Chapter 1

ROCKET DYNAMICS

1.1 Introduction

In a broad sense, propulsion is the act of changing the motion of a body. Propulsion mechanisms provide forces which move bodies that are initially at rest, change a constant velocity motion, or overcome retarding forces when a body is propelled through a medium. There are two essential elements in any propulsive mechanism: the energy source and an energy conversion device to transpose the energy into the form most suitable for propulsion. In an automobile, for example, a chemical combustion process of fuel with air furnishes the energy input, which is then transformed in an engine into thermal energy of a gas and subsequently by transformation into the mechanical energy through a rotating shaft and wheels to imparting momentum to the vehicle.

1.2 Rocket

A rocket engine is the device or mechanism that converts the energy into suitable form and ejects stored matter to derive momentum. The working fluid or the ejected matter in rocket propulsion is called the propellant .

1.2.1 Classification of Rockets

Among many possible energy sources, four are considered to be useful in rocket propulsion: the chemical combustion reaction, nuclear reaction, captured radiation energy from an emitter such as the sun, and Jet, Rocket, Nuclear, Ion and Electric Propulsion electric energy which is stored or created in the vehicle. Accordingly, the various propulsion devices can be categorized into

1. Chemical propulsion
2. Nuclear energy propulsion
3. Solar energy propulsion and
4. Electric energy propulsion

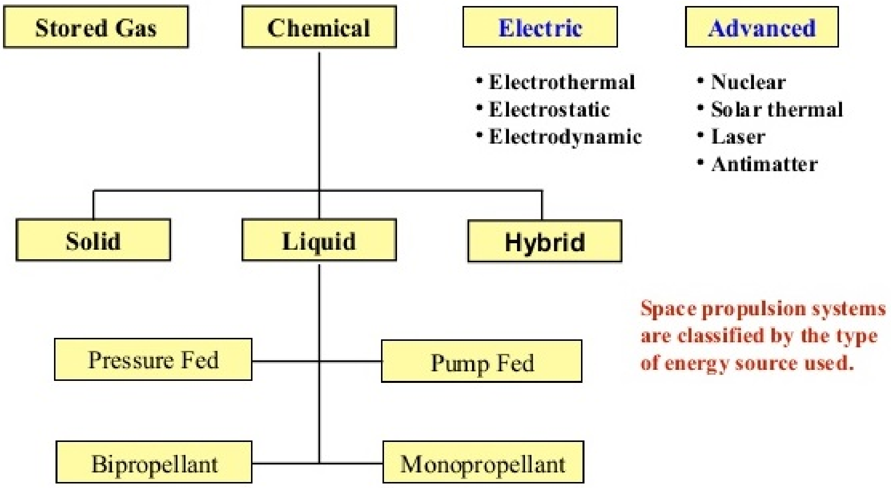

FIGURE 1.1: Classification of Rockets

1.2.1.1 Chemical Propulsion:

1. Solid propellant rockets

   It consist of a case or tube in which the propellants are packed. Modern rockets uses cases made of a thin and lightweight metal such as aluminum. Making the case from thin metal reduces the overall weight of the structure and increases flight performance. However, the heat from the burning propellants could easily melt through the metal. To prevent this, the inner walls of the case have to be insulated.

The upper end of the rocket is closed off and capped with a payload section or recovery parachutes. The lower end of the rocket is constricted with a narrow opening called the throat, above a larger cone-shaped structure, called the nozzle. By constricting the opening, the throat causes the combustion products to accelerate greatly as they race to the outside (second law). The nozzle aims the exhaust straight downward so that the rocket travels straight upward (third law).

To appreciate how the throat of the rocket accelerates the combustion products, turn on the water for a garden hose. Open the nozzle to the widest setting. Water slowly flows out. Next, reduce the opening of the nozzle. Water quickly shoots out in a long stream (second law) and the hose pushes back on you (third law). The propellant in solid rockets is packed inside the insulated case. It can be packed as a solid mass or it may have a hollow core. When packed as a solid mass, the propellant burns from the lower end to the upper end. Depending upon the size of the rocket, this could take a while.

With a hollow core, the propellants burn much more rapidly because the entire face of the core is ignited at one time. Rather than burning from one end to the other, the propellant burns from the core outward, Solid Propellant Rocket End-burning and hollow core rockets towards the case. The advantage of a hollow core is that the propellant mass burns faster, increasing thrust (second law). To make solid rockets even more powerful, the core doesn't have to be round. It can have other shapes that increase the surface area available for burning. The upper ends of the space shuttle SRBs had star-shaped cores. When ignited, the large surface area of the star points boosted liftoff thrust. In about one minute, however, the points burned off, and the thrust diminished somewhat. This was done on purpose because the space shuttle begins accelerating through the sound barrier. Passing through causes vibrations that are diminished by the temporary thrust reduction of the SRBs (second law).

