

Mechanical Design Concepts for Non-Mechanical Engineers

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IDC TECHNOLOGIES
Worldwide Offices

AUSTRALIA

Telephone: 1300 138 522 • Facsimile: 1300 138 533

West Coast Office

1031 Wellington Street, West Perth, WA 6005
PO Box 1093, West Perth, WA 6872

INDIA

Telephone : +91 44 3061 8525
131 G.N. Chetty Road, Chennai 600017

IRELAND

Telephone : +353 1 473 3190 • Facsimile: +353 1 473 3191
Caoran, Baile na hAbhann, Co. Galway

MALAYSIA

Telephone: +60 3 5192 3800 • Facsimile: +60 3 5192 3801
26 Jalan Kota Raja E27/E, Hicom Town Center
Seksyen 27, 40400 Shah Alam, Selangor

NEW ZEALAND

Telephone: +64 9 263 4759 • Facsimile: +64 9 262 2304
Parkview Towers, 28 Davies Avenue, Manukau City
PO Box 76-142, Manukau City

SINGAPORE

Telephone: +65 6224 6298 • Facsimile: + 65 6224 7922
100 Eu Tong Sen Street, #04-11 Pearl's Centre, Singapore 059812

SOUTH AFRICA

Telephone: +27 87 751 4294 or +27 79 629 5706 • Facsimile: +27 86 692 4368
68 Pretorius Street, President Park, Midrand
PO Box 389, Halfway House 1685

UNITED KINGDOM

Telephone: +44 20 8335 4014 • Facsimile: +44 20 8335 4120
Suite 18, Fitzroy House, Lynwood Drive, Worcester Park, Surrey KT4 7AT

UNITED STATES

Toll Free Telephone: 1800 324 4244 • Toll Free Facsimile: 1800 434 4045
10685-B Hazelhurst Dr. # 6175, Houston, TX 77043, USA

Website: www.idc-online.com

Email: idc@idc-online.com



Technology Training that Works

Presents

Mechanical Design Concepts for Non-Mechanical Engineers

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Website: www.idc-online.com

E-mail: idc@idc-online.com

IDC Technologies Pty Ltd
PO Box 1093, West Perth, Western Australia 6872
Offices in Australia, New Zealand, Singapore, United Kingdom, Ireland, Malaysia, Poland, United States of America, Canada, South Africa and India

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Contents

1	Basics of Mechanical Design	1
1.1	Introduction	1
1.2	Basic Concepts	3
1.3	Units of engineering quantities	5
1.4	Friction	6
1.5	Summary	9
2	Mechanical Drawings	11
	Section A – Types of lines and letter used in drawings	11
2.1	Types of lines	11
2.2	Lettering of drawings	14
2.3	Summary of Section A	14
	Section B – Projections	14
2.4	What is projection?	15
2.5	Pictorial projections	17
2.6	Concept of cutting plane and sectional view	18
2.7	Summary of Section B	22
	Section C – Dimensioning	23
2.8	Different systems of dimensioning	23
2.9	Dimensioning practices	23
2.10	Summary of Section C	24
	Section D – Assembly Drawings	24
2.11	Summary of Section D	26
	Section E – Welded Joints	26
2.12	Types of welded joints	26
2.13	Summary of Section E	28
	Section F – Bolt, nut and screw fasteners	28
2.14	Introduction	28
2.15	Summary of Section F	30
	Section G – Keys, keyways and keyed assemblies	30
2.16	Types of keys	32
2.17	Summary of Section G	33
	Section H – Tolerance, limits and fits	33
2.18	Concept of tolerance	33
2.19	Concept of limits	34
2.20	Concept of fit	35
2.21	Summary of Section H	36
	Section I – The role of CAD and CAM	37
2.22	Use of computers for preparation of drawings	37
2.23	CAD software	37
2.24	Computer Aided Manufacturing (CAM)	38
2.25	Summary of Section I	38
	Section J – Office Practice	38
2.26	Drawing number and part name	38
2.27	Summary of Section J	39

