EP145 Introduction to Engineering

Topic 7

Force Related Parameters

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Introduction

In this chapter we will consider some concepts related to **Force** in Engineering.

Details can be found in [1] and [2].

Force

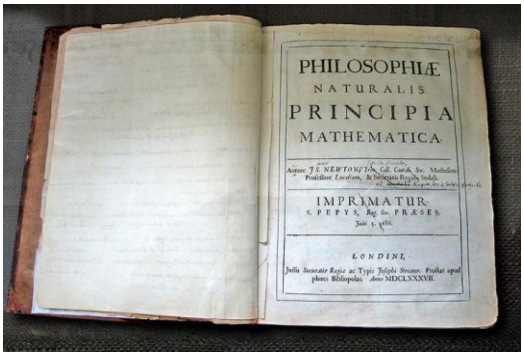
- **What is Force?**
  Force represents the interaction of two objects and it is a push or a pull.

- Units of Force ($F = ma$)
  SI:
  1 Newton = (1 kg)(1 m/s^2)
  1 N = 1 kg.m/s^2

  BG:
  1 pound force = 1 lbf = (1 slug)(1 ft/s^2)
  1 lbf = 4.448 N

Newton's Laws of Motion

In 1687, Newton published his fameoues book:
Mathematical Principles of Natural Philosophy



You can download the book at:
http://archive.org/details/philosophiaenatu00newt

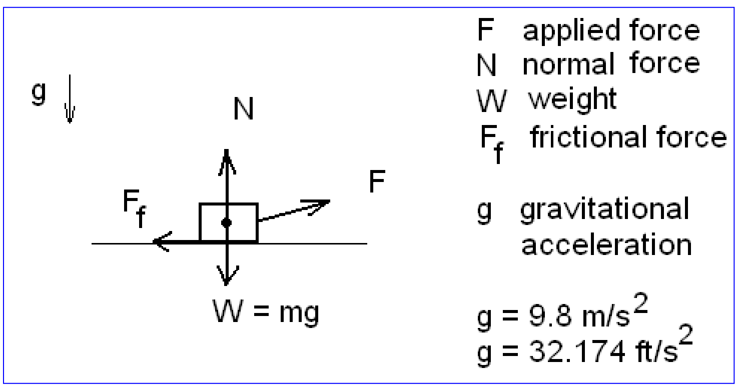
In Principia, Newton mentioned three laws of motion:

1. If net for acting on a body is zero (F = 0) then, the body keeps on doing what it is doing.

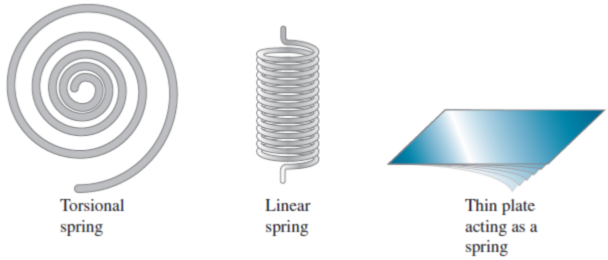
2. If net force acting on the body is non-zero then, the body will accelerate according to: F = ma.

3. Forces are generated in pairs. Any action results in a reaction.

Contact Force



Spring Force



Hooke's Law:

over the elastic range the deformation of a spring is directly proportional to the applied force, according to

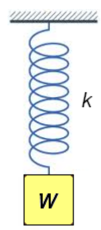
$$F = kx$$

F = applied force (N)

k = spring constant (N/m)

x = deformation of the spring (m)

Example 1



For a given spring, in order to determine the value of the spring constant, we have attached dead weights to one end of the spring, as shown in Figure. We have measured and recorded the deflection caused by the corresponding weights as given in Table.

What is the value of the spring constant?

Weight (N)	The Deflection of the Spring (mm)
5.0	9
10.0	17
15.0	29
20.0	35

Solution will be given in the lecture.