2. Liquid propellant rockets

   They are an invention of the twentieth century. They are far more complex than solid rockets. Generally, a liquid rocket has two large tanks within its body. One tank contains a fuel, such as kerosene or liquid hydrogen. The other tank contains liquid oxygen. When the liquid rocket engine is fired, high-speed pumps force the propellants into a cylindrical or spherical combustion chamber. The fuel and oxidizer mix as they are sprayed into the chamber. There they ignite, creating huge quantities of combustion products that shoot through the throat and are focused downward by the nozzle.

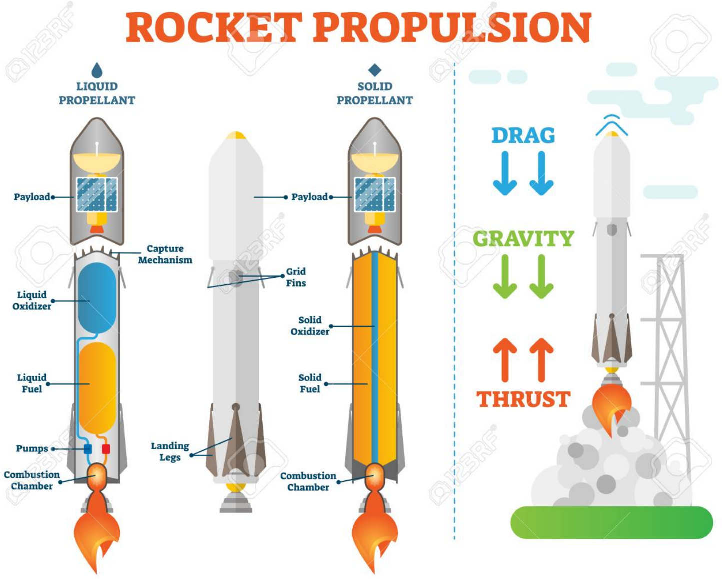

FIGURE 1.2: Classification of Chemical Rockets

1.2.1.2 Nuclear Thermal Propulsion(NTP):

NTP systems work by pumping a liquid propellant, most likely hydrogen, through a reactor core. Uranium atoms split apart inside the core and release heat through fission. This physical process heats up the propellant and converts it to a gas, which is expanded through a nozzle to produce thrust.

NTP rockets are more energy dense than chemical rockets and twice as efficient. Engineers measure this performance as specific impulse, which is the amount of thrust you can get from a specific amount of propellant. The specific impulse of a chemical rocket that combusts liquid hydrogen and liquid oxygen is 450 seconds, exactly half the propellant efficiency of the initial target for nuclear-powered rockets (900 seconds). This is because lighter gases are easier to accelerate. When chemical rockets are burned, they produce water vapor, a much heavier byproduct than the hydrogen that is used in a NTP system. This leads to greater efficiency and allows the rocket to travel farther on less fuel.

NTP systems won't be used on Earth. Instead, they'll be launched into space by chemical rockets before they are turned on. NTP systems are not designed to produce the amount of thrust needed to leave the Earth's surface.

NTP systems offer greater flexibility for deep space missions. They can reduce travel times to Mars by up to 25 percent and, more importantly, limit a flight crew's exposure to cosmic radiation. They can also enable broader launch windows that are not dependent on orbital alignments and allow astronauts to abort missions and return to Earth if necessary.

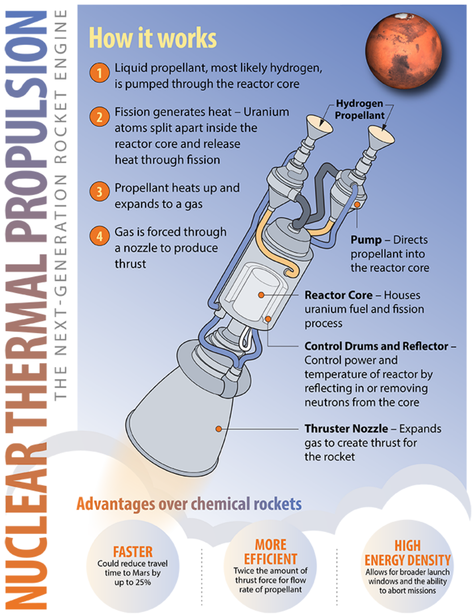

FIGURE 1.3: Nuclear Propulsion

1.2.1.3 Ion Thruster Propulsion:

An ion thruster or ion drive is a form of electric propulsion used for spacecraft propulsion. It creates thrust by accelerating ions using electricity. The positively charged ions migrate toward grids that contain thousands of very precisely aligned holes (apertures) at the aft end of the ion thruster. The first grid is the positively charged electrode (screen grid). A very high positive voltage is applied to the screen grid, but it is configured to force the discharge plasma to reside at a high voltage. As ions pass between the grids, they are accelerated toward a negatively charged electrode (the accelerator grid) to very high speeds (up to 90,000 mph).

