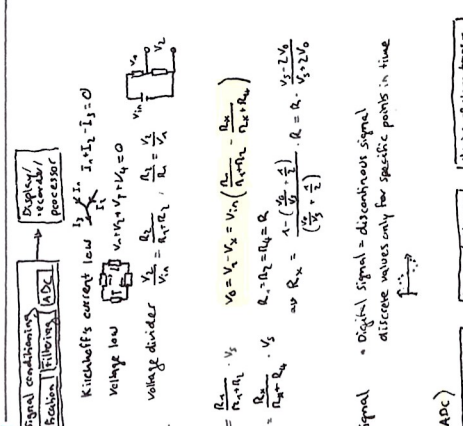
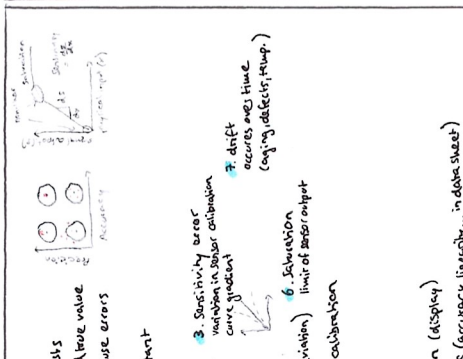


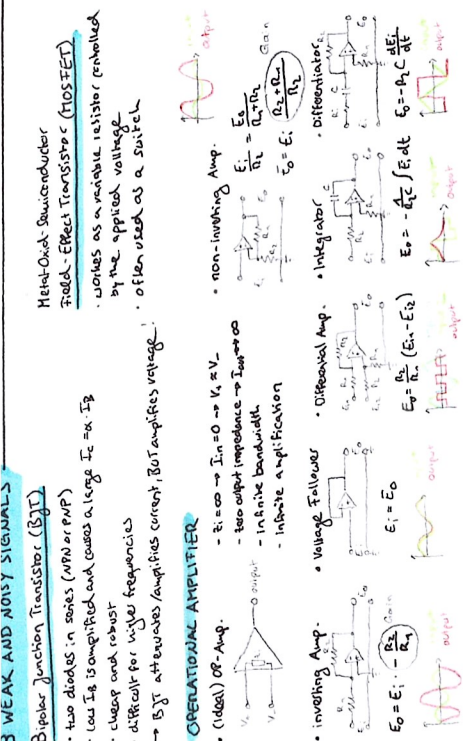
1 MEASUREMENT SYSTEMS



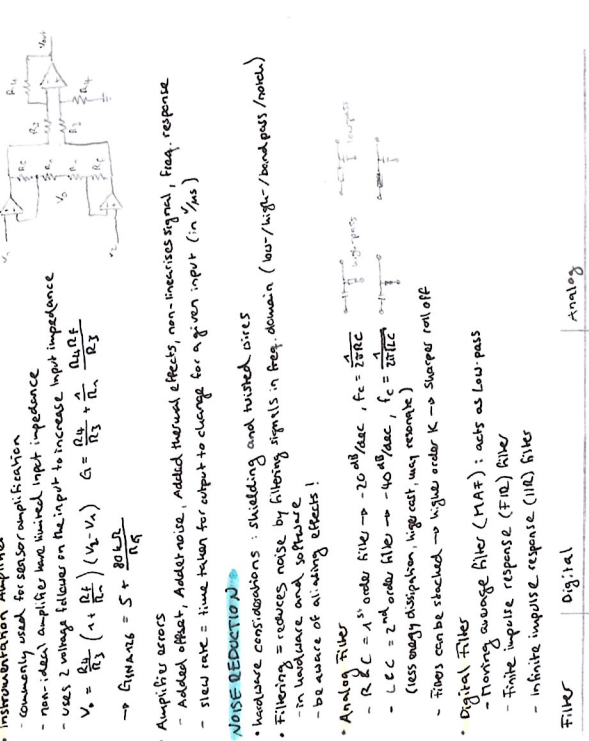
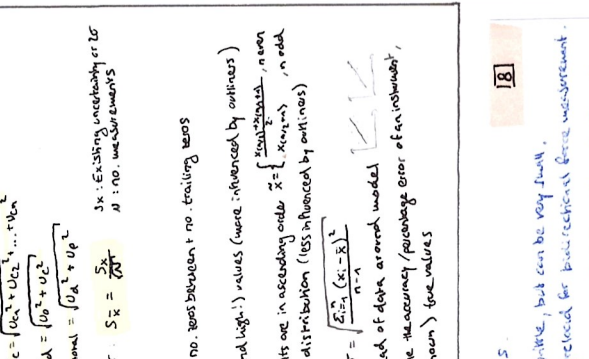
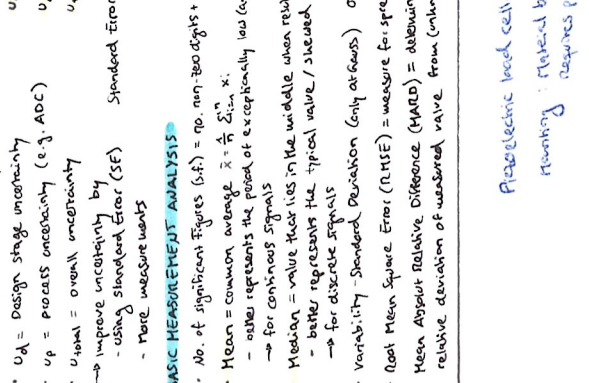
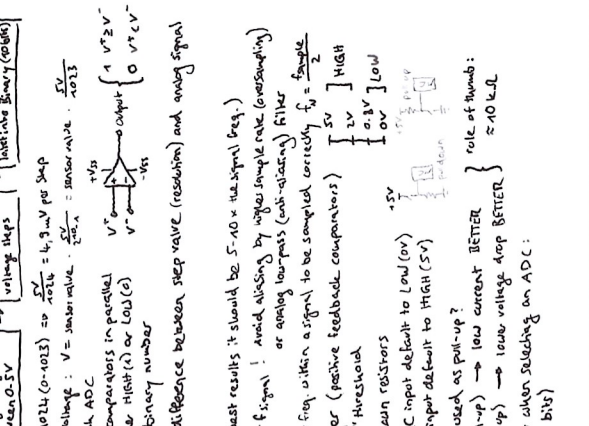
