MECH 401
Mechanical Design Applications
Fundamentals Section – Master Notes

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MECH 401
Mechanical Design Applications

Course Information
- Meeting time:
  - T-Th 8:00 – 9:15
  - DH 1042
- Prerequisites:
  - MECH 311 or CIVI 300
- Texts:
  - Mechanical Engineering Design
    - by Shigley, Mischke, and Budynas
- Goals:
  - Provide design skills to support MECH 407/408 projects
  - Understand the application of engineering analysis to common machine elements
  - Enhance your ability to solve practical design problems using free body diagrams, Mohr’s Circle, beam analysis, etc.

- M. K. O’Malley, PhD
  - MEB 210
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    - Monday 11:00 AM – 12:00

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Syllabus
- General policies
- (20%) Homework
  - Late homework is not accepted
  - Neatness counts!
- (10%) In-class mini-tests (6 total)
- (20%) Project

Overview and introduction of design of machine elements
- Two primary phases of design
  - 1. Inventive phase – creative aspect
  - 2. Engineering phase – understanding of physical reality aspect
    - makes a design unique or clever (MECH 407/408)
    - makes a design work
- This course will focus on 2nd aspect, making our designs work

“Understanding of physical reality”
- Theoretical results
- Empirical results
- Theory helps us understand physical phenomena so that we can address design at a fundamental level
- Theory often falls short, however, in describing complex phenomena, so we must use empirical results

Systems of Units
- Appendix lists units (English, SI), conversion factors, and abbreviations
- Unit
  - A specified amount of a physical quantity by which through comparison another quantity of the same kind is measured
  - Examples?
    - Length, time, temperature
- 2 basic systems of units
  - U.S. customary foot-pound-second system (fps)
  - International System of Units (SI)
Primary dimensions

- Sufficient to conceive of and measure other dimensions
- Examples?

Secondary dimensions

- Measured in terms of primary dimensions
- Examples?

U.S. customary

- Foot-pound-second (fps)
- Inch-pound-second (ips)
  - FPS:
    - Force – pound-force
    - 1000 lbf = 1 kilopound = 1 kip
    - Derived unit of mass is lbf-s²/ft (slug)

SI (mLt)

- Mass, length, and time
  - m – kg
  - L – m
  - t – s
  - F is secondary (Newtons)
  - 1 N ~ 1 apple
    - F = ma
    - 1 N = 1 kg·m/s²

Methodology

- Solving machine component problems
  - Step 1
    - Define/understand
  - Step 2
    - Define/synthesize the structure
    - ID interactions
    - Draw diagrams
  - Step 3
    - Analyze/solve using:
      - Appropriate assumptions
      - Physical laws
      - Relationships
      - Rules
  - Step 4
    - Check – is the answer reasonable?

Homework format

- Start each problem on a new page
- One side of sheet only
- Use straight-edge, work neatly

Known:
- Problem statement
- Schematic
- Given data
- Material properties

Find:
- Concisely state what is to be determined

Solution:
- Assumptions
- Design decisions
- Equations (make number substitutions last)
- Comments (when appropriate)
Introduction to reliability engineering

- We cannot assume that all the quantities that we utilize in failure analysis are deterministic quantities
  - “We know their values absolutely!”
- In many cases, especially in manufacturing, this is NOT the case
  - A part dimension that is supposed to be 1” in diameter might vary between 0.95 and 1.05 inches due to variation in machining process (tool wear)
- Statistics and random variable methods enable designers to deal with variable quantities
  - Reliability Engineering

Definitions

- Random (stochastic) variable
  - A real-valued set of numbers that result from a random process or are descriptive of a random relationship
- For example, if I were to construct a list of everybody’s height in this class...
  - Then height, H, would be considered a random variable

Height example

- Let’s say there are 25 people in this class.
- Construct a histogram to represent the data
- If we divide the (# of people) axis by the total number of people sampled, then we have
  - Probability density function (pdf)
  - PDF gives the probability that a random variable will have a certain value
  - Same shape as the histogram