Surface Frictional Force

$F_{fmax} = \mu_S N = \mu_S mg$

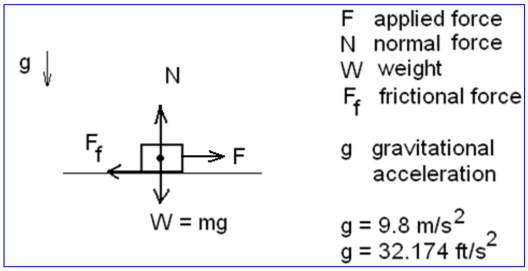
$F_{fkin} = \mu_K N = \mu_K mg$

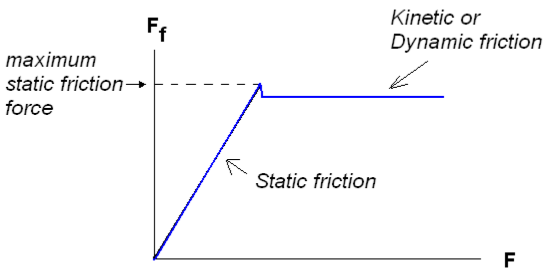
μ_S = *coefficient of static friction*

μ_K = *coefficient of kinetic friction*

In general

$\mu_K < \mu_S$



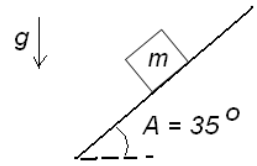


Coefficient of static and kinetic frictions for some materials:

Material 1	Material 2	μ_S	μ_K
Aluminum	Aluminum	1.05 - 1.35	1.40
Cast Iron	Cast Iron	1.10	0.15
Nickel	Nickel	0.70 - 1.10	0.53
Copper	Cast Iron	1.05	0.29
Glass (dry)	Glass (dry)	0.90 - 1.00	0.40
Glass (wet)	Glass (wet)	0.10 - 0.60	0.10
Teflon	Teflon	0.04	0.04
Steel (Mild)	Lead	0.95	0.95

Example 2

An object is placed on an inclined plane As shown in Fig. The mass of the object is m = 2 kg and it is in equilibrium.



(a) What is the magnitude of the static friction force on the object?

(b) What is the value of the coefficient of static friction (μ_S)?

Solution will be given in the lecture.

Example 3

A variable horizontal force acts on a block of mass m = 2 kg which is initially at rest on a table as shown in Fig a.

The acceleration of the block as a function of applied force is drawn in the Fig b.

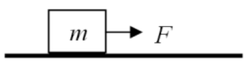


Fig a.

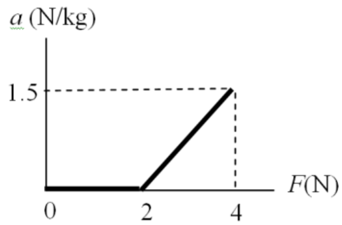


Fig b.

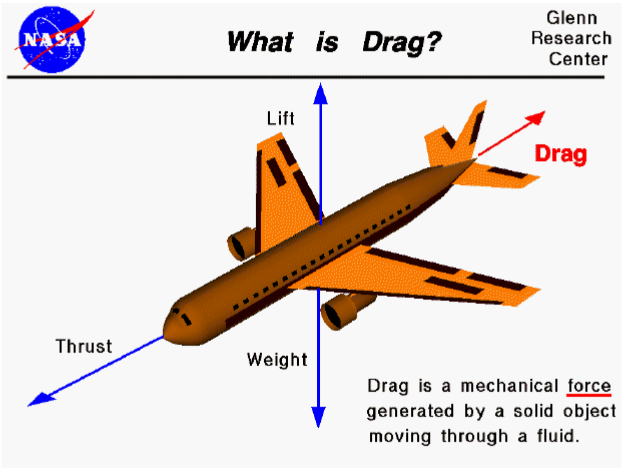
(a) What are the coefficients of static friction (μ_S) and kinetic friction (μ_K) between the table and the block respectively?