2 MEASUREMENT CHARACTERISTICS AND ANALYSIS



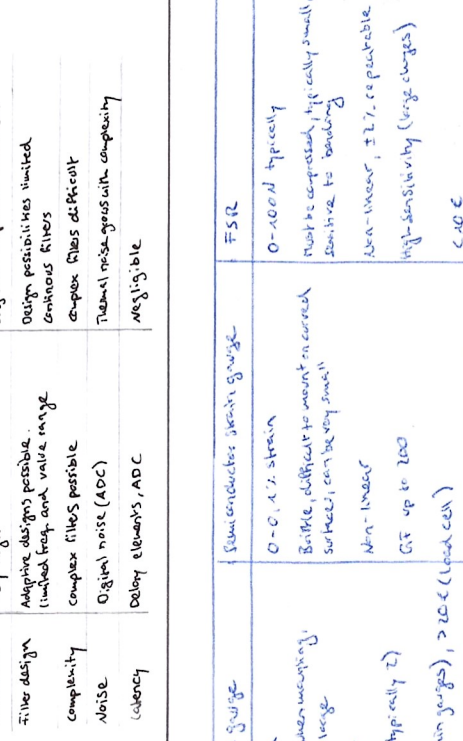
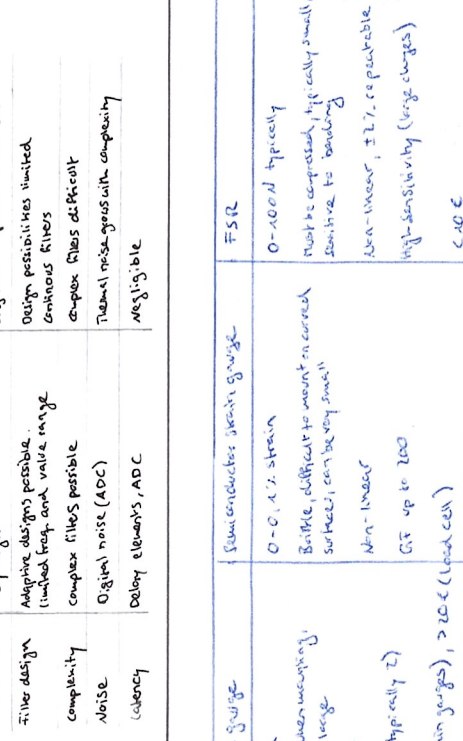
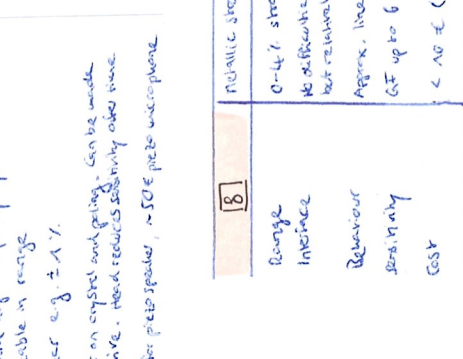
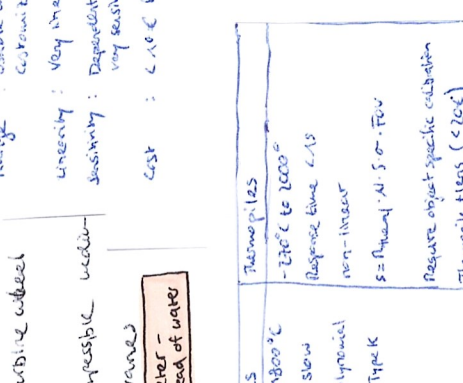
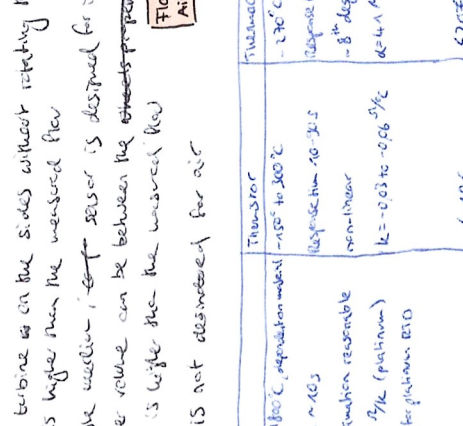
3 WEAK AND NOISY SIGNALS



