Week 3

Summary of Rotary Sensors and Applications

Incremental encoder

- Generates a train of electrical pulses, whose frequency is proportional to angular speed.
- Motor speed and rate control found in machine tools, robots, mixing equipment and textile equipment. It's called incremental because the encoder sends out a stream of pulses that are not related to an absolute standard of rotary position. Hence the incremental encoder is good for measuring speed, don't try to use it for understanding absolute position.

Absolute encoders

- Rotary position sensing
- They're also found in machine tools and robots
- Also used in medical and welding equipment where precise control of position is mission critical for these applications.
- Always knows where it is during rotation and it can also keep track of total revolutions

Resolvers

- Extremely harsh temperature, shock and vibration environments that go beyond the capability of encoders to maintain their signal integrity
- Military, aerospace and construction equipment
- Similar to DC generator
- It's coils output two analog signals arrange at a phase, by 90 degrees. It then generates a voltage, corresponding to the interaction of the resulting magnetic fields
- Unlike temperature sensors, rotary sensors are fully designed around the demands of their application
- The four general categories of rotary sensors scale up in specs and cost for commercial, servo, industrial and heavy duty applications.
    - Commercial grade sensors are lowest cost, used in benign environments found in office machines and medical devices
    - Servo devices resembled from the outside, the small stepper and servo motors who speeds their measure. Because they are usually mounted right next to these high speed motors they need a high temperature rating to handle the high amount of heat given off by the motor windings
    - Industrial grade sensors are usually melted to large motors used in typical industrial blowers, pumps, compressors, and machine tools
    - Heavy duty encoders are used in high vibration environments or to prevent liquid penetration in food and beverage, for marine applications. They come with IP67 or IP68, ingress protection ratings, and may also be ATEX certified, for explosion proof needs

Optical Encoders: How They Work

A beam of light emitted from an LED shines through a rotating glass or etched metal disc divided into transparent and opaque sectors.
The light beam gets detected by a photo sensor when the disk rotates and it displays a transparent sector.
Incremental encoder, the resulting signal is transformed into a square wave, and it's sent to a counter circuit. The count is subject to loss during the power interruption. So as an optional feature, incremental encoders can provide a once per revolution pulse or index mark, as it's called, at the same place in each revolution.

Encoders are defined by their resolution as opposed to their accuracy
Resolution for encoders is defined as the number of pulse outputs per resolution of the disk, PPR for short. The more pulse outputs, the higher the resolution it has.

Limits to resolution

- Width of the LED beam
- The diameter of the disk
- The ability to lay down fine pitch, transparent, or opaque tracks, where the user needs to know only the speed of rotation but not the direction.

Incremental encoders use a single channel output where sensing the direction of movement is not important.

A device with only a single channel is called a tachometer.

Quadrature encoders have dual channels phased 90 degrees apart. These two output signals determine the direction of rotation by protecting the leading or lagging signal in their phase relationship. Improved resolution by sensing the up and down edges of pulse streams in the channels. Achieve 4x resolution.

Incremental encoder

- Spindle, disk, light source, PCB , seal and cover
- The PCB contains a sensor array that creates the signals for the channels

Absolute encoder

- Generates digital words
  - Speed, direction and actual rotational position all at once
- The pulse stream requires multiple light detectors to read every track
- The resolution of an absolute encoder is a function of the number of bits in its digital word
- Output can be in straight binary or in Gray code

For example, a 24 bit encoder has a resolution of 16 million counts per revolution.

Single Turn Absolute Encoder

- The output signal is repeated for every revolution of the encoder's shaft
- There is no ability to count the total number of revolutions, a capability provided by the index marker of an incremental encoder.
- The encoder's shaft turns the primary gear, which then rotates the etched position gears. These gears have tracks position directly beneath the optical sensors on the PCB.

Multi Turn Absolute Encoder counts the total number of revolutions as well as maintains knowledge of absolute rotational position.

