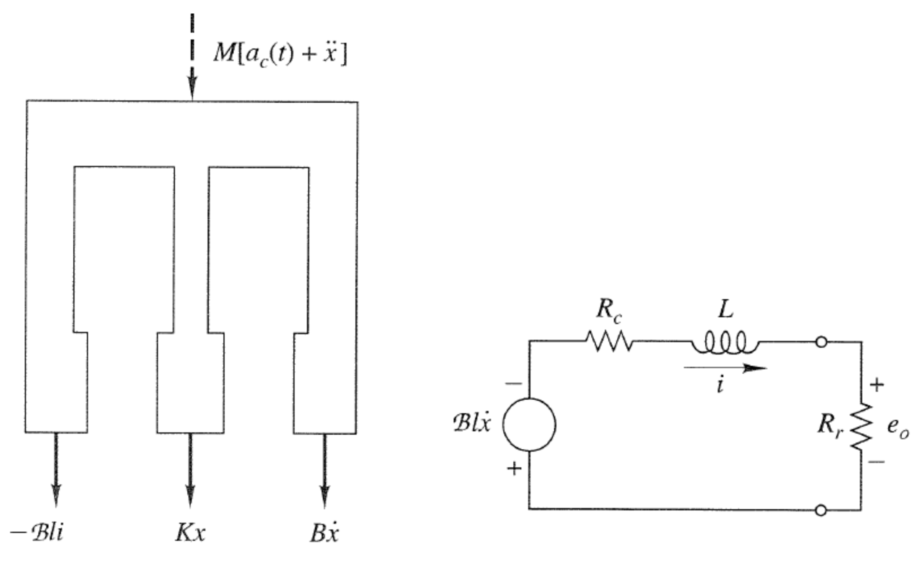




$$
\begin{aligned}
x_r &= x - x_m \\
m\ddot{x}_m &= Kx_r + B\dot{x}_r \quad (B \text{ small}) \\
m\ddot{x} &= m\ddot{x}_r + Kx_r + B\dot{x}_r \\
y &= C_a x_r \text{ (output)} \;\rightarrow \\
Y(s) &= \frac{C_a m}{K} \frac{s^2 X}{1 + \beta s + \gamma s^2} \cong \frac{C_a m}{K} s^2 X \\
y(t) &\cong \frac{C_a m}{K} \cdot \ddot{x} \;\text{ below } \omega_n = \sqrt{K/m}
\end{aligned}
$$

Sensing Acceleration with a Mass-Spring-Damper Device



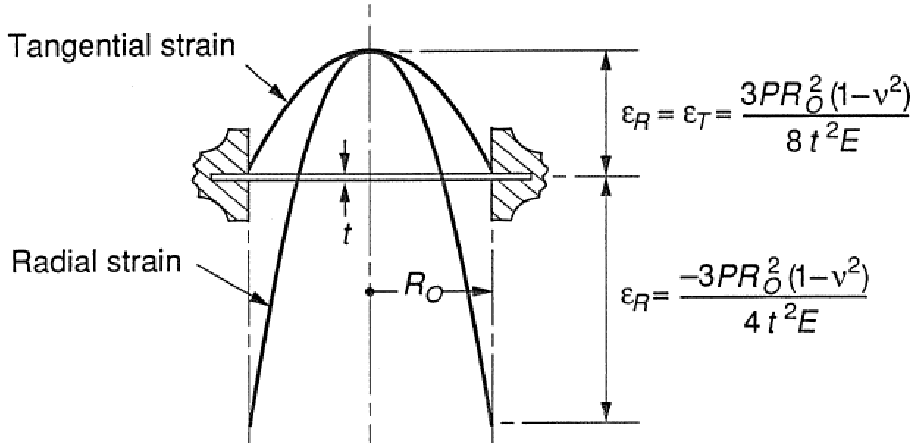


(a) (b)

This implementation will provide a similar second-order lightly damped response; modelling should using the same approach as in Module 2

Sensing Pressure with Strain Gauges

To measure the pressure in a tank you install a thin circular diaphram in the surface of the vessel with a radial acceleroometer mounted on it



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Many designs are available to achieve good **range** and **linearity** – the stiffness of the diaphram determines the range of pressures that can be sensed

Sensing for Industrial Controls – Summary

- Consider every sensor to be as important, potentially, as the actuators and plant.
- A sensor can limit a control system's performance with respect to dynamic range, frequency response (speed of response) and accuracy.
- Modelling is the primary method for assessing a sensor's impact on performance:
  - Modelling based on physics (e.g., accelerometer)
  - Modelling based on least-squares model identification
- Generally, trade-offs must be considered in chosing among the many sensing technologies that can be used: initial cost vs performance, life-cycle cost vs performance, reliability vs performance, . . . , initial cost vs life-cycle cost, . . .