The positively charged ions are accelerated out of the thruster as an ion beam, which produces thrust. The neutralizer, another hollow cathode, expels an equal amount of electrons to make the total charge of the exhaust beam neutral. Without a neutralizer, the spacecraft would build up a negative charge and eventually ions would be drawn back to the spacecraft, reducing thrust and causing spacecraft erosion.

Electrons produced by the discharge cathode are attracted to the dis- charge chamber walls, which are charged to a high positive potential by the voltage applied by the thruster's discharge power supply. Neutral propellant is injected into the discharge chamber, where the electrons bombard the propellant to produce positively charged ions and release more electrons.

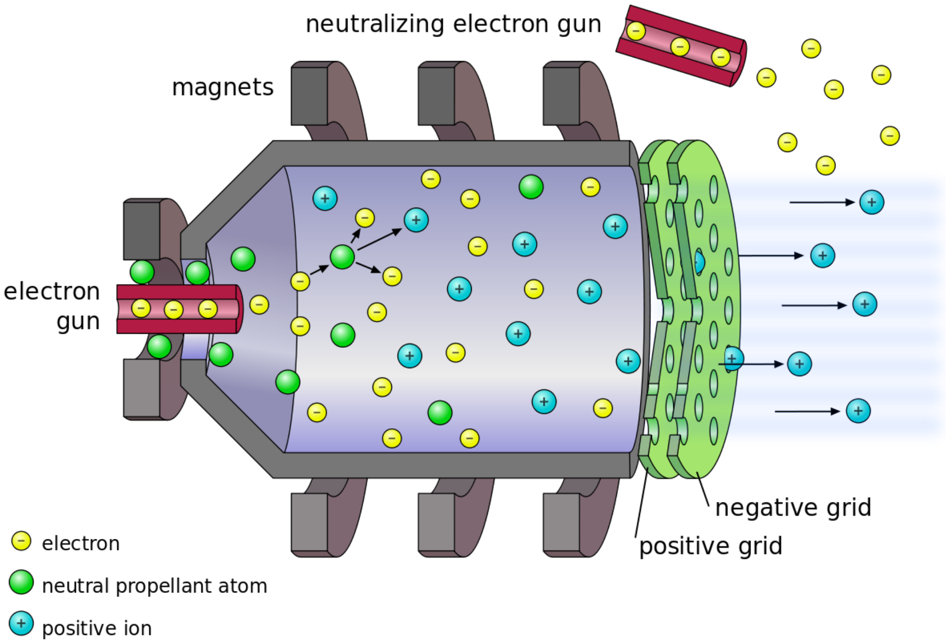

FIGURE 1.4: Ion Propulsion

1.3 Missile

Missile, a rocket-propelled weapon designed to deliver an explosive warhead with great accuracy at high speed. Missiles vary from small tactical weapons that are effective out to only a few hundred feet to much larger strategic weapons that have ranges of several thousand miles.

1.3.1 Classification of Missiles

Missiles are generally classified on the basis of their Type, Launch Mode, Range, Propulsion, Warhead and Guidance Systems. All missiles contain some form of guidance and control mechanism and are therefore often referred to as guided missiles. Launch vehicles are the rocket-powered systems that provide transportation from the earth's surface into the environment of space. A propeller-driven underwater missile is called a torpedo, and a guided missile powered along a low, level flight path by an air-breathing jet engine is called a cruise missile.