Characterizing random variables

- A random variable is not a scalar, but rather a vector
- In this deterministic case, we can say
  - \( x = 63.5 \) inches
- This is a scalar, since it has only a single value
- In the stochastic case, we know that the variable \( x \) can take on many values
  - \( x = 63.5, 68.7, 62.1, \ldots \)
- We define the discrete random variable \( x \) to be a vector of the samples \( x_1, x_2, \ldots, x_n \)
  - We refer to \( x \) as the variate
  - Note, in this sense, a vector can be considered a collection of numbers, not a quantity with direction and magnitude
  - It is helpful to have some scalar quantities that characterize the random variable vector
  - Direction and magnitude won’t do the trick!

Scalar quantities to characterize \( x \)

- Mean
  - \( \mu = \frac{x_1 + x_2 + \ldots + x_n}{N} \)
  - A measure of the central value of a distribution
- Standard deviation
  - \( \sigma = \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} (x_i - \mu)^2} \)
  - A measure of the dispersion or distribution of data
  - Note – this is most useful as a comparative measure
  - By itself, it is not particularly useful!
  - Some people use 1/N instead of 1/(N-1), but 1/(N-1) typically gives better results for small \( N \)
- The notation for mean and standard deviation of a variate are as follows:
  - \( x = (\mu, \sigma) \)
Reliability Engineering, Cont.

- Terminology
  - Population
    - The total set of elements in which we are interested
  - Sample
    - A randomly selected subset of the total population on which measurements are taken
- Describing the shape of a distribution
  - Uniform
  - Normal
  - Log Normal
  - Weibull

Uniform distribution

- Simplest
- All elements have the same value
- Area equal to 1 implies that all samples in the given range of x have the same value of f(x), where f(x) describes the distribution

Normal distribution

- Also called Gaussian distribution
- \( f(x) = \frac{1}{\sigma \sqrt{2\pi}} \exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right) \)

Normal distribution with mean and standard deviation:

- This IS a complete characterization
- CDF of Normal (Gaussian) Distribution cannot be found in closed form
- Generalized description of normal CDF:

  \[ Z = \frac{x - \mu}{\sigma} \]

  Note: \( F(x) = \int_{-\infty}^{x} f(u)\,du \)

Linear Regression

- Obtaining a best-fit to a set of data points
- Linear regression when best fit is a straight line
- Correlation coefficient tells you how good the fit is

Limits and fits

- Capital letters – hole
- Lowercase letters – shaft
- Basic size – same for both members of the fit
- Deviation – difference between a size and corresponding basic size
- Upper deviation
  - Max-size
  - Min-size
- Lower deviation
  - Fundamental deviation
    - Either upper or lower, whichever is closer to basic size
  - Tolerance
    - Difference between max and min deviations
Dimensions and tolerances

- Nominal size
- Basic size
- Limits
- Tolerance
- Clearance
- Interference
- Allowance

Materials and Processes

- Must always make “things” out of materials
- Must be able to manufacture this “thing”
- Topics first introduced in Materials Science course (MSCI 301)
- How do we determine the properties of a material?
  - Tables
- How were these values determined?
  - Generally via destructive testing

Material properties

- Listed in tables
- Statistical variation
- Values listed are minimums
- Best data from testing of prototypes under intended loading conditions

Material parameters

- Parameters of interest in material selection for design?
  - Strength
  - Stiffness
  - Weight
  - Toughness
  - Conductivity
  - Thermal
  - Corrosion resistance

Primary parameters of interest in material selection

- Strength
  - Amount of load (or weight, or force) a part can take before breaking or bending
- Stiffness
  - Amount of deflection or deformation for a given load
- Weight
- All of these depend on geometry
  - EXTENSIVE values
- We would like to derive results that are independent of size (geometry)
  - INTENSIVE values
Extensive vs. Intensive values

- Extensive
  - Weight (kg)
  - Strength (N)
  - Stiffness (N/m)

- Intensive
  - Density (kg/m³)
  - Yield strength or Ultimate Strength (N/m²)
  - Modulus of Elasticity (N/m²)

How do we determine these values?

