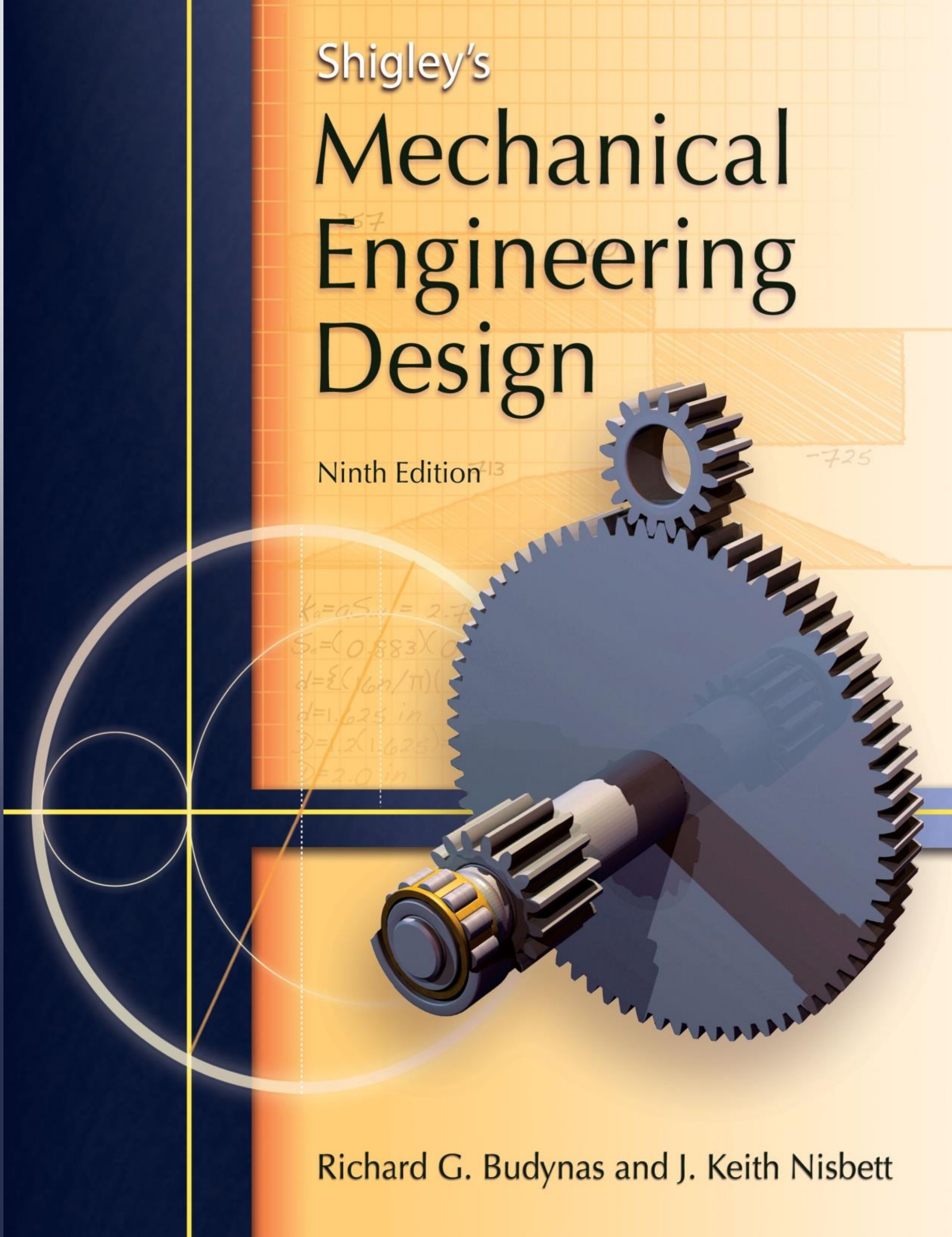
Lecture Slides

Chapter 1

Introduction to Mechanical Engineering Design



Chapter Outline

Design

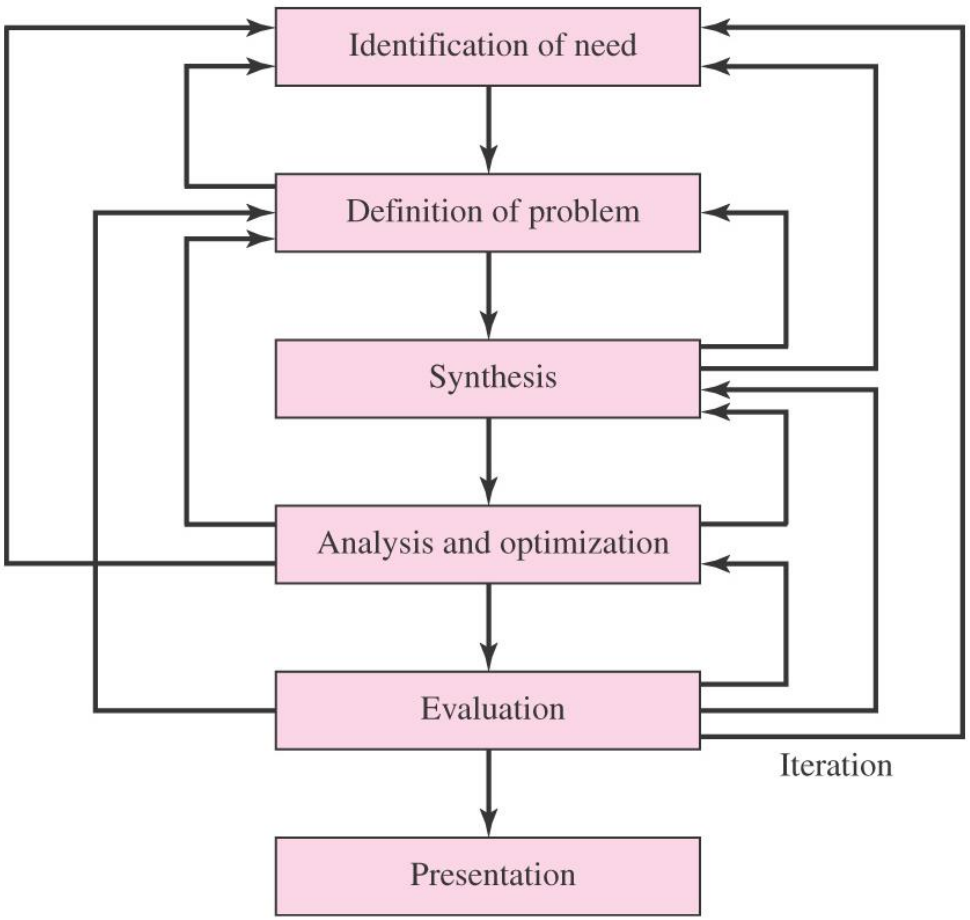
- To formulate a plan for the satisfaction of a specified need
- Process requires innovation, iteration, and decision-making
- Communication-intensive
- Products should be
  - Functional
  - Safe
  - Reliable
  - Competitive
  - Usable
  - Manufacturable
  - Marketable

Mechanical Engineering Design

- Mechanical engineering design involves all the disciplines of mechanical engineering.
- Example
  - Journal bearing: fluid flow, heat transfer, friction, energy transport, material selection, thermomechanical treatments, statistical descriptions, etc.

The Design Process

- Iterative in nature
- Requires initial estimation, followed by continued refinement



Design Considerations

- Some characteristics that influence the design

1	Functionality	14	Noise
2	Strength/stress	15	Styling
3	Distortion/deflection/stiffness	16	Shape
4	Wear	17	Size
5	Corrosion	18	Control
6	Safety	19	Thermal properties
7	Reliability	20	Surface
8	Manufacturability	21	Lubrication
9	Utility	22	Marketability
10	Cost	23	Maintenance
11	Friction	24	Volume
12	Weight	25	Liability
13	Life	26	Remanufacturing/resource recovery

Computational Tools

- Computer-Aided Engineering (CAE)
  - Any use of the computer and software to aid in the engineering process
  - Includes
    - Computer-Aided Design (CAD)
      - Drafting, 3-D solid modeling, etc.
    - Computer-Aided Manufacturing (CAM)
      - CNC toolpath, rapid prototyping, etc.
    - Engineering analysis and simulation
      - Finite element, fluid flow, dynamic analysis, motion, etc.
    - Math solvers
      - Spreadsheet, procedural programming language, equation solver, etc.