3	Engineering Materials	41
3.1	Mechanical properties of materials	41
3.2	Processing of metals and alloys	43
3.3	Stress and strain in metals	46
3.4	Normal stress and shear stress	48
3.5	Tensile and hardness testing	48
3.6	Stress and strain diagram	52
3.7	Alloy production and properties	55
3.8	Fracture of metals	60
3.9	Corrosion types and control	64
3.10	Summary	66
4	Mechanical Design	67
4.1	Introduction	67
4.2	Codes and standards	70
4.3	Design considerations	70
4.4	Factor of safety	76
4.5	Mechanical components	77
4.6	Fasteners/screwed joints	105
4.7	Fastener failure	112
4.8	Compression members	116
4.9	Summary	121
5	Keys, Keyways and Splines	123
5.1	Keys and keyways	123
5.2	Keyways	126
5.3	Setscrews and pins for torque transmission	127
5.4	Splines	128
5.5	Spline failures	133
6	Bearings	135
6.1	Introduction	135
6.2	Plain or sliding contact bearings	135
6.3	Operation of sleeve bearings	136
6.4	Rolling contact or anti-friction bearings	138
6.5	Ball bearing	139
6.6	Roller bearing	144
6.7	Other bearing types	147
6.8	Bearing selection considerations	148
6.9	Bearing loads	149
6.10	General installation considerations	151
6.11	Bearing materials	151
6.12	Bearing lubrication	154
6.13	Bearing life	156
6.14	Bearing clearance and preloading	157
6.15	Bearing failures	159

7	Gears and Gear Drives	179
7.1	Introduction	179
7.2	Gear geometry	179
7.3	Spur gears	181
7.4	Helical gears	185
7.5	Bevel gears	188
7.6	Worm gears	191
7.7	Gear trains	192
7.8	Gear load carrying capacity	196
7.9	Selection of gear drives	197
7.10	Service factor	199
7.11	Gear installation	204
7.12	Backlash and adjustment	205
7.13	Gear lubrication	218
7.14	Gear materials	220
7.15	Gear failures causes and remedies	223
8	Variable Speed Drives	237
8.1	Introduction	237
8.2	Variable speed belt drives	239
8.3	Mechanical couplings	240
8.4	Copp variator	240
8.5	Hydrostatic drives	242
8.6	Gearboxes	243
8.7	Constant mesh gearbox	243
8.8	Sliding mesh type	244
8.9	Synchromesh gearbox arrangement	245
9	Belt Drives	249
9.1	Flat belts	249
9.2	V-belts	253
9.3	Timer or toothed belts	258
9.4	Belt selection	261
9.5	Installation of flat belts	264
9.6	Installation of V-belts	272
9.7	Belt materials	276
9.8	Belt service factors	277
10	Chain Drives	285
10.1	Introduction	285
10.2	Selection of chain and sprocket	289
10.3	Silent chains	294
10.4	Chain lubrication	297
10.5	Installation and maintenance	299
10.6	Drive selection	304
10.7	Service factoring for chain drives	304

11	Couplings	307
11.1	Introduction	307
11.2	Rigid couplings	307
11.3	Flexible couplings	309
11.4	Service factoring and coupling load characteristics	312
11.5	Universal joints	314
12	Clutches	319
12.1	Introduction	319
12.2	Clutch classification	320
12.3	Positive mechanical clutches	322
12.4	Mechanical friction clutches	325
12.5	Electro-magnetic clutches	331
12.6	Hydraulic couplings and torque converters	335
13	Brakes	337
13.1	Introduction	337
13.2	Mechanical brakes	342
13.3	Electromagnetic brakes	345
13.4	Pneumatic brakes	347
13.5	Hydraulic brakes	350
13.6	Brake selection and performance	353
14	Prime Movers	355
14.1	Introduction	355
14.2	Internal combustion engines	358
14.3	Hydraulic motors	358
14.4	Air motors	359
14.5	Steam turbines	359
14.6	Electric motors	360
14.7	DC motors	362
14.8	AC motors	363
14.9	AC poly-phase motors	365
14.10	3-phase squirrel-cage induction motors	366
14.11	AC synchronous motors	368
15	Fluid Engineering	371
15.1	Pumps	371
15.2	Compressors	382
15.3	Turbines	386
15.4	Flow in pipes	392
15.5	Thermodynamics	398
15.6	Reversibility	405
15.7	Summary	405