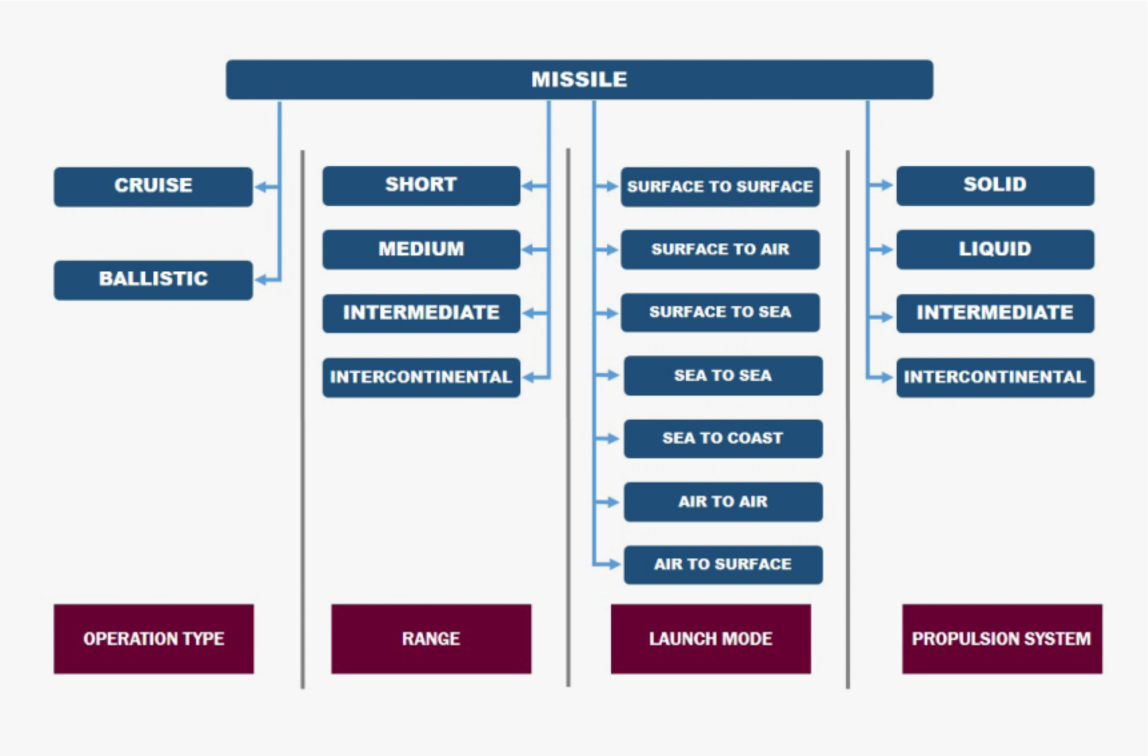

FIGURE 1.5: Classification of Missiles

1.3.1.1 On the Basis of Type:

1. Cruise Missile: A cruise missile is an unmanned self-propelled (till the time of impact) guided vehicle that sustains flight through aerodynamic lift for most of its flight path and whose primary mission is to place an ordnance or special payload on a target. They fly within the earth's atmosphere and use jet engine technology. These vehicles vary greatly in their speed and ability to penetrate defenses.Cruise missiles can be categorized by size,

speed (subsonic or supersonic), range and whether launched from land, air, surface ship or submarine.

Depending upon the speed such missiles are classified as:

(a) Subsonic cruise missile

(b) Supersonic cruise missile

(c) Hypersonic cruise missile

Subsonic cruise missile flies at a speed lesser than that of sound. It travels at a speed of around 0.8 Mach. The well- known subsonic missile is the American Tomahawk cruise missile. Some other examples are Harpoon of USA and Exocet of France.

Supersonic cruise missile travels at a speed of around 2-3 Mach i.e.; it travels a kilometer approximately in a second. The modular design of the missile and its capability of being launched at different orientations enable it to be integrated with a wide spectrum of platforms like warships, submarines, different types of aircraft, mobile autonomous launchers and silos. The combination of supersonic speed and warhead mass provides high kinetic energy ensuring tremendous lethal effect. BrahMos is the only known versatile supersonic cruise missile system which is in service.

Hypersonic cruise missile travels at a speed of more than 5 Mach. Many countries are working to develop hypersonic cruise missiles. BrahMos Aerospace is also in the process of developing a hypersonic cruise missile, BrahMos-II, which would fly at a speed greater than 5 Mach.

2. Ballistic Missile: A ballistic missile is a missile that has a ballistic trajectory over most of its flight path, regardless of whether or not it is a weapon-delivery vehicle. Ballistic missiles are categorized according to their range,maximum distance measured along the surface of earth's ellipsoid from the point of launch to the point of impact of the last element of their payload. The missile carry a huge payload. The carriage of a deadly warhead is justified by the distance the missile travels. Ballistic missiles can be launched from ships and land based facilities. For example, Prithvi I, Prithvi II, Agni I, Agni II and Dhanush ballistic missiles are currently operational in the Indian defense forces.

