Sampling Rate, $f_s$, Less than $2f_{max}$

(See Figure 12.22)

Sampling Rate, $f_s$, Equals $2f_{max}$

(See Figure 12.23)
Sampling Rate, $f_s$, Greater than 2 $f_{\text{max}}$

(See Figure 12.24)

How Many Bits Does One Need for the ADC?
- If transducer is nonlinear, then ADC precision must be larger than the precision specified in the problem.
- \[ y = f(x) \]
- \[ \Delta_x = \frac{r_x}{n_x} \]
- \[ \Delta_y = \min\{f(x + \Delta_x) - f(x)\} \text{ for all } x \text{ in } r_x \]
- \[ n_y = \frac{r_y}{\Delta_y} \]
- Example: $0 \leq x \leq 1$ with desired resolution $\Delta_x = 0.01$.

Fixed Sampling Rate

(See Figures 12.25, 12.26, and 12.27)

Specifications for the Analog Signal Processing

(See Figures 12.28, 12.29, and 12.30)
Impedance Loading

(See Figure 12.31)

How Fast Must the ADC Be?

- *ADC conversion time* must be smaller than quotient of sampling interval by number of multiplexor signals.
- If $f_s$ is sampling frequency, $m$ is number of multiplexor signals, $t_{max}$ is settling time of the multiplexer, and $t_c$ is ADC conversion time, then without S/H:
  \[ m \cdot (t_{max} + t_c) < \frac{1}{f_s} \]
- With S/H, must include acquisition time, $t_{aq}$, and aperture time, $t_{ap}$:
  \[ m \cdot (t_{max} + t_{aq} + t_{ap} + t_c) < \frac{1}{f_s} \]

Impedance Loading Problem and Solution

(See Figures 12.32 and 12.33)

Specifications for the S/H

- A S/H is required if the analog input changes more than one resolution during the conversion time.
- A S/H is required if:
  \[ \frac{dz}{dt} \cdot t_c > 0.5\Delta_z \]
  where $\frac{dz}{dt}$ is maximum slope of ADC input voltage, $\Delta_z$ is the ADC resolution, and $t_c$ is the ADC conversion time.
Synchronized Sampling (See Figure 12.34)

Analysis of Noise
- Any system will fail if signal is overwhelmed by noise.
- **Fundamental noise** (i.e., cannot be removed):
  1. Thermal noise (or white noise)
  2. Shot noise
  3. $1/f$ noise
  4. Transducer limitations
- **Added noise** includes many disturbing external factors:
  1. Magnetic induction
  2. Displacement currents, or capacitive coupling
  3. Impedance loading
  4. Common mode rejection ratio (CMRR)
  5. Frequency response
  6. Motion artifact

Thermal Noise (See Figures 12.35 and 12.36, and Table 12.8)

Root Mean Square (RMS) (See Figure 12.37 and Table 12.9)
Thermal Noise: Example Analysis

(See Figure 12.38 and Table 12.10)

Shot Noise
- Arises from statistical uncertainty when counting events.
- For example, thermal cameras count individual photons.

\[ n = \frac{dn}{dt} \Delta t \]

where \( \frac{dn}{dt} \) is the count rate, and \( \Delta t \) is the count time.
- The shot noise is:

\[ \text{Shot noise} = \sqrt{\frac{dn}{dt} \Delta t} \]
- The S/N ratio is:

\[ S/N = \frac{n}{\sqrt{n}} = \sqrt{dn/dt \Delta t} \]
- Tradeoff between accuracy and measurement time.

1/f or Pink Noise
- Present in devices with connections between conductors, and results from fluctuating conductivity.
- Important for low-bandwidth applications.
- Wire-wound resistors do not have 1/f noise, but semiconductors do.
- 1/f noise for a carbon resistor:

\[ V_c = (10^{-6})\sqrt{1/RF} \sqrt{\Delta \gamma} \]

(See Table 12.11)

Transducer Limitations
- Certain transducers have intrinsic limitations due to their design or construction.
- For example, wire-wound potentiometer as a position transducer is limited by the number of wire turns.
Magnetic Field Induction

- Magnetic fields can induce a voltage.
- One of two sources of 60 Hz noise.
- Changing magnetic field must pass through a wire loop.
- Noise is proportional to strength of magnetic field, $B$, area of the loop, $S$, and geometric factor, $K$.

(See Figure 12.39)

Displacement Currents or Capacitive Coupling

(See Figure 12.40)

Impedance Loading

(See Figure 12.41)

Common Mode Rejection Ratio (CMRR)

(See Figure 12.42)
**Frequency Response and Motion Artifact**

- All instrumentation systems are band-limited.
- As frequency increases, gain decreases.
- Gain error usually affects the instrument objective.
- Motion can introduce errors in many ways.
- Moving cables can induce currents, change connector impedance, or disconnect.
- Acceleration of the transducer often affects its response.

**Temperature Measurement System**

- Range of $T$ is 0 to 50°C with resolution of 0.25°C, and a frequency range of 0 to 0.1Hz.
- Transducer has slope of 10°C/s and resistance:
  \[ R = 100 + 0.4T \]
  (See Figure 12.43)

- Needed ADC precision is $50^\circ C/0.25^\circ C = 200$, so 8-bits.
- Use bridge circuit to convert RTD resistance into voltage.
- ADC range 0 to 5V and $V_1 - V_2$ is 0 to 0.0191V, so amp needs gain of 261.
- If ADC conversion time is $25\mu s$, no S/H needed because:
  \[ 10^\circ C/s \cdot 25\mu s = 0.00025^\circ C << 0.25^\circ C \]
- Noise must be less than the resolution ($75\mu V$).
  \[ \text{Amplifier noise} \leq \frac{\text{resolution}}{2} = 37\mu V \]

- One-pole low-pass analog filter needed to pass signal from 0 to 0.1Hz, reject noise $>0.1$Hz, and prevent aliasing.
  (See Figure 12.44)
- To prevent aliasing, $Z_2$ must be less than ADC resolution for all frequencies larger than or equal to $0.5f_s$.
  (See Figure 12.45)
- Effective output impedance is 100Ω. Input impedance of amp must high enough not to affect ADC ($>51.2$ kΩ).
Amplifier and Low-Pass Filter
(See Figure 12.46 and Table 12.12)

Amplifier and Filter
(See Figures 12.48 and 12.49)

Force Measurement System
(See Figure 12.47 and Table 12.13)

Thermocouple Interface
(See Figure 12.50)
Thermocouple Interface
(See Table 12.14)

Heart Sound Measuring System
(See Figure 12.52)

Heart Sounds
(See Figure 12.51)

Position Measurement System
(See Figure 12.53 and 12.54)