Acquiring Technical Information

- Libraries
  - Engineering handbooks, textbooks, journals, patents, etc.
- Government sources
  - Government agencies, U.S. Patent and Trademark, National Institute for Standards and Technology, etc.
- Professional Societies (conferences, publications, etc.)
  - American Society of Mechanical Engineers, Society of Manufacturing Engineers, Society of Automotive Engineers, etc.
- Commercial vendors
  - Catalogs, technical literature, test data, etc.
- Internet

  Access to much of the above information

A Few Useful Internet Sites

- www.globalspec.com
- www.engnetglobal.com
- www.efunda.com
- www.thomasnet.com
- www.uspto.gov

The Design Engineer's Professional Responsibilities

- Satisfy the needs of the customer in a competent, responsible, ethical, and professional manner.
- Some key advise for a professional engineer
  - Be competent
  - Keep current in field of practice
  - Keep good documentation
  - Ensure good and timely communication
  - Act professionally and ethically

Ethical Guidelines for Professional Practice

- National Society of Professional Engineers (NSPE) publishes a Code of Ethics for Engineers and an Engineers' Creed.
- www.nspe.org/ethics
- Six Fundamental Canons
- Engineers, in the fulfillment of their professional duties, shall:
  - Hold paramount the safety, health, and welfare of the public.
  - Perform services only in areas of their competence.
  - Issue public statements only in an objective and truthful manner.
  - Act for each employer or client as faithful agents or trustees.
  - Avoid deceptive acts.
  - Conduct themselves honorably, responsibly, ethically, and lawfully so as to enhance the honor, reputation, and usefulness of the profession.

NSPE Engineers’ Creed

- As a Professional Engineer I dedicate my professional knowledge and skill to the advancement and betterment of human welfare.
- I pledge:
  - To give the utmost of performance;
  - To participate in none but honest enterprise;
  - To live and work according to the laws of man and the highest standards of professional conduct;
  - To place service before profit, the honor and standing of the profession before personal advantage, and the public welfare above all other considerations.
- In humility and with need for Divine Guidance, I make this pledge.

Standards and Codes

- Standard
  - A set of specifications for parts, materials, or processes
  - Intended to achieve uniformity, efficiency, and a specified quality
  - Limits the multitude of variations
- Code
  - A set of specifications for the analysis, design, manufacture, and construction of something
  - To achieve a specified degree of safety, efficiency, and performance or quality
  - Does not imply absolute safety
- Various organizations establish and publish standards and codes for common and/or critical industries

Standards and Codes

- Some organizations that establish standards and codes of particular interest to mechanical engineers:

