Design of Machine Elements

Chapter 1: Introduction

What is a machine?

A machine is a device that transforms or transmits energy to perform a specific task, typically involving mechanical motion. (But, ML?!)

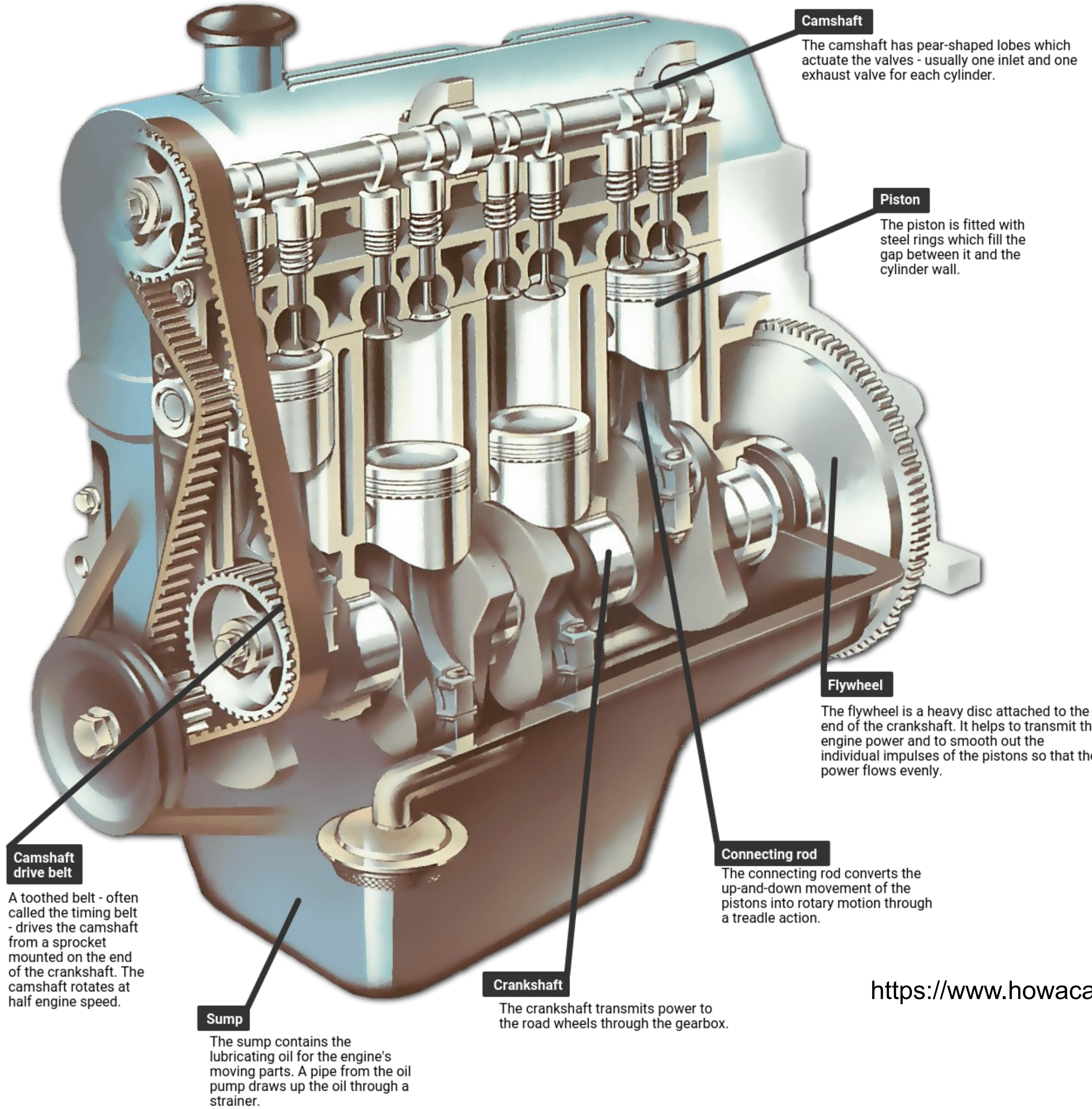
Key characteristics:

- Composed of multiple components (machine elements).
- Involves energy conversion or transmission
- Designed to achieve specific function(s) (e.g., lifting, cutting, transporting).

Examples:

- Simple machines: Lever, pulley, screw .
- Complex machines: Car engine, wind turbine, CNC machine.