FIGURE 1.6: Missiles on the basis of its type

1.3.1.2 On the basis of Launch Mode:

1. Surface-to-Surface Missile: A surface-to-surface missile is a guided projectile launched from a hand-held, vehicle mounted, trailer mounted or fixed installation. It is often powered by a rocket motor or sometimes fired by an explosive charge since the launch platform is stationary.
2. Surface-to-Air Missile: A surface-to-air missile is designed for launch from the ground to destroy aerial targets like aircrafts, helicopters and even ballistic missiles. These missiles are generally called air defense systems as they defend any aerial attacks by the enemy.
3. Surface (Coast)-to-Sea Missile: A surface (coast)-to-sea missile is designed to be launched from land to ship in the sea as targets.
4. Air-to-Air Missile: An air-to-air missile is launched from an aircraft to destroy the enemy aircraft. The missile flies at a speed of 4Mach.
5. Air-to-Surface Missile: An air-to-surface missile is designed for launch from military aircraft and strikes ground targets on land, at sea or both. The missiles are basically guided via laser guidance, infrared guidance and optical guidance or via GPS signals. The type of guidance depends on the type of target.

6. Sea-to-Sea Missile: A sea-to-sea missile is designed for launch from one ship to another ship.
7. Sea-to-Surface (Coast) Missile: A sea-to-surface missile is designed for launch from ship to land based targets.
8. Anti-Tank Missile: An anti-tank missile is a guided missile primarily designed to hit and destroy heavily-armored tanks and other armored fighting vehicles. Anti-tank missiles could be launched from aircraft, helicopters, tanks and also from shoulder mounted launcher.

1.3.1.3 On the basis of Range:

This type of classification is based on maximum range achieved by the missiles. The basic classification is as follows:

1. Short Range Missile
2. Medium Range Missile
3. Intermediate Range Ballistic Missile
4. Intercontinental Ballistic Missile

1.3.1.4 On the basis of Propulsion:

1. Solid Propulsion: Solid fuel is used in solid propulsion. Generally, the fuel is aluminum powder. Solid propulsion has the advantage of being easily stored and can be handled in fuelled condition. It can reach very high speeds quickly. Its simplicity also makes it a good choice whenever large amount of thrust is needed.
2. Liquid Propulsion: The liquid propulsion technology uses liquid as fuel. The fuels are hydrocarbons. The storage of missile with liquid fuel is difficult and complex. In addition, preparation of missile takes considerable time. In liquid propulsion, propulsion can be controlled easily by restricting the fuel flow by using valves and it can also be controlled even under emergency conditions. Basically, liquid fuel gives high specific impulse as compared to solid fuel.

3. Hybrid Propulsion: There are two stages in hybrid propulsion - solid propulsion and liquid propulsion. This kind of propulsion compensates the disadvantages of both propulsion systems and has the combined advantages of the two propulsion systems.
4. Ramjet: A ramjet engine does not have any turbines unlike turbojet engines. It achieves compression of intake air just by the forward speed of the air vehicle. The fuel is injected and ignited. The expansion of hot gases after fuel injection and combustion accelerates the exhaust air to a velocity higher than that at the inlet and creates positive push. However, the air entering the engine should be at supersonic speeds. So, the aerial vehicle must be moving in supersonic speeds. Ramjet engines cannot propel an aerial vehicle from zero to supersonic speeds.
5. Scramjet: Scramjet is an acronym for Supersonic Combustion Ramjet. The difference between scramjet and ramjet is that the combustion takes place at supersonic air velocities through the engine. It is mechanically simple, but vastly more complex aerodynamically than a jet engine. Hydrogen is normally the fuel used.
6. Cryogenic: Cryogenic propellants are liquefied gases stored at very low temperatures, most frequently liquid hydrogen as the fuel and liquid oxygen as the oxidizer. Cryogenic propellants require special insulated containers and vents which allow gas to escape from the evaporating liquids. The liquid fuel and oxidizer are pumped from the storage tanks to an expansion chamber and injected into the combustion chamber where they are mixed and ignited by a flame or spark. The fuel expands as it burns and the hot exhaust gases are directed out of the nozzle to provide thrust.

1.3.1.5 On the basis of Warhead :

1. Conventional Warhead: A conventional warhead contains high energy explosives. It is filled with a chemical explosive and relies on the detonation of the explosive and the resulting metal casing fragmentation as kill mechanisms.
2. Strategic Warhead: In a strategic warhead, radio active materials are present and when triggered they exhibit huge radio activity that can wipe out even cities. They are generally designed for mass annihilation.

1.3.1.6 On the basis of Guidance Systems:

1. Wire Guidance: This system is broadly similar to radio command, but is less susceptible to electronic counter measures. The command signals are passed along a wire (or wires)dispensed from the missile after launch.

2. Command Guidance: Command guidance involves tracking the projectile from the launch site or platform and transmitting commands by radio, radar, or laser impulses or along thin wires or optical fibers. Tracking might be accomplished by radar or optical instruments from the launch site or by radar or television imagery relayed from the missile.