Measuring Encoder Speed

Encoders are almost always used to measure speed and position of a rotating device.

Single cycle method

- Measure from the rising edge to the rising edge on a single channel that gives us the period of one cycle of the encoder.
- The most accurate way to do it. T
- The reason is that the duty cycle of the waveform often varies as the speed of the device increases.
- This results in a lower resolution

Half cycle method

- Signal change occurring every two edges (a rising and falling edge) of the encoder's output
- This results in a higher resolution

Quarter cycle method

- Fastest update you can have four measurements per cycle of any given channel. However, that's even less accurate than the single cycle method
- This results in the highest resolution

The duty cycle is a ratio of how long the signal is high over the entire period of the signal and that single cycle method the duty cycle can vary quite a bit. But since we are always measuring from the rising edge to the rising edge variations of the duty cycle actually have no effect on the measurement.

Quadrature is an encoder spec that refers to the spacing between the rising edge on one channel as compared to the rising edge on the next channel. Normally, you'd want this to be one quarter of a cycle or 90 degrees. However in practice this number also there is due to a number of factors and therefore making a measurement over the quarter cycle is going to result in additional error over the single cycle. It does have the advantage however of getting four measurements in the same time that the single cycle method gets you one measurement.

All of these methods do not measure speed directly they measure period therefore, you have to use software to take the inverse of this number.

Encoder speed could be measured directly simply by counting edges in the pulse train

Optical Encoders: Applications

Motor Speed

- The most common one is to mount an encoder directly to a motor shaft at the back of the motor.
- RPM is directly measured by the encoder
- Allows for a closed loop feedback system

Spool and Cut

- Absolute encoder is mounted to a roller of diameter D of a fabric cutting machine
- R = number of revolutions measured by the encoder
- L = length of fabric cut = pie x D x R
- The resolution of the encoder directly effects the accuracy of the cut length

CNC Milling Machine

- Absolute encoder is mounted to the motor driving each lead screw
- R = # of revolutions
- L = lead (travel) per revolution
- D = distance travelled = LxR
- Resolution = L/PPR (pulse per revolution)

Issues with Encoders

- Dirt and liquid contamination may foul the disk, causing random pulse counting error
- LEDs may fade or burn out, leading to system failure
- Incremental encoders lose position knowledge if power is removed
- The biggest problems using encoders are mechanical
    - Sensors need to be precisely aligned to their axis of rotation
    - Shaft end float and total indicated runout (TIR) must be within the encoders specs (wabble of the encounter relative to its axis)

There's three major ways to configure an encoder

- C-Face encoder mounts it directly to the face of the motor and encoder wheel mounts to the motor shaft
- Motor shaft extends through round hole in the encoder. Attach encoder with clamp and prevent rotation with torque arm
- Encoder shaft attaches to drive shaft via flex coupling and encoder attached to machine body via a foot mount. Shaft alignment is an issue

On the electrical side, it's mostly about preventing signal noise from disrupting the encoder's digital signal.

Encoder Wire Guidelines

- Route machine power and signal lines separately
- Use shielded, twisted cable for signal lines
- Maintain continuity of wires and shields from encoders to the controller. This minimizes radiation and induced noise problems and ground loops
- Ground the encoder case and wire shields

Resolvers: How They Work

A resolver is a very specialized transformer that measures angular position with high accuracy

The outside of a resolver looks like an electric motor, but the inside windings are that of a transformer

A stator has three windings, a primary one and two two-phase ones.

- Primary winding is excited by external AC current. Electromagnetic induction induces current in the first winding of the rotor.
    - Windings are co-linear along the axis
    - The same current is induced in the first winding of the rotor, regardless of the rotor's angular position.
- Second winding, by electromagnetic induction, current is induced in the secondary windings of the stator, which are fixed at right angles to each other
    - The stator produces two alternating currents that are 90 degrees out of phase with each other, varying as the sine or cosine of the rotor angle.
    - They are also sinusoidal in time, varying as the AC line voltage frequency.