4



5



4 TEMPERATURE

RTO - RESISTANCE TEMPERATURE DETECTOR (resistance)

- $R(T) = R_0 [1 + \alpha (T - T_0)]$ (1st order linear approx.)
- temperature coefficient α dependent on material
- reference resistor, $R_0 = 150 \Omega$ at $T_{ref} = T_0 = 0^\circ$, $R_{20} = 150 \Omega$
- balanced bridge $V_o = 0V$ if $R_1 = 33.36 \Omega \rightarrow R(T) = \frac{R_0}{R(T)} \rightarrow R(T) = 33.36 \Omega$
- $R(T) = R_0 [1 + \alpha (T - T_0)] \Rightarrow T = \frac{R(T)}{\alpha} - T_0 = 116.7^\circ C$
- considerations: wire wound RTO, coated element RTO, thin film RTO
- tolerance: highest accuracy $\pm 0.1^\circ C$
- elimination of lead wire effect through multi-wire RTO

THERMISTOR (resistance)

- $R(T) = R_0 e^{\frac{1}{T} - \frac{1}{T_0}}$ $\rightarrow \frac{1}{T} = \frac{1}{R_0} \ln \left(\frac{R(T)}{R_0} \right) + \frac{1}{T_0}$
- with universal bridge ($R_1 = R_2 = R_3 = R_4 = R_0$): (in small temp. range can assume)
- $\frac{1}{T} = \frac{1}{T_0} + \beta \cdot \ln \left(\frac{R(T)}{R_0} \right)$ (linear $R(T) = k \cdot \Delta T$)
- NTC: Negative temperature coefficient β
- relative resistance of transistor to temperature: Steinhart-Hart Eqn. $\frac{1}{T} = A + \frac{B}{T} + C \ln(R)^3$
- inrush current limiters (NTC limits initial power until it warms up)

THERMOCOUPLES (Seebeck effect)