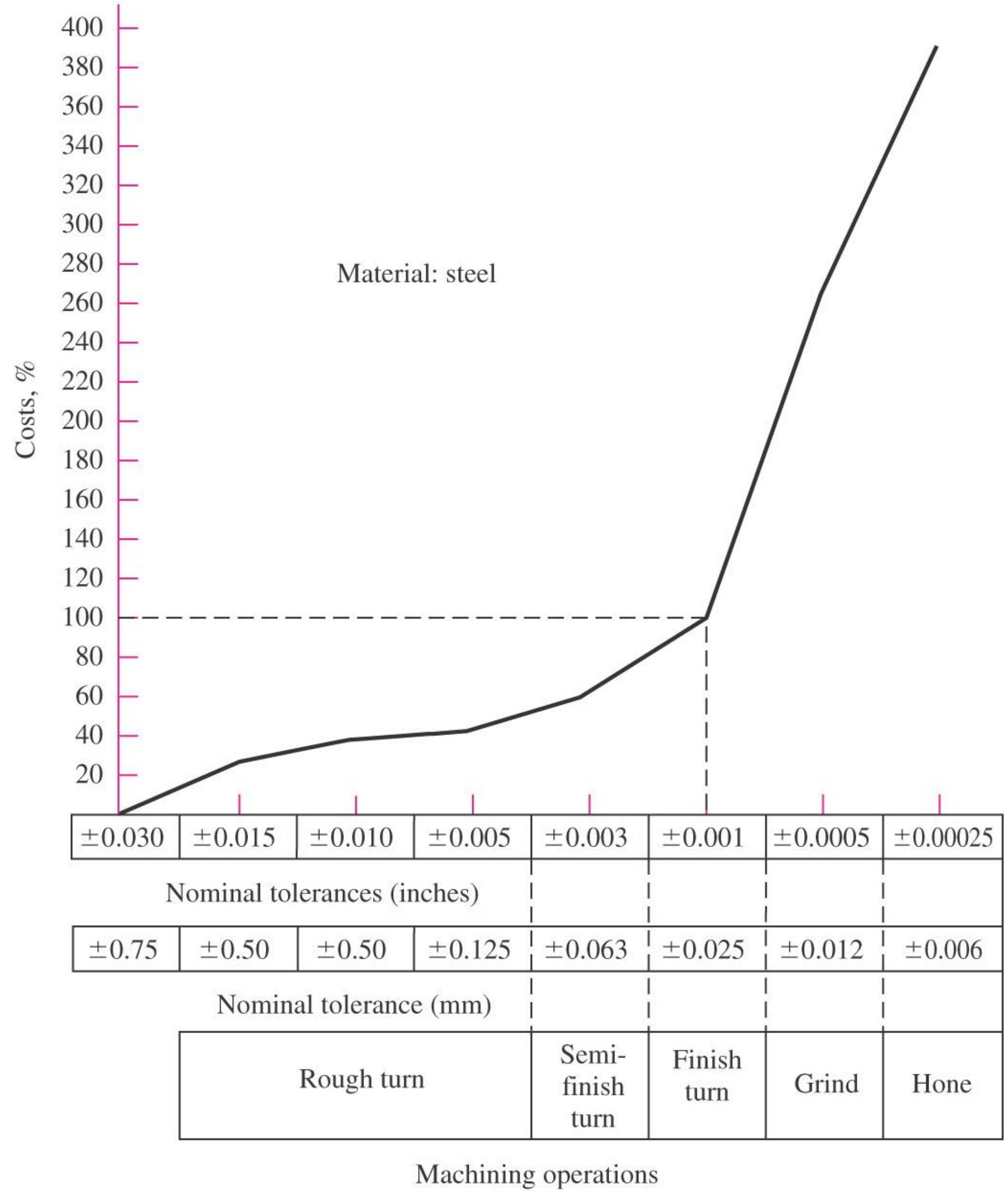
Aluminum Association (AA)
American Bearing Manufacturers Association (ABMA)
American Gear Manufacturers Association (AGMA)
American Institute of Steel Construction (AISC)
American Iron and Steel Institute (AISI)
American National Standards Institute (ANSI)
American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE)
American Society of Mechanical Engineers (ASME)
American Society of Testing and Materials (ASTM)
American Welding Society (AWS)
ASM International
British Standards Institution (BSI)
Industrial Fasteners Institute (IFI)
Institute of Transportation Engineers (ITE)
Institution of Mechanical Engineers (IMechE)
International Bureau of Weights and Measures (BIPM)
International Federation of Robotics (IFR)
International Standards Organization (ISO)
National Association of Power Engineers (NAPE)
National Institute for Standards and Technology (NIST)
Society of Automotive Engineers (SAE)

Economics

- Cost is almost always an important factor in engineering design.
- Use of standard sizes is a first principle of cost reduction.
- Table A-17 lists some typical preferred sizes.
- Certain common components may be less expensive in stocked sizes.