The resolver is an analog device
The relative magnitude of the voltages is the sine of the rotor angle theta divided by the cosine of the rotor angle theta. This product is tension theta and the angle theta is calculated by taking the arch tangent.

Resolver Details

- Better resolvers are brushless
- The input voltages to the static primary winding is usually less than 26 volts AC
- Industrial grade resolvers are designed around the 50 or 60 hertz AC
- Resolvers for marine or aviation use are designed around 400 hertz
- Military grade resolvers may go as high as 12,000 hertz.
- That resolver to digital converters run the signals on the stator secondary windings through an era amplifier
    - This has the advantage of cancelling out noise injected on both windings
- The # of revolutions must be counted by an external sensor
- Multiple speed resolver has 2n pair of secondary windings
    - Higher resolution and higher accuracy
    - Deliver n cycles of sine waves in one rotation

Issues with resolvers

- Multiple speed resolvers do not understand absolute position
- A single speed resolver must be mounted on the same shaft as the multiple speed resolver to measure the absolute position
- Most resolvers have solely analog output
- Have trouble outputting a zero signal -> imperfections in winding

Resolvers: Applications

Motor Speed in harsh environment

- Resolver mounted to the back face of the motor
- The resolver to digital electronics is mounted remotely

Military and aerospace

- Target acquisition and radar systems
- Outdoor, high temps
- High EMI/RFI environment (Electromagnetic Interference / Radio Frequency Interference) can throw off the electronic of encoders

Industrial Robots

- Large robots have high inertial forces, which lead to significant shock/vibration at the rotary joints

Resolver Mechanical Configurations

- A frameless resolver contains mounts directly to the motor shaft
- Motor shaft extends through round hole in the resolver. Attach resolver with tether
- Use a flange to mount resolver to motor frame. Shaft alignment is an issue

Accuracy = is the difference between your resolver signal reading and the actual angle of rotation

You need to know what the AC voltage and frequency of your electrical system supplying power to the resolver is.

The transformation ratio, or TR for short, is the ratio of output to input voltage at max magnetic coupling.

As per transformers, it is proportional to the ratio of the number of effective turns in the stator secondary winding, so that it turns in the rotor primary winding.

The transformation ratio tells you the nominal output voltage of the resolver.

Flow Sensors and Applications

A sensor is purely a transducer that outputs a tiny electrical signal
A meter contains the sensor, but it also takes the signal and converts it into a digital or analog signal

Variable

- The first flow meter
- Consists of glass float rising up inside a tapered tube
- Not very accurate

Differential Pressure

- The most popular in the market
- Measures the pressure upstream and downstream of an obstruction
- Highly accurate and reliable
- Works well with almost all gases and liquids

Vortex

- Measures the vibrational frequency of vortices downstream of an obstruction
- Flow rate is correlated to the frequency measured
- Works for low viscosity fluids, less accurate at high Re (Reynolds number)
- Susceptible to vibrations in the pipe

Ultrasonic

- Measure the Doppler frequency shift caused when an ultrasonic signal is reflected by suspended particles or gas bubbles in the flow stream
- Flow rate is correlated to frequency shift
- High reliability

- Requires at least 100 ppm > 100 micron size particle or bubbles
- Use only for liquids

Turbine

- Kinetic energy in the flow stream turns the blades on a rotor
- Flow rate is correlated to the angular velocity of the spinning rotator shaft
- Works well with clean, low viscosity fluids and moderate flow rates
- Good turndown
  - Can accurately measure a wide range of flow rates—from relatively low flows to higher flows—without losing precision
- Not accurate for low flow rates

Thermal mass

- Current flow in the sensors heats ~ 1% of the gas diverted to a small bypass tube
- Some heat is lost to the flowing fluid
- The amount of heat loss is proportional to the flow rate
- Works well with clean gases with well-known properties