- Voltage creates a Temp. difference (Seebeck effect) vs. temp diff. creates a voltage (Seebeck)
- Setup: Measurement junction, reference junction at known temperature (compensating voltage is added to thermocouple voltage $\rightarrow$ CJC cold junction compensation), voltage equation
- $V_o = T_{ref} + V_{ref-TC} = V_o - TC$
- Example: $V_{max} = 0.66 mV$, $T_{ref} = 20^\circ C$ (measured with RTO or Transistor)
- 1) NIST table: $T_{ref} = 20^\circ C \rightarrow V_{ref} = 0.738 mV$
- 2) $V_C = V_{max} + V_{ref} = 0.66 mV + 0.738 mV = 1.406 mV$
- 3) NIST table: $V_C = 1.406 mV \rightarrow T_C = 36.33^\circ C$ (linear interpolation)

THERMOPILES (Seebeck effect + IR radiation)

- multiple thermocouple junctions in series $\rightarrow$ increased sensitivity, reduced nonlinearity
- $V_{TP} = S \cdot \epsilon_{obj} \left(\frac{1}{T_{obj}^4} - \frac{1}{T_{ref}^4} \right)$ ϵ_{obj} : Emissivity of object, S : instrument factor
- lower temp. detected with increasing distance from object $I \sim \frac{1}{r^2}$
- higher temp. detected with higher viewing angle
- very fast contactless measurement

IMPORTANCE OF..

- Response time = time for 63.2% change in temperature
- Sensor size: the larger the sensor the slower response time (more material to heat)
- Sensor connection: largest amount of least through conduction $Q = \frac{k \cdot A \cdot \Delta T}{L}$



	Indirect velocity measurement	Applied SWA
Range	Dependent on measurement sampling rate and displacement measurement range	Actual, dependent on wave properties in medium
Measurement type	Discrete measurement	Depend on wave used
Interface	Indoor	Approx. direct, dependent on wave, CW or PLD, and angle
Behaviour	Dependent on sample material	Dependent on freq. measurement method
Resolution	Dependent on displacement and thing measurement	Dependent on frequency measurement
Sensitivity	Deriving from displacement sensor	$> 100 \times$
Accuracy		
Cost		

5 DISTANCE - VISIBLE (0.5um - 5um)

- Continuous Measurement $\Rightarrow$ Resolution depends only on digitization (ADC)
- Discrete Measurement $\Rightarrow$ Resolution depends on discrete steps in sensor value
- POTENTIOMETER (continuous)
- Resistance of wire depends on its length $R = \rho \frac{L}{A} \rightarrow L = \frac{R \cdot A}{\rho}$
- linear displacement $V_o = V_s \cdot \frac{R_x}{R_x + R_t}$ • Angular displacement
- Limitations due to manufacturing
- Backlash: small change of slider position will not change the resistance $\rightarrow$ limits resolution
- Range: length is limited
- Solution: Max. and Min. resistance at the ends (el angle $\rightarrow$ med. angle)
- Friction: wiper contact adds friction in system
- Potentiometer errors
- Impedance matching error (c): max. variation from linear behaviour
- Residual resistance (R): resistance when at the limits of travel

TIME OF FLIGHT (continuous)

- 1. Direct Measurement (pulse echo): Distance = $\frac{V_{wave} \cdot t}{2}$
- 2. Pulse angle method (CW): Distance = $\frac{V_{wave} \cdot \phi}{4 \cdot \pi \cdot f}$
- Limitations
- Wave attenuation: object is too far away
- No wave reflection: object is too small, angle $\angle \phi$, Fine object is not facing sensor
- Wave absorption: object is too soft

TRIANGULATION (continuous)

- Resolution depends on light detector, ADC and lens design
- Influence of environment: Filters, black markers, direct sunlight
- Incremental encoders with optical Encoder or Hall effect Encoder
- Incremental encodes $\Delta \theta = \frac{360^\circ}{N}$ N: no. of pulses (PPR)
- cores number of HLT states for relative position
- Indoning: separate phase (t) with a signal point used to identify absolute (zero) position

ENCODER

- 3. Absolute encoding
- Each position is assigned a unique binary pattern (Binary code / Grey code)
- Require sensor per binary phase needed $\Delta \theta = \frac{360^\circ}{4 \cdot N}$ N: no. of pulses (PPR)
- 4. Quadrature Encoding
- two phases 90° apart
- uses both rising and falling edges of signal
- can determine direction



Information	incremental	absolute	direction
# phase	2	4	2
Direction	no	yes	yes
Position	relative	yes	relative