Tolerances

- Close tolerances generally increase cost
  - Require additional processing steps
  - Require additional inspection
  - Require machines with lower production rates

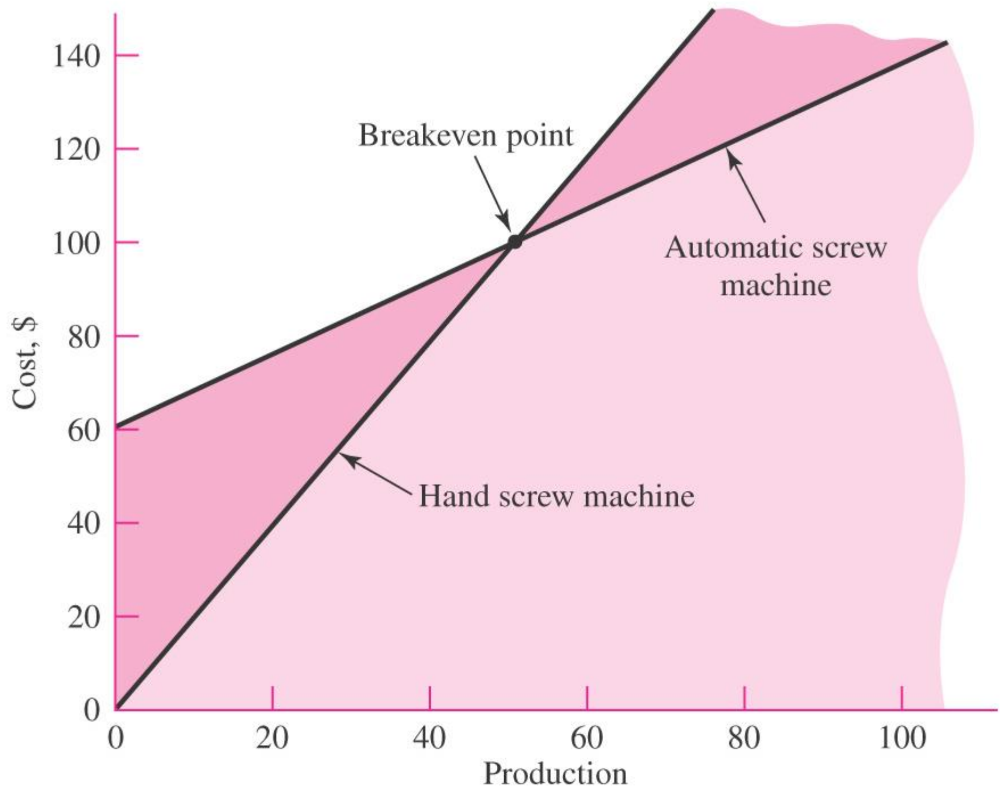


Breakeven Points

- A cost comparison between two possible production methods
- Often there is a breakeven point on quantity of production

EXAMPLE

- Automatic screw machine
  - 25 parts/hr
  - 3 hr setup
  - $20/hr labor cost
- Hand screw machine
  - 10 parts/hr
  - Minimal setup
  - $20/hr labor cost
- Breakeven at 50 units



Safety and Product Liability

- *Strict Liability* concept generally prevails in U.S.
- Manufacturer is liable for damage or harm that results because of a defect.
- Negligence need not be proved.
- Calls for good engineering in analysis and design, quality control, and comprehensive testing.

Stress and Strength

- Strength
  - An inherent property of a material or of a mechanical element
  - Depends on treatment and processing
  - May or may not be uniform throughout the part
  - Examples: Ultimate strength, yield strength
- Stress
  - A state property at a specific point within a body
  - Primarily a function of load and geometry
  - Sometimes also a function of temperature and processing

Uncertainty

- Common sources of uncertainty in stress or strength
  - Composition of material and the effect of variation on properties.
  - Variations in properties from place to place within a bar of stock.
  - Effect of processing locally, or nearby, on properties.
  - Effect of nearby assemblies such as weldments and shrink fits on stress conditions.
  - Effect of thermomechanical treatment on properties.
  - Intensity and distribution of loading.
  - Validity of mathematical models used to represent reality.
  - Intensity of stress concentrations.
  - Influence of time on strength and geometry.
  - Effect of corrosion.
  - Effect of wear.
  - Uncertainty as to the length of any list of uncertainties.