Coriolis

- Flow is contained inside a U-shaped or triangular-shaped tube, where a vibratory element causes it to oscillate
- The tube twists in a direction perpendicular to both the direction of mechanical vibration and the direction of fluid flow
- An optical sensor correlates the angle of twist to the flow rate directly measuring mass flow, not volume flow
- Can measure fluid density
- More accurate with liquids than gases
- Susceptible to air bubbles-> fool sensory to thinking the mass flow rate is lower
- Expensive

Variable Area Flow Sensors

- Flow always enters the tube on the bottom so that the dynamic forces of the rushing flow and the natural buoyancy of the float act vertically up
- The downward force is gravity
- A higher volumetric flow rate through a given area increases flow speed and drag force so that the float will always be pushed upwards
- The fluid is also rushing around the edges of the float
- At a constant flow rate the float stops moving as the forces reach equilibrium
- Applications
  - For startup of complex process before control networks are installed

    - As a backup measure for power outages
    - Where accurate readings are not needed and funds are limited
    - Hospital room and dental offices have them for dispensing gases

Differential Pressure Flow Sensing

- An orifice plate in the guts of the instrument creates a sudden pressure drop in the flow.
- Pressure is measured upstream and downstream and then the flow rate is calculated from the Bernoulli equation
- Orifice plates are usually a discs with a bunch of holes
- The smaller the area for fluid, the higher the difference between the pressures
- Bernoulli
    - $P + 1/2pV^2 + pgh = constant$
    - P = pressure
    - p = density
    - V = Velocity
    - g = Gravitational acceleration
    - h = Height
    - $Q = V * A$
        - Q = flow rate
        - V = Velocity
        - A = Cross section of pipe
- Applications
    - High accuracy for flow rates at very high pressures and temps
    - When versatility of measurement is needed

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Vortex Flow Meters

- Vortex flowmeters operate via the von Karman effect
- An obstacle called the bluff body is placed in the flow field, and creates a series of downstream vortices and shed downstream
- The vortices change the pressure at a cyclical frequency as measured by a piezoelectric sensor
- These shed and create a cyclical pressure further downstream
- Higher frequency corresponds to higher flow
- Applications
    - High accuracy reading for the flow of stream in power plants
    - You need high turndown
    - Fast installation

Ultrasonic Flow Meters

- The transmitter sends an ultrasonic signal into a liquid flow stream filled with suspended particles or air bubbles
- The signal is reflected back to the receiver by the particles
- The frequency of the reflected signal is higher, due to the fact that the particles are moving in the flow stream
- The doppler effect
- Applications
    - High accuracy readings at the highest temp
    - Non-contact measurement – easy installation and no disturbance of the flow field
    - Temp installation
    - High price

Turbine Flow Meters

- A rotor with multiple fan blades installed in a pipe perpendicular to the flow direction
- The faster the liquid flows, the faster the speed of rotation of the blade to the flow rate of the liquid
- As the blade pass the edge of the pipe, a magnet sensor registers a pulse
- The magnetic sensors are located outside of the flow to avoid contamination
- A transmitter processes the pulse signals and calculates the flow rate
- Sense both forward and reverse flow
- K factor correlates flow rate with angular speed of rotation
- Applications
    - Accurate measurement of clean liquids and gases at an affordable price
    - Custody transfer of hydrocarbons and natural gas but at a higher price
    - Simple installation
    - Popular for measuring flow of clean water between water districts

Thermal Mass Flow Meters

- ~1% of the main flow is diverted by a bypass to a flow sensor tube
- The bypass usually takes the form of a metal screen with many holes
- The bypass along with laminar flow element causes the flow to go from turbulent to laminar -> needed for good measurement
- The sensor tube has upstream and downstream heating coils wrapped around its exterior
- Equal and constant currents flow through both coils
- The gas heats up as it flow through the sensor tube which makes T2 > T1