	Indirect magnetic field relay sensors
Range	Dependent on sensor length
Measurement type	Requires counting
Interface	Friction from construction of linear guidance
Behaviour	Linear
Resolution	Dependent on magnetic field strength and coil
Sensitivity	Dependent on ADC or freq. measurement
Accuracy	
Cost	$> 100 \times$

6 DISTANCE - MICRO (nm - 1mm)

- CAPACITIVE SENSORS
- $C = \frac{\epsilon A}{d}$ $\epsilon = \frac{\epsilon_0 \epsilon_r A}{d}$ A: area of plates, ϵ : dielectric constant, d: gap width between plates
- change of d: $C \propto \frac{1}{d}$
- change of A: $C \propto A$
- change of ϵ : $C_{total} = \epsilon_1 \epsilon_r \frac{A}{d} + \epsilon_2 \epsilon_r \frac{A}{d} = C_1 + C_2$, $C_{total} = C_1 + C_2 = \frac{\epsilon_1}{d} (L \cdot x) + \frac{\epsilon_2}{d} (L \cdot (L-x))$, $\epsilon_1 = 8.8542 \cdot 10^{-12} \frac{F}{m}$
- Measuring capacitance
- 1. Measuring time constant $\tau = R \cdot C \rightarrow V_c = V_s (1 - e^{-\frac{t}{\tau}})$ τ : time of 63.2% charge
- 2. capacitance bridge $\frac{1}{j\omega C_x} = \frac{1}{j\omega C_s} \cdot \frac{V_s}{V_c} = \frac{1}{j\omega C_s} \cdot \frac{V_s}{V_c} \cdot \frac{1}{V_c} = \frac{1}{j\omega C_s} \cdot \frac{V_s}{V_c} \cdot \frac{1}{V_c}$ $V_c = 0$: $C_x = \frac{Q \cdot C_s}{Q \cdot C_x}$
- INDUCTIVE SENSORS
- $F = \frac{\phi}{R}$ ϕ : magnetic force, R : magnetic flux, R : reluctance
- $R = \frac{l}{\mu_0 \mu_r A}$ A: cross-sectional area, μ_r : rel. permeability, $\mu_0 = 4\pi \cdot 10^{-7} \frac{Vs}{Am}$, l : length of the path
- self induction of a coil $L = \frac{N^2 \cdot \phi}{I} = \frac{N^2}{R}$ L: inductance, N: no. of turns
- Single-coil setup $V_{sec coil} = N \cdot \frac{d\phi}{dt}$
- Two-coil setup $V_{sec coil} = \frac{d\phi}{dt} \cdot N$
- Linear-Variable-Differential Transformer
- Mutual induction: the two sides of the sec. coil winding are in opposite directions
- Difference in voltage and phase angle is proportional to the position of the core



LASER INTERFEROMETRY

- wave 1 travels a known reference distance
- wave 2 travels a unknown distance to target object
- From interference pattern the relative phase difference ϕ can be calculated
- with ϕ and wave length $\rightarrow$ calculate the difference in displacement (optical path difference OPD)
- $\phi = \frac{2\pi}{\lambda} \cdot OPD = \frac{2\pi}{\lambda} \cdot 2 \cdot x$ $x = \frac{\lambda}{4} \cdot \frac{\phi}{2\pi}$ N: counts of rings without initial point

CHOOSING SENSOR

- Identify the value to be measured $\rightarrow$ physiological background
- Identify what this value is physically
A) what causes the pk value to occur?
B) what does influence / change?
- Identify how are we allowed to measure it
A) destructive or non-destructive?
B) invasive or non-invasive?
 $\rightarrow$ non-destructive, invasive = more comfortable to the patient, cheaper, faster to get regulatory approval
- Identify which of the signals have the largest SNR
 $SNR = \frac{Signal}{Noise} = \frac{Signal}{\sqrt{A_{noise}}} \approx \frac{A(Signal)}{A(Noise)}$ $\frac{Signal}{Noise}$ $\frac{Signal}{Noise}$
only for sinusoidal signals
- Identify specific measurement characteristics needed
Cost, accuracy, low noise, repeatability, resolution, high freq. measurement, speed $\rightarrow$ 5:1 signal
- Evaluate potential sensors
 $\rightarrow$ information from: Data sheet, manufacture, simulation
 $\rightarrow$ Eval. Matrix, VDI guidelines
- Identify best sensor compatible for system setup and any other additional equipment needed
A) can system interpret Analog signal? (need an ADC)
B) can system sample fast enough? (need faster ADC)
C) does signal need amplification / reduction?
D) V.S? (don't be the same or lower)