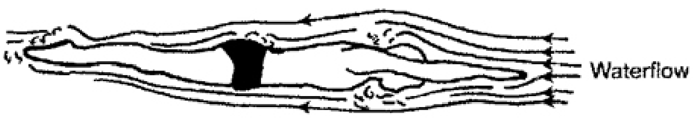
(b) Plot the frictional force (F_f) versus applied force (F) graph for the block.

Solution will be given in the lecture.

Drag Force

In fluid Mechanics, drag force (air resistance or fluid resistance) is a force that resists the motion of a body moving through a fluid.





Small drag in streamlined position

Large drag in unstreamlined position

At low speeds, drag force is proportional to the speed of the solid in the fluid:

$$F_d = bv$$

where

b is constant that depends on the properties of the fluid and the dimensions of the object.

v is the speed of the object.

At high speeds, drag force is proportional to the square of the speed:

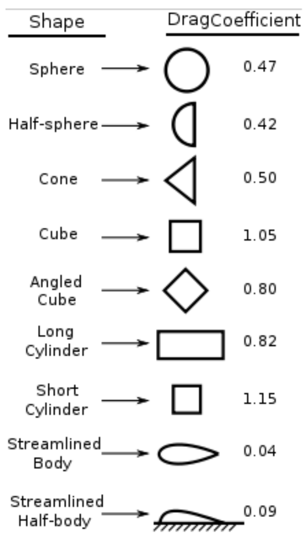
$$F_d = \frac{1}{2}\rho v^2 C_d A$$

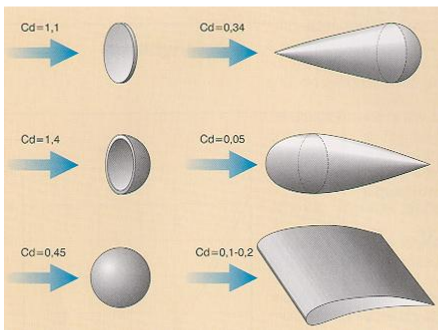
where

ρ is density of the fluid

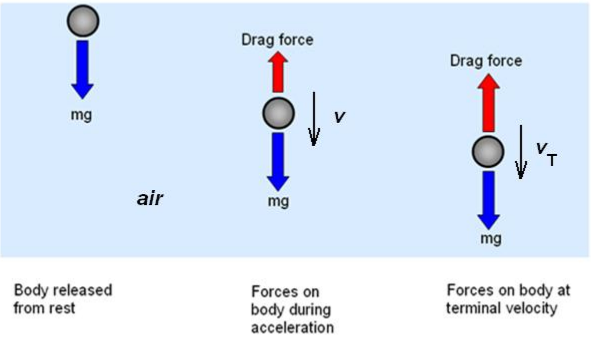
A is the crossectional area of object

C_d is the drag coefficent.





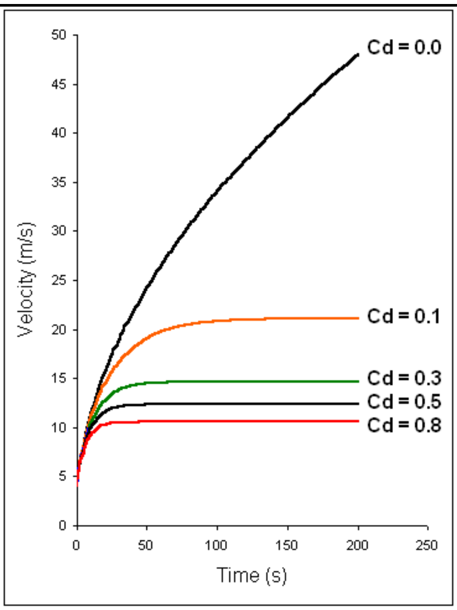
The speed of falling objects reaches a terminal (final) value due to drag force. (Terminal speed is a constant).



At low speeds:

$$F_d = bv_T = mg$$

Terminal speed is: $$v_T = \frac{mg}{b}$$



Velocity of a falling abject as a function of time for the different values of drag coefficient, C_d.