3. Terrain Comparison Guidance: Terrain Comparison (TERCOM) is used invariably by cruise missiles. The system uses sensitive altimeters to measure the profile of the ground directly below and checks the result against stored information.

4. Terrestrial Guidance: This system constantly measures star angles and compares them with the pre-programmed angles expected on the missile's intended trajectory. The guidance system directs the control system whenever an alteration to trajectory is required.

5. Inertial Guidance: This system is totally contained within the missile and is programmed prior to launch. Three accelerometers, mounted on a platform space-stabilized by gyros, measure accelerations along three mutually perpendicular axes; these accelerations are then integrated twice, the first integration giving velocity and the second giving position. The system then directs the control system to preserve the pre-programmed trajectory. This systems are used in the surface-to-surface missiles and in cruise missiles.

6. Beam Rider Guidance: The beam rider concept relies on an external ground or ship-based radar station that transmits a beam of radar energy towards the target. The surface radar tracks the target and also transmits a guidance beam that adjusts its angle as the target moves across the sky.

7. Laser Guidance: In laser guidance, a laser beam is focused on the target and the laser beam reflects off the target and gets scattered. The missile has a laser seeker that can detect even miniscule amount of radiation. The seeker provides the direction of the laser scatters to the guidance system.The missile is launched towards the target,the seeker looks out for the laser

reflections and the guidance system steers the missile towards the source of laser reflections that is ultimately the target.

8. RF and GPS Reference: RF (Radio Frequency) and GPS (Global Positioning System) are examples of technologies that are used in missile guidance systems. A missile uses GPS signal to determine the location of the target. Over the course of its flight, the weapon uses this information to send commands to control surfaces and adjusts its trajectory. In a RF reference, the missile uses RF waves to locate the target.

Differentiate between tactical and strategic missiles

Ans. A tactical missile is used for attacking or defending ground troops, nearby military or strategic installations, military aircraft, or war missiles. Strategic missiles with a range of 3000 km or more have been two- or three stage surface-to-surface rocket-propelled missiles. Early designs used liquid propellant rocket engines and some are still in service.

Guided missiles

When missiles are launched from an aircraft at a relatively high initial velocity, or when projectiles are given stability by spinning them on their axis, their accuracy of reaching a target is increased two- to ten-fold, compared to a simple fin-stabilized rocket launched from rest. These are called guided missiles. In guided air-to-air and surface-to-air rocket-propelled missiles the time of flight to a given target, usually called the time to target tt, is an important flight performance parameter.

1.4 Airframe components

There are many parts that make up a rocket. For design and analysis, engineers group parts which have the same function into systems. There are four major systems in a full scale rocket; the structural system, the payload system, the guidance system, and the propulsion system.

The structural system, or frame, is similar to the fuselage of an airplane. The frame is made from very strong but light weight materials, like titanium or aluminum, and usually employs long

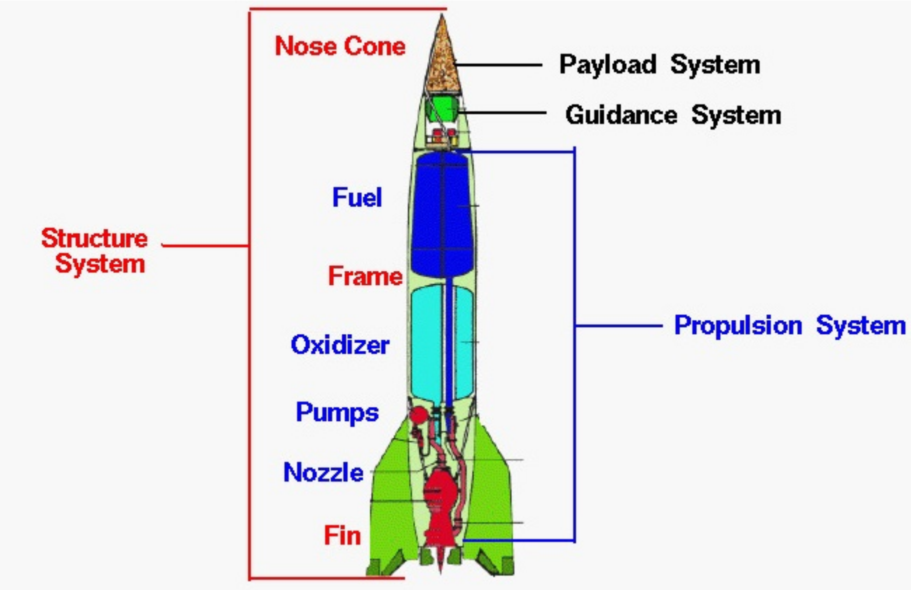

FIGURE 1.7: Airframe components of a Rocket

”stringers” which run from the top to the bottom which are connected to ”hoops” which run around around the circumference. The ”skin” is then attached to the stringers and hoops to form the basic shape of the rocket. The skin may be coated with a thermal protection system to keep out the heat of air friction during flight and to keep in the cold temperatures needed for certain fuels and oxidizers. Fins are attached to some rockets at the bottom of the frame to provide stability during the flight.