16	Theory of Heat Transfer	407
16.1	Heat basics	407
16.2	Heat transfer	409
16.3	Laws of thermodynamics	411
16.4	Thermal cycles	413
16.5	Heat exchangers	420
16.6	Heat pumps	423
16.7	Air conditioning	425
16.8	Summary	426
17	Mechanical Vibrations	427
17.1	Introduction	428
17.2	Terminology: Frequency, Amplitude and Phase	433
17.3	Natural and forcing frequencies	447
17.4	Vibration measurement: Sensors, analyzers and Interpretation	450
18	Manufacturing	485
18.1	Foundry process	485
18.2	Heat treatment	488
18.3	Hot working of metals	489
18.4	Cold working of metals	491
18.5	Pressing	493
18.6	Numerical control	496
18.7	Sawing	500
18.8	Broaching	500
18.9	Shapers and shaping	501
18.10	Welding	501
18.11	Brazing	502
18.12	Computer aided manufacturing (CAM)	503
18.13	Manufacturing processes in oil and gas industry	504
18.14	Summary	504
19	Maintenance	505
19.1	Introduction	506
19.2	Maintenance philosophies	508
19.3	Tighten, lubricate, clean (TLC)	510
19.4	Condition monitoring methods and failure analysis	513
19.5	Scheduling maintenance	541
20	Mechanical Engineering Codes and Standards	545
20.1	Need for standardization	545
20.2	Overview of standards	546
20.3	Benefits of standardization	547
20.4	Mechanical engineering standards	548
20.5	ISO 9000/1	548
20.6	Six Sigma	550
20.7	Summary	551

Appendix A	Practical Exercises	553
Appendix B	Answers to Practical Exercises	597

Basics of Mechanical Engineering

Mechanical Engineering, as its name suggests, deals with the mechanics of operation of mechanical systems. This is the branch of engineering which includes design, analysis, testing, manufacturing and maintenance of mechanical systems. The mechanical engineer may design a component, a machine, a system or a process. Mechanical engineers will analyze their design using the principles of motion, energy, and force to ensure the product functions safely, efficiently, reliably, and can be manufactured at a competitive cost.

Learning objectives

- Basic concepts
- Units for engineering quantities
- Friction and its importance

1.1 Introduction

Mechanical engineering plays a dominant role in enhancing safety, economic vitality, enjoyment and overall quality of life throughout the world. Mechanical engineers are concerned with the principles of force, energy and motion.

Mechanical engineering is a diverse subject that derives its breadth from the need to design and manufacture everything from small individual parts and devices (e.g. microscale sensors and inkjet printer nozzles) to large systems (e.g. spacecraft and machine tools). The role of a mechanical engineer is to take a product from an idea to the marketplace. In order to accomplish this, a broad range of skills are needed. Since these skills are required for virtually everything that is made, mechanical engineering is perhaps the broadest and most diverse of engineering disciplines.

Mechanical engineers play a central role in such industries as automotive (from the car chassis to its every subsystem — engine, transmission, sensors); aerospace (airplanes, aircraft engines, control systems for airplanes and spacecraft); biotechnology (implants, prosthetic devices, fluidic systems for pharmaceutical industries); computers and electronics (disk drives, printers, cooling systems, semiconductor tools); microelectromechanical systems (MEMS) (sensors, actuators, micropower generation); energy conversion (gas turbines, wind turbines, solar energy, fuel cells); environmental control (HVAC, air-conditioning, refrigeration, compressors); automation (robots, data and image acquisition, recognition, control) and manufacturing (machining, machine tools, prototyping, micro fabrication).

2 Mechanical Design Concepts for Non-Mechanical Engineers

The main areas of study in this branch are:

- Materials
- Solid and fluid mechanics
- Thermodynamics
- Heat transfer
- Control, instrumentation
- Specialized mechanical engineering subjects include biomechanics, cartilage-tissue engineering, energy conversion, laser-assisted materials processing, combustion, MEMS, micro fluidic devices, fracture mechanics, nanomechanics, mechanisms, micropower generation, tribology (friction and wear) and vibrations.

1.2 Basic concepts

1.2.1 Force

A foundation concepts in physics, a force may be thought of as any influence which tends to change the motion of an object. A force can be described as the push or pull upon an object resulting from the object's interaction with another object. Whenever there is an interaction between two objects, there is a force upon each of the objects. When the interaction ceases, the two objects no longer experience the force. Forces only exist as a result of an interaction.