Example 4

Calculate the drag force acting on a wooden sphere (density 0.83 g/cm^3 and radius 8 cm) falling through air (density 1.23 kg/m^3)

(a) for low speeds with b = 0.5 kg/s and v = 1 m/s.

(b) for high speeds with C_d = 0.5 and v = 25 m/s.

Solution will be given in the lecture.

Example 5

Estimate the terminal speed of a wooden sphere (density 0.83 g/cm^3 and radius 8 cm) falling through air (density 1.23 kg/m^3)

(a) for low speeds with b = 0.5 kg/s

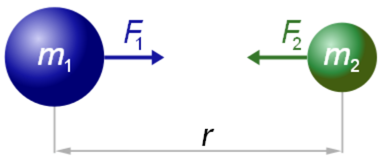
(b) for high speeds with C_d = 0.5

Solution will be given in the lecture.

Gravitational Force

Newton's law of universal gravitation states that:

every particle in the Universe attracts every other particle with a force that is directly proportional to the product of their masses and inversely proportional to the square of the distance between them.



$$F = G\frac{m_1 m_2}{r^2}$$

$F_1 = F_2 = F$

where G is called the universal gravitational constant and has the value:

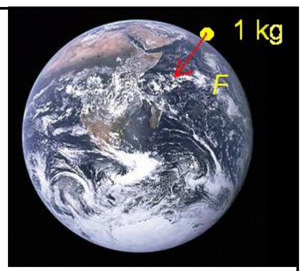
$G = 6.673 \times 10^{-11}\ \text{N.m}^2/\text{kg}^2$

Example 6

What is the magnitude of the gravitational force acting on an object whose mass is 1 kg due to Earth?

Mass of Earth is $M_E = 6 \times 10^{24}$ kg.

Radius of Earth $R_E = 6.4 \times 10^{6}$ m.



Solution:

$$F = G\frac{M_E m}{R_E^2} = (6.673\times10^{-11}\,\text{N.m}^2/\text{kg}^2)\frac{(6\times10^{24}\,\text{kg})(1\,\text{kg})}{(6.4\times10^{6}\,\text{m})^2} = 9.8\ \text{kg.m/s}^2$$

Note that gravitational acceleration is given by:

$$g = \frac{F}{m} = \frac{9.8\ \text{kg.m/s}^2}{1\ \text{kg}} = 9.8\ \text{m/s}^2$$

Example 7

Two people have the same mass of $m_1 = m_2 = 75$ kg.

(a) What is the magnitude of the gravitational force between the people if the separation between them is 0.5 m.

(b) What is the value of the force exerted by Earth on each of them?

Solution:

(a) $$F = (6.673\times10^{-11}\,\text{N.m}^2/\text{kg}^2)\frac{(75\,\text{kg})(75\,\text{kg})}{(0.5\,\text{m})^2} = 1.5\times10^{-6}\,N$$

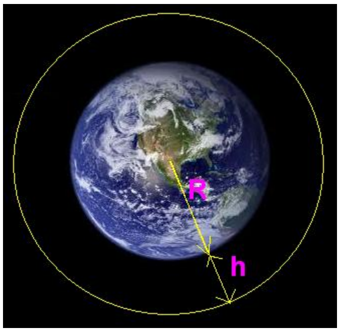
(b) $$F = mg = (75\,\text{kg})(9.8\,\text{m/s}^2) = 735.0\,N$$

The ratio:

$$\frac{735\,N}{1.5\times10^{-6}\,N} \approx 10^8$$

Free-Fall Acceleration *g* as a function of altitude *h*:

$$g = \frac{F}{m} = \frac{GM_E}{(R_E + h)^2}$$



Altitude h(km)	g(m/s²)
0	9.80
1000	7.33
2000	5.68
3000	4.53
4000	3.70
5000	3.08
6000	2.60
7000	2.23
8000	1.93
9000	1.69
10000	1.49
50000	0.13

Example 8

The International Space Station operates at an altitude of 350 km.
It has a weight (measured at the Earth's surface) of 4.22 $\times 10^6$ N.
What is its weight when in orbit?

Solution will be given in the lecture.