The payload system of a rocket depends on the rocket’s mission. Many countries developed guided ballistic missiles armed with nuclear warheads for payloads. The same rockets were modified to launch satellites with a wide range of missions; communications, weather monitoring, spying, planetary exploration, and observatories, like the Hubble Space Telescope. Special rockets were developed to launch people into earth orbit and onto the surface of the Moon.

The guidance system of a rocket may include very sophisticated sensors, on-board computers, radars, and communication equipment to maneuver the rocket in flight. Many different methods have been developed to control rockets in flight. The V2 guidance system included small vanes in the exhaust of the nozzle to deflect the thrust from the engine. Modern rockets typically rotate the nozzle to maneuver the rocket. The guidance system must also provide some level of stability so that the rocket does not tumble in flight.

Most of a full scale rocket is propulsion system. There are two main classes of propulsion systems, liquid rocket engines and solid rocket engines. The V2 used a liquid rocket engine consisting of fuel and oxidizer (propellant) tanks, pumps, a combustion chamber with nozzle, and the associated plumbing. The Space Shuttle, Delta II, and Titan III all use solid rocket strap-ons.

The various rocket parts described above have been grouped by function into structure, payload, guidance, and propulsion systems. There are other possible groupings. For the purpose of weight determination and flight performance, engineers often group the payload, structure, propulsion structure (nozzle, pumps, tanks, etc.), and guidance into a single empty weight parameter. The remaining propellant weight then becomes the only factor that changes with time when determining rocket performance.

1.5 Inertia and Non Inertia Reference frames:

A reference frame is specified by an ordered set of three mutually orthogonal, possibly time dependent, unit-length direction vectors. A reference frame has an associated center. A coordinate system specifies a mechanism for locating points within a reference frame. Velocity is a frame dependent quantity but acceleration is frame independent. If force is frame dependent, then Newton's law will be valid in all frames $\overrightarrow{F} = m * \overrightarrow{a}$

1.5.1 Types of Reference frames

1.5.1.1 Inertial Reference frame

A frame of reference in which isolated object(object that experience no real forces) is found to move with constant velocity is called as Inertial frame of reference. There can be infinite number of Inertial frames but relative velocity between them must be constant.

In most of the cases this reference frame is fixed to the ground because we want to find out what is the force respect to a ground fixed coordinate system. For example in this case of the rocket, we have to send the rocket out from the ground and we want to find out what is the force required to actually or what is the thrust required to actually accelerate the rocket away from the ground.

The force acting depends on the coordinate system, the choice of the coordinate system. For example, if you take this rocket, then suppose for an observer who is sitting inside the rocket, he throws a ball upwards, so when he does that, if force is required to throw the ball upwards and that force is different than if a observer who is sitting on the ground has to throw a ball at the same speed but considering the acceleration of the rocket. So, if you at the ball which is thrown by the observer sitting inside the rocket from a ground fixed coordinate system the ball has an acceleration imparted by the observer inside the rocket as well as the acceleration of the rocket itself.

1.5.1.2 Non-Inertial Reference frame

In practical applications we often encounter situations where we have to use a accelerating control volume. In the derivation of Reynolds transport theorem we have assumed that the that our coordinate system for defining the fluid velocity is fixed to the control volume. If the control volume is accelerating, it means that the reference frame is also accelerating and such a reference frame is known as a non-inertial frame of reference. There are many non-inertial (that is, accelerating) frames that one needs to consider, such as elevators, merry-go-rounds, and so on.

One such application is when we try to find using integral analysis the thrust acting on the rocket. While we try to do that, we actually put a control volume around the rocket and try to find the force but a rocket moves, it accelerates and the control volume attached to the rocket also have to accelerate. So, now we will see how to change our equations to accommodate this acceleration of the reference frame which is attached to the control volume. So, this is the case of an accelerating control volume.

1.6 Aerodynamic Forces on a Rocket

Aerodynamic forces are generated and act on a rocket as it flies through the air. Forces are vector quantities having both a magnitude and a direction. The single aerodynamic force is broken into two components: **the drag force** which is opposed to the direction of motion, and **the lift force** which acts perpendicular to the direction of motion. Aerodynamic forces are mechanical forces. They are generated by the interaction and contact of a solid body with a fluid, a liquid or a gas. Aerodynamic forces are not generated by a force field, in the sense of the gravitational field,or an electromagnetic field.