There are four fundamental forces in the universe: the gravity force, the nuclear weak force, the electromagnetic force, and the nuclear strong force in ascending order of strength. In mechanics, forces are seen as the causes of linear motion, whereas the cause of rotational motion is called a torque. The action of forces in causing motion is described by Newton's Laws.

Force is a quantity which is measured using the standard metric unit called the Newton. A Newton is abbreviated by a "N". To say "10.0 N" means 10 Newtons of force. One Newton is the amount of force required to give a 1 kg mass an acceleration of 1 m/s².

$$\text{Force} = \text{mass} \times \text{acceleration}$$
$$F = m \times a = 1 \text{ kg} \times 1 \text{ m} / \text{s}^2$$

A force is a vector quantity — it has both magnitude and direction. To fully describe the force acting upon an object, you must describe both the magnitude (size or numerical value) and the direction. Thus, 10 Newtons is not a full description of the force acting upon an object. In contrast, 10 Newtons downwards is a complete description of the force acting upon an object; both the magnitude (10 Newtons) and the direction (downwards) are given.

A torque is a special form of force that turns an axle in a given direction. It is sometimes called a rotational force. You can create a torque by pushing on a rod or lever that rotates an axle. Likewise, a torque on an axle can result in a linear force at a distance from the center of the axle.

Torque equals force multiplied by moment arm. Pushing on a rod that rotates an axle can create a torque on that axle. Likewise, a torque on an axle can result in a linear force at a radius from the center.

The relationship between torque and force is:

$$T = FR$$

or

$$F = T/R$$

where

T is the torque in newton-meters

F is the force (Newtons)

R is the radius or distance from the center to the edge (meters)

R is also sometimes called the *moment arm*. The force, F , is applied perpendicular to the radius, lever or moment arm.

1.2.2 Work

Work refers to an activity involving a force and movement in the direction of the force.

A work is done on an object when the force acts on it in the direction of motion or has component in the direction of motion.

In order to accomplish work on an object there must be a force exerted on the object and it must move in the direction of the force.

Work = Force x distance moved in direction of force

Work is measured in joules (J). The formula for this is:

$$J = N \times m$$

Where force is measured in Newtons and distance in meters.

For a constant force F which moves an object in a straight line from x_1 to x_2 , the work done by the force

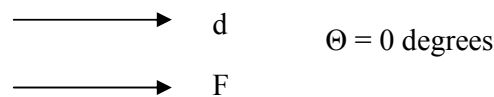
$$\text{Work} = \text{force} \times (x_2 - x_1)$$

Mathematically, work can be expressed by the following equation:

$$W = F \times d \times \cos \Theta$$

where F is the force, d is the displacement, and the angle (θ) is defined as the angle between the force and the displacement vector. Perhaps the most difficult aspect of the above equation is the angle " θ ." θ is defined as the angle between the force and the displacement.

- A force acts from the right on an object and it is displaced to the right. In such an instance, the force vector and the displacement vector are in the same direction. Thus, the angle between F and d is 0 degrees.



- A force acts from the left on an object and it is displaced to the right. In such an instance, the force vector and the displacement vector are in the opposite direction. Thus, the angle between F and d is 180 degrees.



- A force acts upward on an object as it is displaced to the right. In such an instance, the force vector and the displacement vector are at right angles to each other. Thus, the angle between F and d is 90 degrees.



For the more general case of a variable force $F(x)$ which is a function of x , the work is still the area under the force curve, and the work expression becomes an integral.

4 Mechanical Design Concepts for Non-Mechanical Engineers

$$\text{Work} = \int_{x_1}^{x_2} F(x) dx$$

Work is not done when there is no motion or when the force is perpendicular to the motion.

Let us apply the work equation to determine the amount of work done by the applied force in each of the three situations described below.

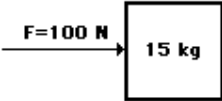
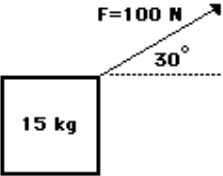
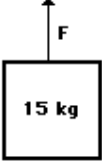
Diagram A	Diagram B	Diagram C
		
A 100 N force is applied to move a 15 kg object a horizontal distance of 5 meters at constant speed.	A 100 N force is applied at an angle of 30° to the horizontal to move a 15 kg object at a constant speed for a horizontal distance of 5 m.	An upward force is applied to lift a 15 kg object to a height of 5 meters at constant speed.