Uncertainty

- Stochastic method
  - Based on statistical nature of the design parameters
  - Focus on the probability of survival of the design's function (reliability)
  - Often limited by availability of statistical data

Uncertainty

- Deterministic method
  - Establishes a *design factor,* n_d
  - Based on absolute uncertainties of a *loss-of-function parameter* and a *maximum allowable parameter*

$$n_d = \frac{\text{loss-of-function parameter}}{\text{maximum allowable parameter}} \quad (1\text{–}1)$$

  - If, for example, the parameter is load, then

$$\text{Maximum allowable load} = \frac{\text{loss-of-function load}}{n_d} \quad (1\text{–}2)$$

Example 1-1

Consider that the maximum load on a structure is known with an uncertainty of ±20 percent, and the load causing failure is known within ±15 percent. If the load causing failure is *nominally* 2000 lbf, determine the design factor and the maximum allowable load that will offset the absolute uncertainties.

Solution

To account for its uncertainty, the loss-of-function load must increase to 1/0.85, whereas the maximum allowable load must decrease to 1/1.2. Thus to offset the absolute uncertainties the design factor, from Eq. (1–1), should be

$$n_d = \frac{1/0.85}{1/1.2} = 1.4 \qquad \textbf{Answer}$$

From Eq. (1–2), the maximum allowable load is found to be

$$\text{Maximum allowable load} = \frac{2000}{1.4} = 1400 \text{ lbf} \qquad \textbf{Answer}$$

Design Factor Method

- Often used when statistical data is not available
- Since stress may not vary linearly with load, it is more common to express the design factor in terms of strength and stress.

$$n_d = \frac{\text{loss-of-function strength}}{\text{allowable stress}} = \frac{S}{\sigma(\text{or } \tau)} \qquad (1\text{–}3)$$

- All loss-of-function modes must be analyzed, and the mode with the smallest design factor governs.
- Stress and strength terms must be of the same type and units.
- Stress and strength must apply to the same critical location in the part.
- The *factor of safety* is the realized design factor of the final design, including rounding up to standard size or available components.

Example 1-2

A rod with a cross-sectional area of A and loaded in tension with an axial force of $P = 2000$ lbf undergoes a stress of $\sigma = P/A$. Using a material strength of 24 kpsi and a *design factor* of 3.0, determine the minimum diameter of a solid circular rod. Using Table A–17, select a preferred fractional diameter and determine the rod's *factor of safety*.

Solution

Since $A = \pi d^2/4$, $\sigma = P/A$, and from Eq. (1–3), $\sigma = S/n_d$, then

$$\sigma = \frac{P}{A} = \frac{P}{\pi d^2/4} = \frac{S}{n_d}$$

Solving for d yields

$$d = \left(\frac{4Pn_d}{\pi S}\right)^{1/2} = \left(\frac{4(2000)3}{\pi(24\,000)}\right)^{1/2} = 0.564 \text{ in}$$ **Answer**

From Table A–17, the next higher preferred size is $\frac{5}{8}$ in $= 0.625$ in. Thus, when n_d is replaced with n in the equation developed above, the factor of safety n is

$$n = \frac{\pi S d^2}{4P} = \frac{\pi(24\,000)0.625^2}{4(2000)} = 3.68$$ **Answer**

Thus rounding the diameter has increased the actual design factor.