- The heater coils are also resistors, whose electrical resistance increased with higher temps
- Which means $R_{HT2} > R_{HT1}$
- Use a Wheatstone bridge to detect the difference in resistances
- The differential voltage in the circuit is proportional to the flow rate
- Calibrate the system to determine the proportionality constants
- Applications
    - High accuracy reading of clean low flow gases
    - Popular in the semiconductor industry for dispensing minute doses of gases
    - Also using for dosing Co2, N2, and O2

Coriolis flow meters

- All the flow is diverted from the main pipe into a flow tube
- Temp is measured by RTD
- The flow tube is vibrated by a magnetic coil where the frequency of electrical oscillations transfers to a frequency of mechanical vibrations
- The vibrating tube interacting with the dynamic force causes the tube to twist at the frequency of drive coil
- The optical pickup measures the twist angle which is proportional to the mass flow rate
- Applications
    - Non-contact direct measurement of mass flow, as opposed to volume flow
    - Very high mass flow rates found in high volume chemical, petrochemical, and municipal water plants
    - Production of volatile chemicals where explosion proof ratings are critical to the use of the flow meter

A two-channel encoder counts both the leading and trailing edges of the pulse signals from its two channels. You have an encoder with a single channel that has a resolution of 300 Pulses Per Revolution (PPR). Now, if you add a second channel to this encoder how much can the resolution of the encoder be improved by adding a second channel, without changing any other specifications? Increase it from 300 PPR to 1200 PPR

An absolute encoder is mounted to the motor driving the X-axis lead screw of a CNC milling machine. If the encoder has a spec of 1250 PPR, a lead of 1.5 mm, and the lead screw moves a distance of 250 mm, how many revolutions of the lead screw will the encoder count and what is the resolution of the X-axis? 166.7 revolutions of the lead screw and the resolution is .0012 mm

A multiple speed resolver has 64 sets of secondary windings. Relative to a single speed resolver of the same basic design, how much more accurate will it be? 32 times as accurate

Your resolver has a maximum tracking rate of 27 revolutions per second (rps) and gives rotational accuracy of 15.3 arc minutes. If you need a rotational accuracy of 0.2 degrees and your motor shaft rotates at 1140 rpm, can you use your resolver? Why or why not? No. The resolver accuracy of 15.3 arc minutes is worse than the required accuracy of 0.2 degrees, and the tracking rate of 27 rps is faster than the motor speed of 1140 rpm.

You want to measure the flow rate of air of density 1.225 kg/m3 in a differential pressure meter. The upstream pressure is 30 N / m2 and the downstream pressure is 27 N / m2. The meter has an area of 0.2 m2. What is the flow rate? 0.443 m3/sec

A vortex meter used to measure the flow rate of steam has an accuracy of +/- 1.5% of rate. If the true mass flow rate of the steam is 20 kg / sec, what is the maximum error in the reading? 0.3 kg/sec

An ultrasonic flow meter has more than enough flow capacity to measure the flow rate of any flow in a process area. However, the maintenance department notes a leaky pipe, and replaces it with a much larger than the previous one. The pipe material is extremely expensive because it must not rust when in contact with corrosive fluid inside. Now the flow meter does not fit on the outside of the pipe. You can no longer measure the flow rate. How do you solve this problem? You buy a larger clamp for the flow meter than can fit on the larger pipe.

The k-factor for a turbine meter for flow in a 3/4” (19.1 mm) diameter pipe is 689 pulses per liter. Your magnetic pickup assembly recorded 1000 pulses in a period of 1 second. What is the flow rate in the pipe? 87 L/min

Suppose the temperature differential between downstream and upstream flow meters at constant flow is represented by ΔT. If the flow in the pipe decreases, what happens to ΔT? ΔT decreases

What does zero-point stability mean in a coriolis meter? Zero-point stability measures the oscillation of the flow meter electronics around a zero reading. You add it to the accuracy spec to get the true accuracy of
a coriolis meter.