Cut-Section of an Engine



https://www.howacarworks.com/basics/the-engine

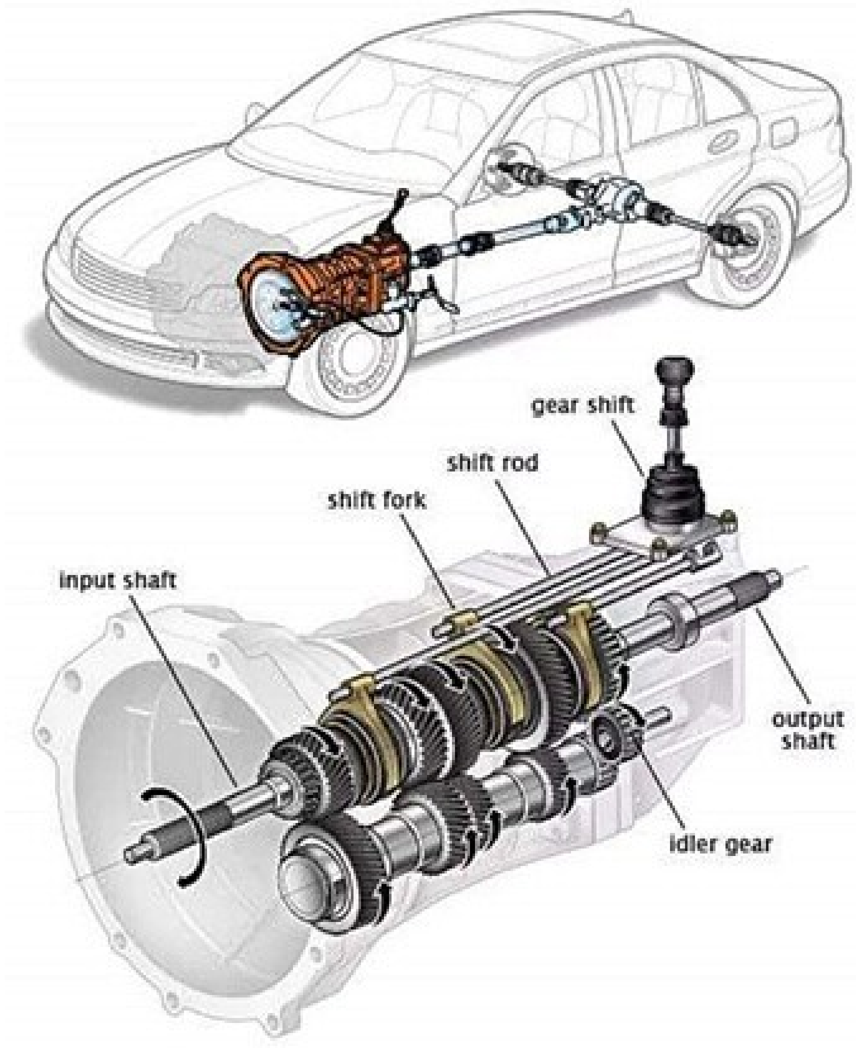
What are machine elements?

Machine elements are the fundamental components that make up a machine, each designed to perform a specific function.

Examples:

- Shafts
- Screws, Fasteners
- Weldments
- Springs
- Bearings
- Gears
- Clutches
- Brakes
- Couplings
- Flywheels
- Belts
- Chains

Gearbox



https://sunwayautoparts.com/understanding-car-transmission-system-and-transmission-parts/

Design

To formulate a plan for the satisfaction of a specified need

- Process requires innovation, iteration, and decision-making
- Communication-intensive

- **Engineering Design ≠ Invention**

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.
- Almost everything involves mechanics of solids and, certainly, mechanics.

The Design Process

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

- Earlier subjects
- (Mechanics of Solids,
- Fluid Mechanics)
- focussed primarily on Analysis and Evaluation