Reliability

- *Reliability, R* – The statistical measure of the probability that a mechanical element will not fail in use
- *Probability of Failure*, p_f – the number of instances of failures per total number of possible instances

$$R = 1 - p_f \qquad (1\text{–}4)$$

- Example: If 1000 parts are manufactured, with 6 of the parts failing, the reliability is

$$R = 1 - \frac{6}{1000} = 0.994$$ or 99.4 %

Reliability

- *Series System* – a system that is deemed to have failed if any component within the system fails
- The overall reliability of a series system is the product of the reliabilities of the individual components.

$$R = \prod_{i=1}^{n} R_i \qquad (1\text{-}5)$$

- Example: A shaft with two bearings having reliabilities of 95% and 98% has an overall reliability of

$$R = R_1 R_2 = 0.95\,(0.98) = 0.93 \qquad \text{or } 93\%$$

Dimensions and Tolerances

- *Nominal size* – The size we use in speaking of an element.
  - Is not required to match the actual dimension
- *Limits* – The stated maximum and minimum dimensions
- *Tolerance* – The difference between the two limits
- *Bilateral tolerance* – The variation in both directions from the basic dimension, e.g. 1.005 ± 0.002 in.
- *Unilateral tolerance* – The basic dimension is taken as one of the limits, and variation is permitted in only one direction, e.g.

$$1.005 \begin{array}{l} +0.004 \\ -0.000 \end{array} \text{ in}$$

Dimensions and Tolerances

- *Clearance* – Refers to the difference in sizes of two mating cylindrical parts such as a bolt and a hole.
  - Assumes the internal member is smaller than the external member
  - *Diametral clearance* – difference in the two diameters
  - *Radial clearance* – difference in the two radii
- *Interference* – The opposite of clearance, when the internal member is larger than the external member
- *Allowance* – The minimum stated clearance or the maximum stated interference or mating parts

Example 1-3

A shouldered screw contains three hollow right circular cylindrical parts on the screw before a nut is tightened against the shoulder. To sustain the function, the gap w must equal or exceed 0.003 in. The parts in the assembly depicted in Fig. 1–4 have dimensions and tolerances as follows:

$$a = 1.750 \pm 0.003 \text{ in} \qquad b = 0.750 \pm 0.001 \text{ in}$$

$$c = 0.120 \pm 0.005 \text{ in} \qquad d = 0.875 \pm 0.001 \text{ in}$$

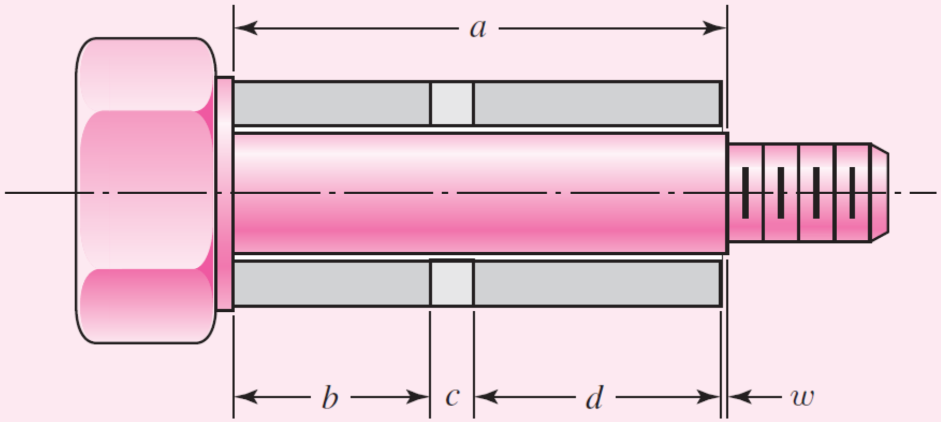


Figure 1-4

All parts except the part with the dimension d are supplied by vendors. The part containing the dimension d is made in-house.

(*a*) Estimate the mean and tolerance on the gap w.

(*b*) What basic value of d will assure that $w \geq 0.003$ in?

Example 1-3 (Continued)

Solution

(*a*) The mean value of w is given by

$$\bar{w} = \bar{a} - \bar{b} - \bar{c} - \bar{d} = 1.750 - 0.750 - 0.120 - 0.875 = 0.005 \text{ in}$$ **Answer**

For equal bilateral tolerances, the tolerance of the gap is

$$t_w = \sum_{\text{all}} t = 0.003 + 0.001 + 0.005 + 0.001 = 0.010 \text{ in}$$ **Answer**

Then, $w = 0.005 \pm 0.010$ in, and

$$w_{\text{max}} = \bar{w} + t_w = 0.005 + 0.010 = 0.015 \text{ in}$$

$$w_{\text{min}} = \bar{w} - t_w = 0.005 - 0.010 = -0.005 \text{ in}$$

Thus, both clearance and interference are possible.