Diagram A Answer:

$$W = (100 \text{ N}) \times (5 \text{ m}) \times \cos(0 \text{ degrees}) = 500 \text{ J}$$

The force and the displacement are given in the problem statement. It is said (or shown or implied) that the force and the displacement are both to the right. Since F and d are in the same direction, the angle is 0 degrees.

Diagram B Answer:

$$W = (100 \text{ N}) \times (5 \text{ m}) \times \cos(30 \text{ degrees}) = 433 \text{ J}$$

The force and the displacement are given in the problem statement. It is said that the displacement is to the right. It shows that the force is 30 degrees above the horizontal. Thus, the angle between F and d is 30 degrees.

Diagram C Answer:

$$W = (147 \text{ N}) \times (5 \text{ m}) \times \cos(0 \text{ degrees}) = 735 \text{ J}$$

1.2.3 Energy

Energy is the capacity for doing work. You must have energy to accomplish work – it is like the "currency" for performing work. In the process of doing work, the object which is doing the work exchanges energy with the object upon which the work is done. When the work is done on the object it gains energy. The energy acquired by the objects upon which work is done is known as mechanical energy.

Mechanical energy is the energy which is possessed by an object due to its motion or due to its position. Mechanical energy can be either kinetic energy (energy of motion) or potential energy (stored energy of position). Objects have mechanical energy if they are in motion and/or if they are at some position relative to a zero potential energy position.

Mechanical energy = Kinetic energy + Potential energy

Potential Energy PE = mass of the object x acceleration of gravity x height of the object

$$PE = m \times g \times h$$

g represents the acceleration of gravity (9.8 m/s/s on Earth)

Kinetic Energy is depend on two variables: the mass and the speed

The following equation is used to represent the kinetic energy (KE) of an object.

$$KE = 1/2 \times m \times v^2$$

1.2.4 Power

Power is the rate at which work is done. It is the work/time ratio. Mathematically, it is computed using the following equation.

$$\text{Power} = \text{work} / \text{time} = (\text{force} \times \text{displacement}) / \text{time}$$

The standard metric unit of power is the Watt. As is implied by the equation for power, a unit of power is equivalent to a unit of work divided by a unit of time. Thus, a Watt is equivalent to a Joule/second. For historical reasons, the term ‘horsepower’ is occasionally used to describe the power delivered by a machine. One horsepower is equivalent to approximately 750 Watts.

Most machines are designed and built to do work on objects. All machines are typically described by a power rating. The power rating indicates the rate at which that machine can do work upon other objects. Thus, the power of a machine is the work/time ratio for that particular machine. The power rating relates to how rapidly the engine can accelerate the car.

1.3 Units of engineering quantities

Table 1.1 gives the most common units of engineering quantities that you will come across.

Figure 1.1 shows a representation of the linkage of basic mechanical units.

Table 1.1
Units of engineering quantities

	SI units	US common
Length (L)	Meter m	Foot ft
Time (T)	Second s	Second s
Mass (M)	Kilogram kg	Slug
Velocity (L/T)	m / s	ft/s
Acceleration (L/T ²)	m/ s ²	ft/ s ²
Force (M L/ T ²)	kg m / s ² = Newton N	slug ft/ s ² = pound lb
Work (M L ² / T ²)	N m = J joule	lb ft = ft lb
Energy (M L ² / T ²)	joule	ft lb
Power (M L ² / T ³)	J / s = W watts	ft lb/s