7 VELOCITY

INDIRECT VELOCITY MEASUREMENT

- velocity is distance over time $v = \frac{dx}{dt} = x$
- discrete measurement
- average velocity over a short Δx or Δt
- Differentiation increase uncertainty and amplifies noise
- velocity from acceleration $\rightarrow$ uncertainty $v_x = v_y$ if increased over time

DOPPLER SHIFT

- A source sending wave (freq. f_s) and a recipient receiving this wave are moving relative to each other $\rightarrow$ frequency shift Δf or v_{rel}
 $f_R = f_S \left(\frac{c + v_{rel}}{c + v_s} \right)$
- Velocity of source/receiver determined from measuring f_R
- Sender & Receiver at one point, moving object
 $f_R = f_S \left(\frac{c + v_{object}}{c + v_{wave}} \right) \left(\frac{c + v_{wave}}{c + v_{receiver}} \right)$

- continuous-wave (CW) ultrasound
 - cannot determine the location of the measured velocity
 - continuous velocity measurement
 - Pulsed wave (PW) ultrasound
 - the time for the pulse to return is proportional to depth $\rightarrow$ can determine location
 - discrete velocity measurement
- Determining the frequency from time domain signal by Discrete time FT (Fourier Transformation) $f_{max} = \frac{1}{\Delta t}$ $f_{min} = \frac{1}{\Delta t}$ (sample window)
- Frequency center $f = \frac{\text{measuring}}{\text{window}}$ (signal comes too measuring window window)
- Limitations: Influence of angle
 - only velocity component inline creates Doppler shift $v_{rel} = v_{object} \cdot \cos(\theta)$
 - no perpendicular movement

INDUCED MAGNETIC FIELD VELOCITY SENSORS

- If the magnet is pulled by a coil (magnet), change in flux is directly proportional to v_{object}
 $\frac{d\Phi}{dt} \propto v_{object} \propto V_{coil}$, $V_{coil} = N \cdot \frac{d\Phi}{dt}$ N : no. of turns

1) LVT - Linear Velocity Transducer

- Requires calibration to determine operating characteristics
- $V_o = 2 \cdot B \cdot l \cdot V_{coil}$

2) Tachometer (OC) - Rotary velocity transducer

- Equivalent to a low friction DC motor used in reverse (generator)
- Cal rotaries in magnetic field
- Requires commutators (added friction)
- Output $v_{output} = K \cdot \omega$ ω : rotational velocity

3) Tachometer (AC) - Rotary velocity transducer

- Magnet rotates in between coil
- AC voltage generated
- only measures speed in one direction

SELECTING INA

- Example 1:
- expected voltage signal: $35mV \rightarrow 10mV = 55mV$
 - INA operating region 0.8-4.1V $V_{ref} = 1.5V$ $V_{FS} = 1.5V$
 - 4.2V $\rightarrow 1.5V \rightarrow 2.7V$
 - Gain $G = \frac{200mV}{5mV} = 40$
 - $G = 5$, $\frac{200mV}{10mV} \rightarrow R_G = \frac{200mV}{10mV} = 20$ $\rightarrow R_G = 4.4$
- Example 2:
- max signal voltage $\pm 1.5mV$
 - $V_S = 2.5V$ $V_{ref} = 2.5V$
 - INA operating region 0.8-4.1V
 - Arduino 0-5V $\rightarrow 2.5V = 2.5V$
 - $\frac{200mV}{10mV} = 20$ $\rightarrow R_G = 4.4$
- Example 3:
- Common-mode voltage (V_{CM})
 - Voltage level common to both inputs (V_{ref} and V_S)
 - Reference voltage (V_{REF})
 - set V_{ref} to middle of operating region (bipolar signal) lower end of operating region (unipolar signal)
-

8 FORCE

$F = m \cdot g$

- Stress $\sigma = \frac{F}{A} = E \cdot \epsilon$
- Strain $\epsilon = \frac{\Delta L}{L} = \frac{\sigma}{E}$
- Strain results in change in resistance $R = \frac{\rho \cdot L}{A}$
 $\frac{\Delta R}{R} = \frac{\Delta L}{L} (1 + 2\nu) + \frac{\Delta \rho}{\rho}$ $\pi = \frac{\Delta R}{R} \cdot \frac{L}{\Delta L}$
- $\frac{\Delta R}{R} = E_{axial} (1 + 2\nu + \pi E) = E_{axial} \cdot GF$