(*b*) If w_{min} is to be 0.003 in, then, $\bar{w} = w_{\text{min}} + t_w = 0.003 + 0.010 = 0.013$ in. Thus,

$$\bar{d} = \bar{a} - \bar{b} - \bar{c} - \bar{w} = 1.750 - 0.750 - 0.120 - 0.013 = 0.867 \text{ in}$$ **Answer**

Linked End-Of-Chapter Problems

Table 1–1

Problem Numbers for Linked End-of-Chapter Problems*

3–1	4–50	4–74											
3–40	5–65	5–66											
3–68	4–23	4–29	4–35	5–39	6–37	7–7	11–14						
3–69	4–24	4–30	4–36	5–40	6–38	7–8	11–15						
3–70	4–25	4–31	4–37	5–41	6–39	7–9	11–16						
3–71	4–26	4–32	4–38	5–42	6–40	7–10	11–17						
3–72	4–27	4–33	4–39	5–43	6–41	7–11	7–19	7–20	7–34	11–27	11–28	13–38	14–36
3–73	4–28	4–34	4–40	5–44	6–42	7–12	7–21	7–22	7–35	11–29	11–30	13–39	14–37
3–74	5–45	6–43	7–13	11–41	13–42								
3–76	5–46	6–44	7–14	11–42	13–42								
3–77	5–47	6–45	7–15	11–18	13–40	14–38							
3–79	5–48	6–46	7–16	11–19	13–41	14–39							
3–80	4–41	4–71	5–49	6–47									
3–81	5–50	6–48											
3–82	5–51	6–49											
3–83	5–52	6–50											
3–84	4–43	4–73	5–53	5–56	6–51								
3–85	5–54	6–52											
3–86	5–55	6–53											
3–87	5–56												

*Each row corresponds to the same mechanical component repeated for a different design concept.

Power Transmission Case Study Specifications

Design Requirements

Power to be delivered: 20 hp
Input speed: 1750 rev/min
Output speed: 85 rev/min
Targeted for uniformly loaded applications, such as conveyor belts, blowers, and generators
Output shaft and input shaft in-line
Base mounted with 4 bolts
Continuous operation
6-year life, with 8 hours/day, 5 days/wk
Low maintenance
Competitive cost
Nominal operating conditions of industrialized locations
Input and output shafts standard size for typical couplings

Power Transmission Case Study Specifications

Design Specifications

Power to be delivered: 20 hp
Power efficiency: >95%
Steady state input speed: 1750 rev/min
Maximum input speed: 2400 rev/min
Steady-state output speed: 82–88 rev/min
Usually low shock levels, occasional moderate shock
Input and output shafts extend 4 in outside gearbox
Input and output shaft diameter tolerance: ±0.001 in
Input and output shafts in-line: concentricity ±0.005 in, alignment ±0.001 rad
Maximum allowable loads on input shaft: axial, 50 lbf; transverse, 100 lbf
Maximum allowable loads on output shaft: axial, 50 lbf; transverse, 500 lbf
Maximum gearbox size: 14-in × 14-in base, 22-in height
Base mounted with 4 bolts
Mounting orientation only with base on bottom
100% duty cycle

Power Transmission Case Study Specifications

Design Specifications

Maintenance schedule: lubrication check every 2000 hours; change of lubrication every 8000 hours of operation; gears and bearing life >12,000 hours; infinite shaft life; gears, bearings, and shafts replaceable

Access to check, drain, and refill lubrication without disassembly or opening of gasketed joints.

Manufacturing cost per unit: <\$300

Production: 10,000 units per year

Operating temperature range: −10° to 120°F

Sealed against water and dust from typical weather

Noise: <85 dB from 1 meter