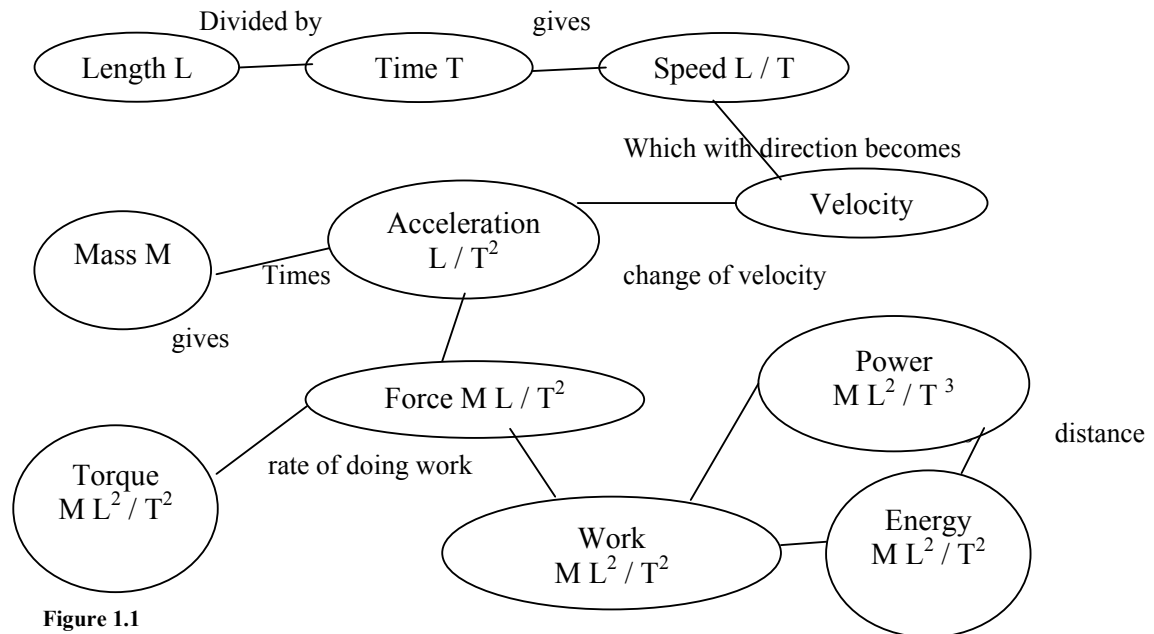


Figure 1.1
Basic Mechanical units

1.4 Friction

Friction is a force that is created whenever two surfaces move or try to move across each other. Friction always opposes the motion or attempted motion of one surface across another surface. Friction is dependant on the texture of both surfaces and the amount of contact force pushing the two surfaces together.

In a machine, friction reduces the ratio of output to input. An automobile, for instance, uses one-quarter of its energy on reducing friction. Yet it is also friction in the tires that allows the car to stay on the road, and friction in the clutch that makes it possible to drive at all. From matches to machines to molecular structures, friction is one of the most significant phenomena in the physical world.

There are advantages and disadvantages of friction. Since friction is a resistance force that slows down or prevents motion, it is necessary in many applications to prevent slipping or sliding. But it can also be a nuisance because it can hinder motion and cause the need for expending energy. A good compromise is necessary to get just enough friction.

Disadvantages of friction:

- makes movement difficult
- machine parts get overheated
- wastes energy
- any device that has moving parts can wear out rapidly due to friction. Lubrication is used not only to allow parts to move easier but also to prevent them from wearing out.

The force of friction is a force that resists motion when two objects are in contact. If we look at the surfaces (Figure 1.2) of all objects, there are tiny bumps and ridges. Those microscopic peaks and valleys catch on one another when two objects are moving past each other.

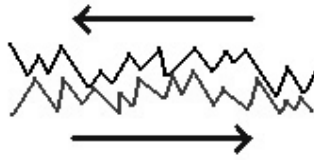


Figure 1.2
Typical surface

There are two types of friction

- Static
- Kinetic

If we try to slide two objects past each other, a small amount of force will result in no motion. The force of friction is greater than the applied force. This is static friction. (Figure 1.3) If we apply a little more force, the object 'breaks free' and slides, although we still need to apply force to keep the object sliding. This is kinetic friction (Figure 1.4). We need not apply quite as much force to keep the object sliding as we originally needed to break free from the static friction.