- Types of quasistatic material testing
  - Tension
  - Compression
  - Bending
  - Torsion

Tensile tests specimens

- What is the difference between these specimens?

  Mild ductile steel tensile test specimen
  Brittle cast iron tensile test specimen

Tensile testing

- Best for general case

  - Why?
    - Uniform loading and uniform cross-section generate uniform stress
    - Compression poses stability problems (buckling)
    - Torsion and bending impose non-uniform stress

Other test specimens – Ductile and Brittle

- Compression
- Bending
- Torsion

Stress-Strain (σ-ε) Curves

- Point A – Proportional limit
- Point B – Elastic limit
- Point C – Yield point
  - Usually defined by permanent set of ε = 0.002 (0.2% offset)
  - For purposes of design, we often assume A-B-C, and call this the yield point
- Slope of O-A = E
  - Young’s Modulus
  - Modulus of elasticity
  - Like stiffness
- Point F – Onset of failure
- Point G, G’ - Fracture
Important design considerations

- \( S_y \) = Yield strength
  - It is the stress level that will result in permanent set
  - At which material undergoes marked decrease in stiffness
  - At which Hooke's Law is no longer valid
- \( S_u \) = Ultimate strength
  - Stress level that will result in fracture

Ductile vs. Brittle Material Behavior

- Ductile material
  - Sustains significant plastic deformation prior to fracture
- Brittle material
  - No significant plastic deformation before fracture

The only true means of determining if a material is ductile or brittle is by testing it (tensile test)

Fatigue testing – measuring endurance

- Most machines are loaded cyclically
  - Any piece of rotating machinery
  - Strength decreases over time
  - "Fatigue strength" depends on number of cycles and the material

How to test?
- Use a rotating beam
- More often vary axial loading over time

Common metals in machine design

- Magnesium
  - Specific stiffness ~ 25 MPa/(kg/m^2)
  - Extremely light (~1/5 steel)
  - Extremely flammable
- Aluminum (very common)
  - Specific stiffness ~ 26
  - Stiffness-to-weight and strength-to-weight comparable to steel
  - 1/3 stiffness of steel
  - 1/3 density of steel

More metals...

- Gray cast iron
  - Specific stiffness ~ 15
  - Decent strength
  - Used where casting makes sense and weight doesn't matter
    - Gears, engine blocks, brake disks and drums
- Brass, bronze
  - Generally soft
  - Good for bearings (bronze)
More metals…

- **Titanium**
  - Specific stiffness ~ 26
  - Excellent strength-to-weight
  - Non-magnetic
  - Non-corrosive (implants)
  - Can be cast
  - Expensive

- **Ductile cast iron**
  - Stronger than gray cast iron
  - Heavy-duty gears, automobile door hinges

More metals…

- **Stainless steel**
  - Non-magnetic
  - Much less corrosive than steel
  - Difficult to machine

- **Steel**
  - Specific stiffness ~ 27
  - Excellent fatigue properties
  - Good stiffness-to-weight
  - Better alloys have excellent strength-to-weight
  - Chromoly bicycle frames

Comparison of Young’s Modulus for various metals

Question…

- Does all steel have the same strength?
- Does all steel have the same stiffness?
- Strength ($S_y, S_u$) depends on alloy and state
- Stiffness ($E$) depends only on metal type
  - i.e., $E$ is a property of the metal and does not change with alloy or state

So what affects the strength of a metal?

- Two primary forms –
  - Alloying
  - Crystal state

- Metal alloys
  - Adding certain elements in trace amounts to a metal can significantly change its strength
  - Since the alloying elements are present in trace amounts, they don’t significantly alter modulus (stiffness) or density

Alloying

- **Steel** – Primary alloying elements:
  - Manganese
  - Nickel
  - Chromium
  - Molybdenum
  - Vanadium

- The alloy is identified by AISI/SAE or ASTM numbering system
  - AISI – American Iron and Steel Institute
  - SAE – Society of Automotive Engineering
  - ASTM – American Society for Testing and Materials
Altering crystal state

- Crystal state of steel can be altered by heat treatment or cold working
  - Quenching
    - Heat to very high (~1400ºF) temp and cool rather suddenly by immersion in water
    - Creates crystal structure called martensite which is extremely strong but brittle

More methods...