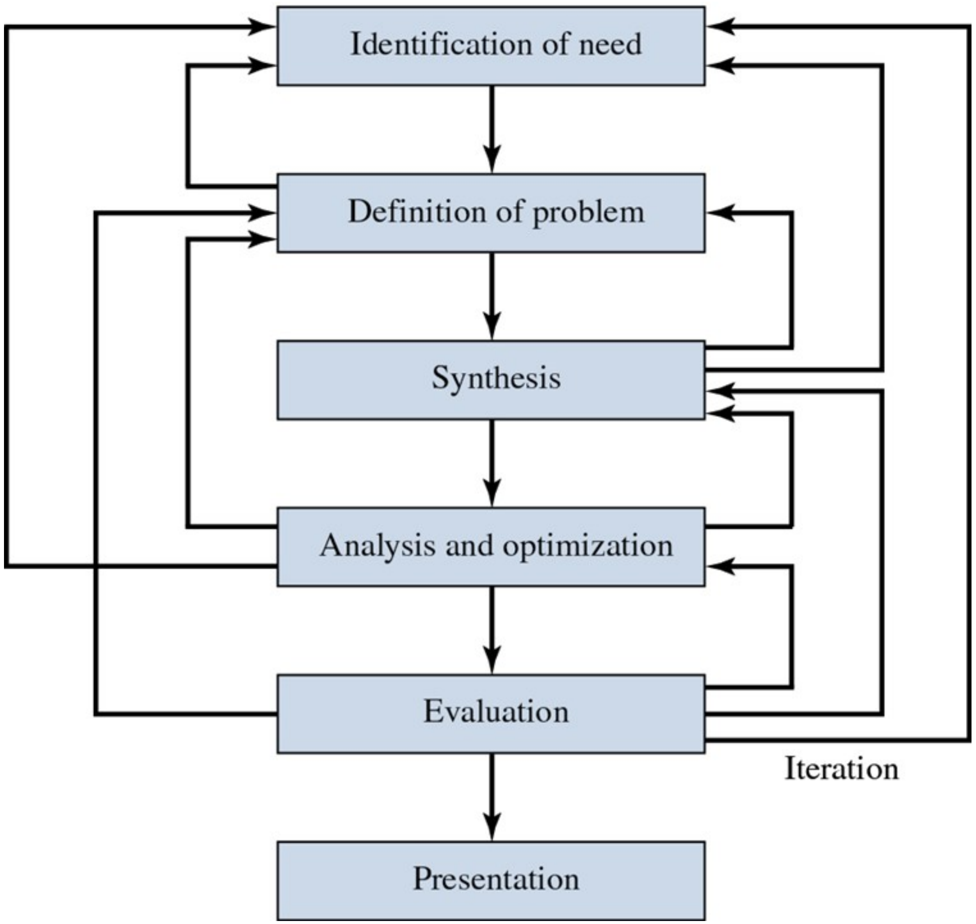


Fig. 1–1

Design Considerations

Some characteristics that influence the design

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

A Few Useful Internet Sites

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

The Design Engineer's Professional Responsibilities

Satisfy the needs of the customer in a competent, responsible, ethical, and professional manner.

Some key advice for a professional engineer

- Be competent
- Keep current in field of practice
- Keep good documentation
- Ensure good and timely communication
- Act professionally and ethically

Standards and Codes

Standards

- A set of specifications for parts, materials, or processes
- Intended to achieve uniformity, efficiency, and a specified quality
- Defines a recognized good practice, or an agreed upon uniformity, or a minimum level of acceptability
- May be generated within a company, across an industry, within a country, or internationally.
- Limits the multitude of variations

Standards and Codes (continued)

Design 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 (continued)

- 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)

In India

Bureau of Indian Standards: https://www.bis.gov.in/

Example:
Boilers and Pressure Vessels Code in India: IS 2825

https://law.resource.org/pub/in/bis/manifest.med.1.html

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.

Table A–17 Preferred Sizes and Renard (R-Series) Numbers

(When a choice can be made, use one of these sizes; however, not all parts or items are available in all the sizes shown in the table.)

Fraction of Inches

$\frac{1}{64}$, $\frac{1}{32}$, $\frac{1}{16}$, $\frac{3}{32}$, $\frac{1}{8}$, $\frac{5}{32}$, $\frac{3}{16}$, $\frac{1}{4}$, $\frac{5}{16}$, $\frac{3}{8}$, $\frac{7}{16}$, $\frac{1}{2}$, $\frac{9}{16}$, $\frac{5}{8}$, $\frac{11}{16}$, $\frac{3}{4}$, $\frac{7}{8}$, 1, $1\frac{1}{4}$, $1\frac{1}{2}$, $1\frac{3}{4}$, 2, $2\frac{1}{4}$, $2\frac{1}{2}$, $2\frac{3}{4}$, 3, $3\frac{1}{4}$, $3\frac{1}{2}$, $3\frac{3}{4}$, 4, $4\frac{1}{4}$, $4\frac{1}{2}$, $4\frac{3}{4}$, 5, $5\frac{1}{4}$, $5\frac{1}{2}$, $5\frac{3}{4}$, 6, $6\frac{1}{2}$, 7, $7\frac{1}{2}$, 8, $8\frac{1}{2}$, 9, $9\frac{1}{2}$, 10, $10\frac{1}{2}$, 11, $11\frac{1}{2}$, 12, $12\frac{1}{2}$, 13, $13\frac{1}{2}$, 14, $14\frac{1}{2}$, 15, $15\frac{1}{2}$, 16, $16\frac{1}{2}$, 17, $17\frac{1}{2}$, 18, $18\frac{1}{2}$, 19, $19\frac{1}{2}$, 20