STRAIN GAUGES

- Gauge factor (GF): $GF = \frac{\Delta R/R}{\epsilon}$ $\rightarrow$ proportional to sensitivity
- Metallic strain gauge: multiple wires in series increase ΔR , approx. linear, GF ≈ 1.2
- Semiconductor SG: $\rightarrow$ non-linear, GF $\approx 100-200$
- Strain gauges and Wheatstone bridge

- Null method (more accurate, slower)
 - if R_x changes adjust R_2 so that $V_B = 0 \rightarrow R_x = R_2 \cdot \frac{R_4}{R_3}$
- Deflection method (less accurate, faster)
 - $V_B \neq 0$, $I_1 = I_2 \rightarrow V_B = V_A \left(\frac{R_1 + R_2}{R_1 + R_2 + R_3 + R_4} \right)$
 - $R_x = R_3 = R_4 = R$, $R_1 = R_2 = R \rightarrow V_B = V_A \left(\frac{\Delta R}{4R} \right)$
 - $\frac{\Delta R}{R} \ll 1 \rightarrow \Delta V_B \approx V_A \cdot \frac{\Delta R}{4R} \Rightarrow \frac{\Delta V_B}{V_A} \approx \frac{GF}{4} \cdot \frac{\Delta R}{R}$
- Multiple gauges bridge increase sensitivity $\frac{\Delta V_B}{V_A} \approx \frac{GF}{4} \cdot (E_1 + E_2 + E_3) \approx \frac{GF}{4} \cdot E_{total}$
- Compensate Bending strain:
 - bending moment creates additional stress $\sigma_x = -\frac{M}{I} \cdot y$, $\frac{\Delta R}{R} = \frac{GF}{4} \cdot \frac{E_{axial}}{E} \cdot (k=2)$
- Compensate Temperature effect:
 - Temperature error on resistance: $\frac{\Delta R}{R} = GF \cdot E + \alpha \cdot \Delta T$
 - $\rightarrow \frac{\Delta V_B}{V_A} = GF \cdot \frac{E_{axial}}{E} \cdot (k=2)$
- Compensate Bending and Temperature

Strain gauge cosine

- Axial force (Tension + Compression)
 - individual & transverse strain $\rightarrow$ by T-Resistor SG
 - R_1, R_2 account for poisson ratio ν , determination $\frac{\Delta R}{R} = -\nu \cdot \frac{\Delta R}{R}$
 - Bending force (moment)
 - two double-grid Resistor SG
 - $E = \frac{\Delta V_B}{V_A}$
- Principle axis unknown
 - use a 0.45, 90- or 0.60, 120-Resistor
 - $\theta =$ Angle between x -axis and max. principle stress
 - $\sigma_{max} = \frac{E}{2} \left[\frac{\epsilon_1 + \epsilon_2}{1 + \nu} + \frac{1}{1 + \nu} \sqrt{(\epsilon_1 - \epsilon_2)^2 + (2\epsilon_3)^2} \right]$
 - $\sigma_{min} = \frac{E}{2} \left[\frac{\epsilon_1 + \epsilon_2}{1 + \nu} - \frac{1}{1 + \nu} \sqrt{(\epsilon_1 - \epsilon_2)^2 + (2\epsilon_3)^2} \right]$
 - $\epsilon_{max} = \frac{E}{2(1 + \nu)} \sqrt{(\epsilon_1 - \epsilon_2)^2 + (2\epsilon_3)^2}$ $\theta = \frac{1}{2} \tan^{-1} \left(\frac{2\epsilon_3}{\epsilon_1 - \epsilon_2} \right)$

FORCE SENSITIVE RESISTOR (FSR)

- Porous conductive polymer sponge
- When compressed pores conduct each other $\rightarrow$ resistance decreases (non-linear)
- no tensile force measurement $\rightarrow$ Preload necessary