Elastic Properties of Solids

Except springs, we have assumed that objects remain rigid when external forces act on them.

In reality, all objects are deformable.
Forces can change the shape or the size of a solid.
Internal forces in the object resist the deformation.

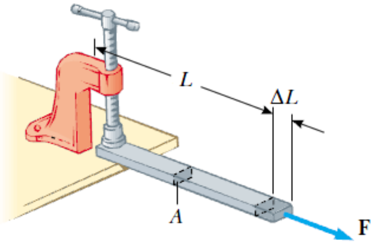
We will discuss the deformation of solids by using the concepts of **stress** and **strain**.

Tensile **stress** is the external force acting on an object per unit cross-sectional area.

$$\text{stress} = \sigma = \frac{F}{A}$$

The result of a stress is (tensile) **strain** defined by

$$\text{strain} = \varepsilon = \frac{\Delta L}{L}$$



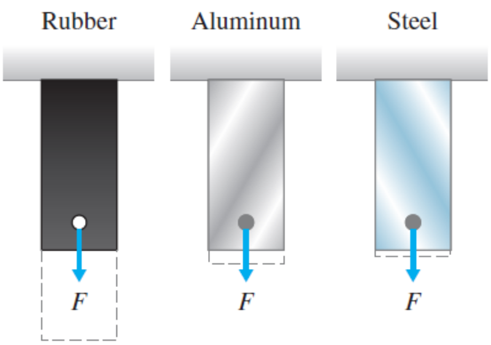
For sufficiently small stresses, strain is proportional to stress;

$$\sigma = E\,\varepsilon$$

stress (N/m^2)

elastic modulus (N/m^2)

strain (dimensionless)



Which piece of material will stretch more, when subjected to the same force?

There are three types of deformation and define an elastic modulus for each:

1. **Young's modulus**
   measures the resistance of a solid to a change in its length

2. **Shear modulus**
   measures the resistance to motion of the planes within a solid parallel to each other

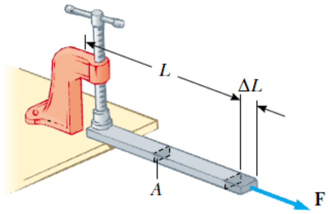
3. **Bulk modulus**
   measures the resistance of solids or liquids to changes in their volume

We will consider only Young's modulus.

Typical Values for Elastic Moduli

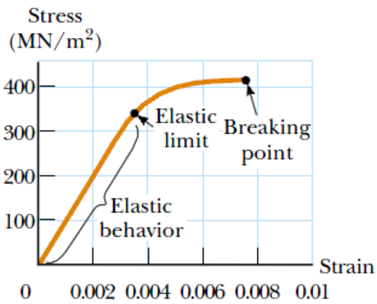
Substance	Young's Modulus (N/m^2)	Shear Modulus (N/m^2)	Bulk Modulus (N/m^2)
Tungsten	35×10^{10}	14×10^{10}	20×10^{10}
Steel	20×10^{10}	8.4×10^{10}	6×10^{10}
Copper	11×10^{10}	4.2×10^{10}	14×10^{10}
Brass	9.1×10^{10}	3.5×10^{10}	6.1×10^{10}
Aluminum	7.0×10^{10}	2.5×10^{10}	7.0×10^{10}
Glass	7.0×10^{10}	3.0×10^{10}	5.2×10^{10}
Quartz	5.6×10^{10}	2.6×10^{10}	2.7×10^{10}
Water	-	-	0.2×10^{10}
Mercury	-	-	2.8×10^{10}

Young's modulus (symbol *E or Y*)
measures the resistance of a solid to a change in its length.



$$Y = \frac{\text{tensile stress}}{\text{tensile strain}} = \frac{\sigma}{\varepsilon} = \frac{F / A}{\Delta L / L}$$

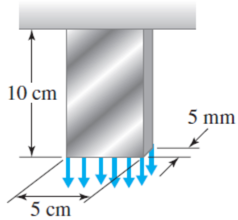
Tensile tests are performed to measure the
modulus of elasticity and strength of solid materials.