- Tempering
  - Reheat to moderate temperature and cool slowly
  - Adds ductility at the expense of decreased strength

- Annealing
  - Resets the alloy to original low strength, ductile state
  - Reheat alloy above critical temperature and allow to cool slowly

More methods...

- Normalizing
  - Between tempering and annealing

- Cold working
  - Another means of increasing strength at the expense of ductility

- Hot working
  - Reheating as the metal is deformed to maintain ductility

Question

- If you're going to have a piece of metal machined, would you rather use a cold worked or hot worked metal?

Steel numbering systems

- Used to define alloying elements and carbon content
- 1st two digits
  - Indicate principal alloying elements
- Last 2 digits
  - Indicate amount of carbon present
  - In 100ths of a percent

Steel number systems

- Plain carbon steel
  - 1st digit – 1
  - 2nd digit – 0
  - No alloys other than carbon are present
  - AISI 1005-1030: Low-carbon steels
  - AISI 1035-1055: Medium-carbon steels
  - AISI 1060-1085: High-carbon steels
  - AISI 11xx series adds sulphur
    - Improves machinability
    - Called free-machining steels
    - Not considered alloys
      - Sulphur does not improve mechanical properties
      - Makes it brittle
### Steel Number Systems

#### Alloy Steels
- Have various elements added in small quantities
- Improve material's
  - Strength
  - Hardness
  - Temperature resistance
  - Corrosion resistance
- Other...
- Nickel
  - Improve strength without loss of ductility
  - Enhances case hardenability
- Molybdenum
  - In combination with nickel and/or chromium
  - Adds hardness
  - Reduces brittleness
  - Increases toughness
- Other alloys used to achieve specific properties

#### Tool Steels
- Medium- to high- carbon alloy steels
- Especially formulated to give:
  - Very high hardness
  - Wear resistance
  - Sufficient toughness to resist shock loads experienced in machining
- Stainless Steels
  - Alloy steels with at least 10% chromium
  - Improved corrosion resistance over plain or alloy steels

### Steel Numbering Systems

#### Martensitic Stainless Steels
- 11.5 to 15% Cr and 0.15 to 1.2% C
- Magnetic
- Can be hardened by heat treatment
- Cutlery

#### Ferritic Stainless Steel
- Over 16% Cr and low C content
- Magnetic
- Soft
- Ductile
- Not heat treatable
- Cookware
- Both martensitic and ferritic called 400 series

#### Austenitic Stainless Steel
- 17 to 25% Cr and 10 to 20% nickel
- Better corrosion resistance (due to Ni)
- Nonmagnetic
- Excellent ductility and toughness
- Cannot be hardened except by cold working
- 300 series
- 300 series very weldable
- 400 series less so

### Aluminum Alloys

#### Principal Alloying Elements
- Copper
- Manganese
- Silicon
- Zinc

#### Alloys are designated by the Aluminum Association numbering system

### Aluminum Alloys, Cont.

#### Aluminum Alloys are also heat-treatable, as designated by the –T classification in the AA numbering system
Aluminum alloys

- Wrought-aluminum alloys
  - Available in wide variety of stock shapes
  - I-beams, angles, channels, bars, etc
  - 1st digit indicates principal alloying element
  - Hardness indicated by a suffix containing a letter and up to 3 numbers
  - Most commonly available and used in machine design applications:
    - 2000 series
    - 6000 series

- 2024
  - Oldest alloy
  - Among the most machinable
  - One of the strongest Al alloys
  - High fatigue strength
  - Poor weldability and formability

- 6061
  - Widely used in structural applications
  - Excellent weldability
  - Lower fatigue strength than 2024
  - Easily machined and popular for extrusion

- 7000 series
  - Aircraft aluminum
  - Strongest alloys

Tensile strengths of metals

Look-up tables for Material properties (in the appendix)