Decimal Inches

0.010, 0.012, 0.016, 0.020, 0.025, 0.032, 0.040, 0.05, 0.06, 0.08, 0.10, 0.12, 0.16, 0.20, 0.24, 0.30, 0.40, 0.50, 0.60, 0.80, 1.00, 1.20, 1.40, 1.60, 1.80, 2.0, 2.4, 2.6, 2.8, 3.0, 3.2, 3.4, 3.6, 3.8, 4.0, 4.2, 4.4, 4.6, 4.8, 5.0, 5.2, 5.4, 5.6, 5.8, 6.0, 7.0, 7.5, 8.5, 9.0, 9.5, 10.0, 10.5, 11.0, 11.5, 12.0, 12.5, 13.0, 13.5, 14.0, 14.5, 15.0, 15.5, 16.0, 16.5, 17.0, 17.5, 18.0, 18.5, 19.0, 19.5, 20

Millimeters

0.05, 0.06, 0.08, 0.10, 0.12, 0.16, 0.20, 0.25, 0.30, 0.40, 0.50, 0.60, 0.70, 0.80, 0.90, 1.0, 1.1, 1.2, 1.4, 1.5, 1.6, 1.8, 2.0, 2.2, 2.5, 2.8, 3.0, 3.5, 4.0, 4.5, 5.0, 5.5, 6.0, 6.5, 7.0, 8.0, 9.0, 10, 11, 12, 14, 16, 18, 20, 22, 25, 28, 30, 32, 35, 40, 45, 50, 60, 80, 100, 120, 140, 160, 180, 200, 250, 300

Renard Numbers*

1st choice, R5: 1, 1.6, 2.5, 4, 6.3, 10

2d choice, R10: 1.25, 2, 3.15, 5, 8

3d choice, R20: 1.12, 1.4, 1.8, 2.24, 2.8, 3.55, 4.5, 5.6, 7.1, 9

4th choice, R40: 1.06, 1.18, 1.32, 1.5, 1.7, 1.9, 2.12, 2.36, 2.65, 3, 3.35, 3.75, 4.25, 4.75, 5.3, 6, 6.7, 7.5, 8.5, 9.5

*May be multiplied or divided by powers of 10.

Stress and Strength

Stress

- A state property at a specific point within a body
- Primarily a function of load and geometry (e.g., F/A, My/I)
- Sometimes also a function of temperature and processing

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

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.

Modeling Uncertainty

Deterministic method (factor of safety method)

- Determines values for a “strength” parameter and a “stress” parameter.
- Provides sufficient margin between the two to predict successful functionality.
- Often used when statistical data is not available
-

Stochastic method (reliability 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

Factor of Safety

- The *factor of safety* is the ratio of a loss-of-function parameter (e.g. yield strength, allowable load, allowable deflection, etc.) to an applied parameter (e.g. stress, load, deflection, etc.).

$$\text{factor of safety} = n = \frac{\text{loss of function parameter}}{\text{applied parameter}} \qquad (1\text{–}1)$$

- One of the most common parameters for factor of safety is stress and strength.

$$n = \frac{\text{Strength}}{\text{Stress}} = \frac{S}{\sigma} \qquad (1\text{–}2)$$

- 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.

Factor of Safety (continued)

- A factor of safety less than unity predicts failure.
- A factor of safety greater than unity predicts a successful design.
- Neither case provides any information about statistical percentage of failures.
- A higher factor of safety may increase confidence in a greater reliability, but there is no data to quantify that confidence.
- All loss-of-function modes must be analyzed, and the mode with the smallest design factor governs.

Factor of Safety and Design Factor

- A design process may start with a factor of safety that it is desired to achieve.
- The desired goal is usually called a *design factor*, n_d.
- The design factor may be used to solve for the maximum allowable value of the applied parameter.

$$\text{Maximum allowable parameter} = \frac{\text{loss of function parameter}}{n_d} \qquad (1\text{–}3)$$

- A realized design, with its use of standard sizes and rounded values, will usually achieve a factor of safety slightly higher than the original design factor.

Selection of Design Factor

Selection of a design factor should include consideration of

- Accuracy of the prediction of the situation, including loads, strengths, wear, environment, manufacturing quality, maintenance, etc.
- Cost of overachieving the requirements
- Consequences of failure

Guidance comes from

- Experience within the industry
- Applicable codes and standards

Example

A rod with a cross-sectional area of A and loaded in tension with an axial force of $P = 8900$ N undergoes a stress of $\sigma = P/A$. Using a material strength of 165 MPa 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 Equation (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

Answer $$d = \left(\frac{4Pn_d}{\pi S}\right)^{1/2} = \left(\frac{4(8900)3}{\pi(165000000)}\right)^{1/2} = 14.35 \text{ mm}$$

From Table A–17, the next higher preferred size is 16 mm. Thus, when n_d is replaced with n in the equation developed above, the factor of safety n is

Answer $$n = \frac{\pi S d^2}{4P} = \frac{\pi(165)16^2}{4(8900)} = 3.73$$

Thus, rounding the diameter has increased the actual design factor.