See also the videos on the course web page:
Tensile_Test_Stainless_Steel_Specimen.avi
Stress_Strain_Test.avi

Example 9

A structural member with a rectangular cross section, as shown in Figure is used to support a load of 4000 N distributed uniformly over the cross-sectional area of the member.
What type of material should be used to carry the load safely?



Solution:

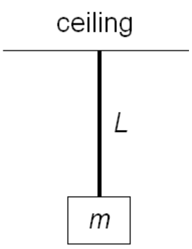
The average tensile stress is:

$$\sigma = \frac{F}{A} = \frac{4000\ \text{N}}{(0.05\ \text{m})(0.005\ \text{m})} = 16 \times 10^{6}\ \text{Pa} = 16\ \text{MPa}$$

So, we can use Steel or Tungsten to carry the load safely.

Example 10

A block mass m = 90 kg is attached to a ceiling by a steel wire of length L = 10 m as shown in Figure. What diameter should the wire have if we dont want it to stretch more than ΔL = 0.5 cm?

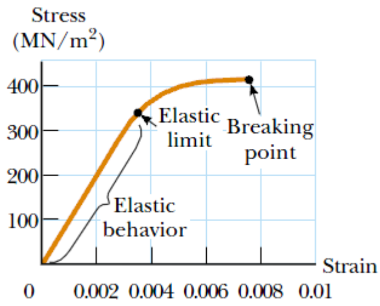


Solution will be given in the lecture.

Example 11

(a) Evaluate Young's modulus for the material whose stress versus strain curve is shown in Figure.

(b) What is the maximum force that can be exerted on a wire made of this material if the wire diameter is 5 mm?



Solution will be given in the lecture.

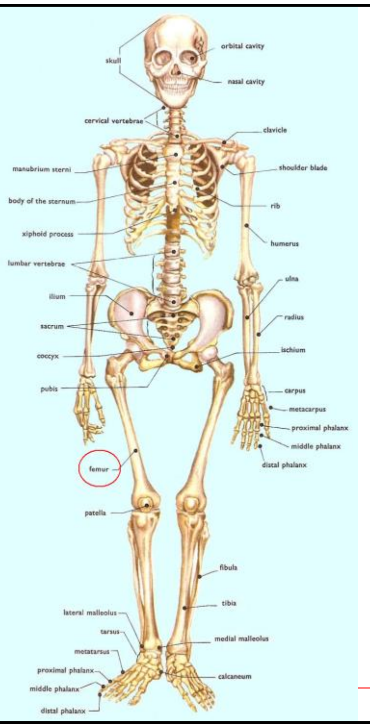
Example 12

Assume that Young's modulus is 1.50 x 10^{10} N/m^2 for bone and that the bone will fracture if stress greater than 1.50 x10^8 N/m^2 is imposed on it.

(a) What is the maximum force that can be exerted on the femur bone in the leg if it has a minimum effective diameter of 2.50 cm?

(b) If this much force is applied compressively, by how much does the 25.0-cm-long bone shorten?

Solution will be given in the lecture.



Four Fundamental Forces (Interactions)

Interaction	Particles affected	Range	Relative Strength	Role in Universe
Strong	Quarks	10^{-15} m	1	Holds quarks together to form nucleons
	Hadrons			Holds nucleons together to form atomic nuclei
Electro-magnetic	Charged particles	∞	10^{-2}	Determines the structure of atoms, molecules, solids and liquids, is important factor in astronomical universe, is responsible for frictional force
Weak	Quarks and Leptons	10^{-18} m	10^{-5}	Mediates transformations of quarks and leptons, helps determine compositions of atomic nuclei
Gravitational	All	∞	10^{-39}	Assembles matter into planets, stars, galaxies.

Questions

Not available.

References

1. P. Kosky et al., *Exploring Engineering*, 2nd Ed. Elsevier Inc. (2010)

2. S. Moaveni, *Engineering Fundamentals*, 4th Ed. Cengage Learning (2011)