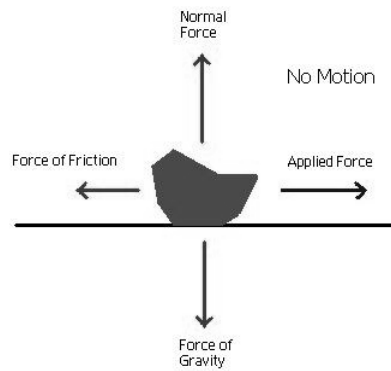


Figure 1.3
Static friction

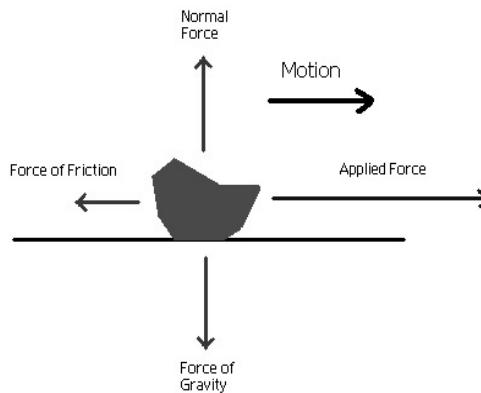


Figure 1.4
Kinetic friction

8 Mechanical Design Concepts for Non-Mechanical Engineers

Figure 1.5 shows the relationship between applied force and frictional force.

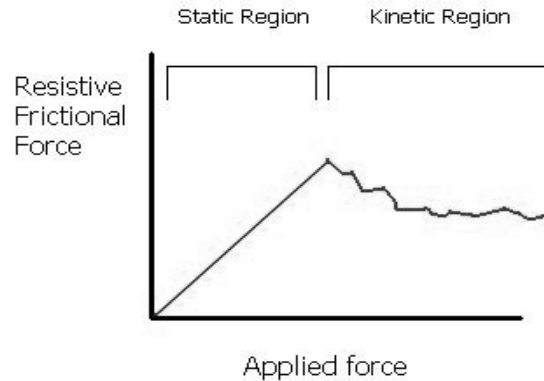


Figure 1.5
Relationship between applied and frictional force

Let's examine the relationship between these two forces and the applied force that creates them. Figure 1.5 shows static frictional force increasing to a maximum with the application of a force then dropping off sharply to a lesser value (kinetic friction) once the object starts moving. We can conclude a few points from this graph such as those listed below.

Static friction:

- Static friction f_s is proportional to F_n (surface normal force)
- It is independent of area
- It reaches a maximum value (which depends on the surface materials) in preventing motion between surfaces, and then drops to the lower value of sliding friction as the object begins to move.

Kinetic friction:

- Kinetic friction f_k is proportional to F_n
- It is also independent of area and speed of surfaces
- It is always less than static friction $f_k < f_s$ (meaning it's easier to push an object once it's moving)

Since friction is proportional to the force pressing the surfaces together (F_n)

$$f \propto F_n$$

which means that,

$$f / F_n = \text{constant}$$

This constant is known as coefficient of friction: μ (the Greek letter 'mu'). Thus we can write the equation as:

$$f = \mu \times F_n$$

Since static friction and kinetic friction are different, there is a μ for each one:

μ_s = coefficient of static friction

μ_k = coefficient of kinetic friction

Table 1.2 shows some common values of coefficients of kinetic and static friction.

$$\text{Static friction } f_s \leq \mu_s F_n$$

$$\text{Kinetic } f_k = \mu_k F_n$$

Note that static friction is expressed as an inequality in the above equation. This is because it varies from zero to a maximum. At the maximum value, and only at the maximum value (just before the object moves), the static frictional force is exactly equal to $\mu_s F_n$, or

$$f_{s \text{ max}} = \mu_s F_n$$

$$\text{Coefficient of friction } \mu = f / F_n$$

Table 1.2
Some common values of coefficients of kinetic and static friction

Surfaces	μ (static) μ_s	μ (kinetic) μ_k
Steel on steel	0.74	0.57
Glass on glass	0.94	0.40
Metal on Metal (lubricated)	0.15	0.06
Ice on ice	0.10	0.03
Teflon on Teflon	0.04	0.04
Tire on concrete	1.00	0.80
Tire on wet road	0.60	0.40
Tire on snow	0.30	0.20

These values are approximate.

1.5 Summary

Mechanical Engineering deals with mechanics of operation on different systems. The various functions that fall within the scope of this branch are designing, manufacturing and maintenance. For this purpose it uses laws of physics and applies them to analyze their performance.

Friction is a force which is created when two surfaces move across each other. It plays very important role in some situations like walking, writing, etc. where you could not do without the force of friction. In some cases friction is less required, so compromise is required.

