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Pivotal principles of Rocket Actuation and Propulsion

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I. Introduction:

Constructing the first-gen, "archaic" rocket.

It began as an experiment which gradually started solidifying, taking a firmer shape each time as the years passed by. The Chinese men first came up with the idea of the *gunpowder*, which then was composed of- charcoal dust, saltpetre (a naturally occurring nitrate) and sulphur. They utilized bamboo tubes which were filled with this mixture and attached it to an arrow(s). Tossing them into fires helped ignite the process through what we now know as a *spontaneous combustion*. The gunpowder-rich, bamboo tubes were able to propel themselves forward with the aid of the power being dissipated from the gas which was escaping the tube. This gave birth to the modern concept of *rocket propulsion*.

Preparatory to propulsion, comes actuation. The latter refers to all the mechanisms which help in the working of a machine, which in our frame of reference, is the rocket. The collective product results in the lift-off of the cylindrical projectile which pierces through the atmosphere, into the outer space. This forward motion is governed by *thrust* and can be further regulated through *thrust vectoring* or a *thrust vector control, TVC*.

Lift-off, a brief delineation.

Engines capable of generating enough thrust are the protagonists of our tale. A rocket consists of the following four, primary systems which are of paramount importance to the same;

1) The structural system consists of the body, the nose cone and the fins of the rocket. It provides the basic framework- the "skeleton" to the enormous trajectile.
2) The propulsion system utilizes the most amount of space. It includes the engine and the oxidizer, along with the fuel tank consisting of the rocket propellant.
3) The variable, payload system is mission-dependant. The versatility of the carrying capacity can range anywhere from a satellite to a human being.
4) Lastly, we have the guidance system. This poses as the *Central Processing Unit (CPU)* of the rocket. It is liable for the manoeuvring of the spaceship, manned and unmanned.

Rocket propulsion is based on Newton's third law of motion. It can be represented as;

action (A) = reaction (R)

The lift-off of a rocket takes place in an angle perpendicular or normal to the surface- the launch pad. To overcome fluid resistance ("drag") as well as the force of gravity, an opposing force will have to be exerted which can help countervail such resistances. This reaction force (R) is what we refer to as the *thrust*.

Rocket launch takes place in four stages;

1) Generation of thrust
2) A powered ascent
3) Staging
4) Cutting-off of the upper stage engine once the rocket enters its' orbital trail

The generation of enough thrust leads to the powered ascent of the craft. During this stage, the required amount of the fuel gets burned continuously leading to a reduction in the weight of the rocket. This leads to an impediment known as the *dead weight* which needs to be reduced in order to increase the resultant efficiency of the system.

So, what leads to the formation of dead weight and how is it overcome?

In a rocket, the propellants weigh the most in terms of mass. Once the mandatory amount of fuel is utilized and burned, the fuel chamber and the oxidizer become pretty nugatory. Thus, the extra "dead" weight has to be transferred to the payload so that it can channel this energy and engage itself to advance towards its' required orbit. The rocket stages which are done playing their part are discarded in order to avoid any additional expenses pertaining to the employment of energy. We refer to this process as *staging*, which can be further modified according to the need of the hour.

At different stages of the launch, the rocket stages that have become redundant keep falling away, thereby reducing the additional mass each time. The guidance system helps maintain the balance and trajectory throughout the entirety of this procedure.

A rocket's skin (often referred to as the *shell* of the rocket) is made from metallic elements, like aluminium (Al), titanium (Ti) and various other composites of carbon (C). These are light and possess strong, metallic properties. The skin also bears a *thermal coating* or *cushion* that helps protect the rocket from extreme temperatures generated due to aerodynamic drag, that is, the air friction.

The streamlined body of the rocket helps it pierce through the various layers of the atmosphere, starting with the lowest layer which also happens to be the thickest layer in the series. The Newtonian law of motion talks about every action force leading to an effectuation of an equal and opposite reaction force. The fuel (which can either be a liquid or a solid component) burns in the oxidizer by way of a combustion reaction. The mass, which is the by-product of this reaction, departs from the nozzle at high-speeds. These exhaust fumes then help the rocket to withdraw itself from the launch complex.

Gravity turn.

(or, a ***zero-lift*** *turn)*

Gravity turn helps a rocket to steer and enter into its' desired trajectory using the power of gravity. This provides the following advantages;

1) Installation of an orbit around the planet
2) Optimizing fuel usage
3) Reduction of aerodynamic stress on the launch vehicle

If the rocket kept advancing upwards without tilting even by the slightest amount, it would soon run out of fuel. The exhaust nozzle(s) can be swivelled, thus providing room for averting such contingencies.

Rocket fuel.

the boosters

Every fuel is paired up with an oxidizer which helps burn the former. Since space is devoid of an atmosphere, it is imperative for a rocket to carry a copious quantity of the oxidizer. As an example, we have aluminium. It is made use of as the fuel in most rockets. To help the metal burn, ammonium perchlorate (AP; NH_4ClO_4) is used as the oxidizer. Together, it is called the *ammonium perchlorate composite propellant*. This inorganic compound reacts with the aluminium through a *binder*, which are contained within a *casing*. Hot gases and water vapour retire from the nozzles resulting in a lift-off of the rocket. Solid fuels undergo rapid combustion due to which they are also short-lived.