Aerodynamic forces are used differently on a rocket than on an airplane.

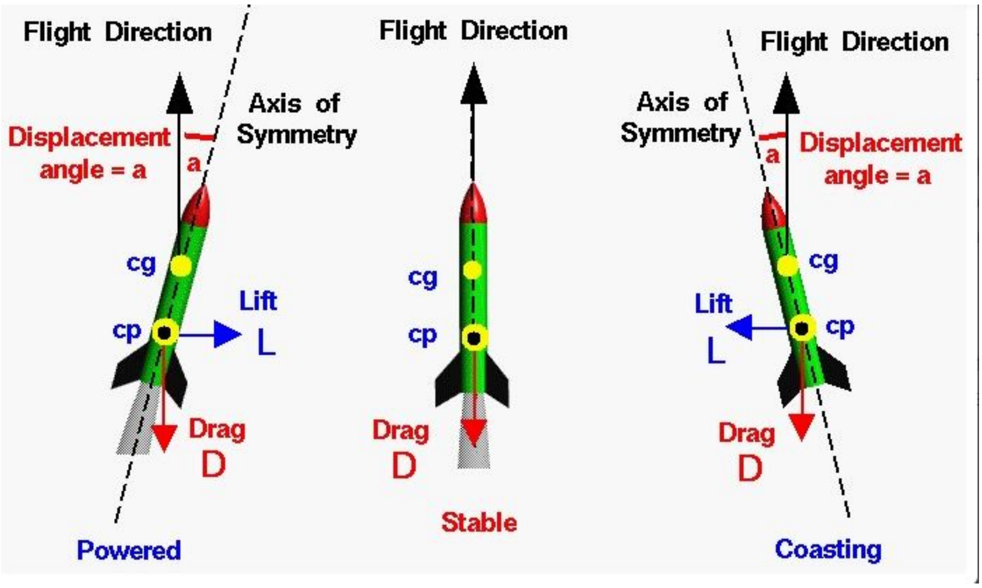

FIGURE 1.8: Aerodynamic forces of a Rocket

1. On an airplane, Lift is used to overcome the weight of the aircraft, but on a rocket, thrust is used in opposition to weight. Because the center of pressure is not normally located at the center of gravity of the rocket, aerodynamic forces can cause the rocket to rotate in flight.
2. The lift of a rocket is a side force used to stabilize and control the direction of flight. Lift occurs when a flow of gas is turned by a solid object. The flow is turned in one direction, and the lift is generated in the opposite direction, according to Newton's third law of action and reaction.
3. While most aircraft have a high lift to drag ratio, the drag of a rocket is usually much greater than the lift.

Two very important points are found on a rocket: center of gravity (CG) and center of pressure (CP). **Center of gravity** is the point on the z axis (center axis through the length of the rocket)

where the amount of mass on both sides of that point is equal. If you are balancing a body with uniform mass distribution, the center of gravity will be in the middle of the object.
Center of pressure is the point along the rocket z axis with the same amount of surface area on both sides. For an object with a simple mathematical shape, it can be found with a simple integral. Generally, it is difficult to calculate and can either be found experimentally—in a wind tunnel—or numerically.
Stability: It is important to know where the CG and CP are in absolute measures and relative to each other. The rocket will always rotate around the center of gravity during flight, and gravity act on that singular point. However, the drag and lift forces do act on the center of pressure, and this decide how stable the rocket is. Stability is usually judged by the stability margin (SM), where the distance between the center of gravity and center of pressure is divided by the diameter d of the rocket body. $SM =$
There are two ways to stabilize rockets: active and passive. Active stabilization is using rocket engines (like gimballing the main thrusters or using smaller engines called Vernier thrusters) to control the attitude of the rocket. Active controlling is expensive and complex, but on large rockets it is necessary to use it.

On smaller rockets, as the ones launched at Andøya Space Center for science, one usually does not need to control the rocket attitude after lift-off and the rocket is then stabilized passively using a controlled spin. The spin is usually induced by the fins by aerodynamic forces.

1.7 Rocket Performance parameters

1. Equivalent velocity $V_{eq} = V_e + (p_e - p_0) * \frac{A_e}{\dot{m}}$

2. Total Impulse: It is the thrust force F integrated over the burning time t.
   $I = F * \triangle t = I = \int F * \triangle t$
   $I = \int \dot{m} * V_{eq} * dt$
   Remember that $\dot{m}$ is the mass flow rate; it is the amount of exhaust mass per time that comes out of the rocket. Assuming the equivalent velocity remains constant with time, we can integrate the equation to get: $I = m * V_{eq}$