PIEZOELECTRIC FORCE SENSORS

- change in force generates a current
- current travels through leakage resistance to create voltage
- Capacitor is charged with this voltage $\rightarrow$ output voltage
- change in force goes to zero (F=0) $\rightarrow$ capacitor discharges through resistor ($\tau = RC$)
- Sensitivity (voltage/force) dependent on frequency
- No tensile forces (Electrodes would tear apart)
- Preload necessary
- Piezo as accelerometer
- When accelerated, the mass applies a force upon the material $F = m \cdot a$
- measure F , constant $m \rightarrow$ calculate a

9 TORQUE

STRAIN GAUGE TORQUE SENSORS

- $\tau = \frac{T \cdot \rho}{J}$ T : Torque (Nm) ρ : Polar moment of inertia (m^4)
- max. shear stress occurs at max. distance from center ($\rho = r_{max}$)
- max. and min. strain along a 45° axis = Axis of principle stress
- single element experiences both axial and radial stress
- use two SG on equal and opposite principle axis (90° apart) to compensate axial bending strain and temperature
- to increase sensitivity use all 4 SG in bridge $\rightarrow$ two strain gauges $\pm 45^\circ$ relative
- Strain gauges measures torsional strain γ $\frac{\gamma}{\epsilon} = GF \cdot \tau$
- $\tau = G \cdot \gamma$ $G = \frac{E}{2(1 + \nu)}$ G : Shear modulus beam (Pa)

DEFLECTION TORQUE SENSORS

- Measure deflection (twisting, bending) of a known stiffness (spring/shaft)
- Determine torque T from angle of twist θ Spring: $T = k \cdot \theta$ Shaft: $T = \frac{G \cdot J}{L} \cdot \theta$
- 1) Sensitive "encoders"
 - two toothed ferromagnetic wheels aligned
 - when rotating, inductive sensor creates sine wave signals
 - phase shift ϕ related to relative angular deflection θ
 - no direct connection to shaft required
 - inductive probe in by power
 - only deflection less than 2° agreeably, price can be lowered
 - unwanted and a source of noise
 - measured wheel can be by
- 2) Measure reluctance of a shaft with an air gap (deflects proportional to strain)
 - operates similar to an LVDT
 - ferromagnetic tube is connected to applied torque
 - two slits orientated along the principle stress axis (45°)
 - when twisted, one slit gets wider and one narrower
 - reluctance changes on each coil respectively
- 3) Measure magnetization of magnetostrictive material
 - Magnetostriction similar to piezo effect
 - in certain ferromagnetic materials strain causes magnetic dipoles to align
 - Magnetic field $\leftrightarrow$ Stress (strain)
 - Sensitivity ($\frac{\Delta B}{B}$) determined by change in magnetic field strength B per stress
 - change in magnetization can be sensed by a stationary magnetic probe (e.g. Hall sensor)
 - new technique used
 - fast torque detection
 - low torque resolution
 - fast with in large bandwidths
 - no strain gauge is not required
 - requires absolute or known resistance (V_{ref})
 - using piezoelectric temp from $-100^\circ C$ to $100^\circ C$
 - is then used to compensate for strain

- MOTOR CURRENT TORQUE SENSOR
- In electric motors, the torque depends on the current to run the motor
- estimate torque from sensing the feeding current
- The (magnetic) torque generated is higher than the load torque due to friction and sensor inertia
- estimated torque needs to be adjusted for more accurate results
- works for both DC and AC motors

SENSOR COMPUTATION

- Direction torque sensor
 - Measures torque on member that is kept stationary due to force
 - Easy setup
- In-line torque sensor / Rotary torque sensor
 - Designed to rotate with the system measuring dynamic torque
 - Connection to sensor difficult
 - Must transmit measurement signal while rotating (communication)
 - A. Sliprings and brushes B. Rotary transformer C. IR or radio FM telemetry

- Influence of inertia of torque sensor
- Adds to overall system rotational inertia $\rightarrow$ would be significant for that system inertia (ω)
- Influence of stiffness of torque sensor
- lowers system stiffness and thus potentially lowers resonant frequency
- sensor should be significantly stiffer than system stiffness
- low stiffness for precision, high stiffness for system performance
- Influence of strain
 - sensing element was to be "flexible" for sufficient sensitivity (strain/length)
 - $E = \frac{F}{A} \cdot L$ T so its rigidity $G \cdot J$ should be small
 - but low rigidity also decreases overall system stiffness
- $\Rightarrow$ Sensitivity vs. Bandwidth (Speed of response), natural frequency