This process of thermal decomposition can be represented as;

$3Al\ (s) + 3NH_4ClO_4\ (s) = Al_2O_3\ (s) + AlCl_3\ (s) + 3NO\ (g) + 6H_2O\ (g)$

the main engines

The main engines run with the help of liquid fuel, mainly liquid hydrogen and liquid oxygen, where the latter is the oxidizer. These two elements combine together to form water (H_2O). The intensity of the energy and steam released is exploited up to a great extent. Generally, liquid fuels are stored in a smaller tank as they do not take up a lot of surface area. On the other hand, gaseous fuels call for a bigger tank.

During lift-off, the boosters chiefly work with the help of solid fuel. Then, it is dropped off or *jettisoned* at the required altitude to reduce the mass of the rocket. Liquid fuel keeps the upward motion ongoing right after.

As we had discussed previously, for a successful flight, the cue is to be able to generate enough thrust. It can be calculated with the help of the following mathematical equation;

=> $\mathbf{F = \dot{m}V_e + A_e\,(p_e - p_0)}$

where,
F = thrust
$\dot{m}$ = mass flow rate
V = velocity
A = area
p = pressure

The amount of thrust produced is;
$\propto$ exit velocity of the exhaust (V)
$\propto$ mass flow rate through the engine ($\dot{m}$)
$\propto$ pressure at the nozzle exit (p)

These variables (V, $\dot{m}$ and p) are dependent on the structure of the nozzle, that is, the design. The smallest cross-sectional area of a nozzle is referred to as its' *throat*. Thus, we can further define the variables as;

A_e = the area ratio from the throat to the exit of the nozzle
p_e = exit pressure
p_0 = free steam pressure
V_e = exit velocity

Mass flow rate ($\dot{m}$)

The mass of a liquid substance with a well-defined density and velocity traversing through a unit cross-sectional is given by;
=> $\boldsymbol{\dot{m} = \rho \mathrm{VA}}$, where all the variables on the RHS are *continuous* and are *constants*

Classification of liquid propellants.
Liquid propellants can be sub-divided further into;
1) **Monopropellants**, also known as nitromethane, undergoes decomposition to give rise to oxygen (O_2) and fuel. The resultant mixture is a high-pressure, high-temperature mixture of a gas. Another widely known example of a monopropellant is ethylene oxide.
2) In a **bipropellant** system, the fuel (ammonia/aniline/hydrazine) and the oxidizer (fluorine/liquid oxygen/nitric acid) are not introduced into the thrust chamber at the same time. A self-igniting, fuel-oxidizer combination is referred to as a *hypergolic combination*.

- Hydrogen peroxide (H_2O_2) can be both used as a monopropellant and a bipropellant.
as a monopropellant
The decomposition of hydrogen peroxide when yielded with a befitting catalyzer can be used alone in a rocket as it produces considerable heat.
as a bipropellant
The surplus oxygen produced after decomposition can also be directed towards burning an additional fuel. This forms a bipropellant system.

The increment of the velocity of gas in a nozzle | a theory by Carl de Laval (1845-1913)
The speed of the jet leaving through the nozzle was known to be slightly above than the velocity of sound. The process of outflow states that, "the velocity of a compressible fluid at the exit, leaving a chamber at high pressure through a convergent nozzle, is equivalent to the velocity of sound (a sonic stream) *corresponding to the temperature prevailing there*".
Carl de Laval, an engineer from Sweden, discovered and proposed that if the velocity of the exiting fluid has to be increased beyond that of sound (a supersonic stream), then "the nozzle after converging to a minimum cross-sectional area has to be *expanded* to a *larger* cross-sectional area". This pathway leading to an area of divergence from an area of convergence has is currently being used as a structural manifestation in many jet engines and turbines.

The Mach number (M/Ma).
=> speed of a body : speed of sound
=> $\mathbf{M} = \boldsymbol{\frac{v}{c}}$
where,
v = speed/velocity of an object
c = speed/velocity of sound
I) For a subsonic flight, the Mach number is less than 1.0
II) For a transonic flight, the Mach number is equivalent to 1.0 (the speed of sound is equated to this speed) ($v \approx c$; where, v = speed of a source)
III) For a supersonic flight, the Mach number is greater than 1.0 ($v > c$)
IV) For a hypersonic flight, the Mach number is greater than 5.0

Shock waves, a propagating disturbance.
A shock wave progresses faster than the local speed of sound in a given, elastic medium. It carries energy and is characterized by an instantaneous change in the temperature, pressure and density of the medium. These changes are violent.
Shock waves are supersonic. Their speed increases with augmenting amplitude. The intensity of these waves are quick to dwindle as some of the energy is expended to heat the medium through which it is being transported. Shock waves emanate from concave corners.
Expansion waves.
The flow of an expansion wave around a convex corner produces a drop in pressure, which transposes from a field of higher value to a field of lower value.
In fluid mechanics, the flow pattern of the air particles encircling a projectile in flight exhibit both shock and expansion waves.

The sonic barrier.
The sonic barrier (or, the sound barrier) is an accretion in the aerodynamic drag and other encumbrances experienced by an aircraft when it approaches or nears the speed of sound. Surmounting this threshold produces a sonic boom.
A sonic boom is a sound affiliated to shock waves. Sonic booms generate colossal amounts of sound energy.

The Doppler shift (Christian Doppler | 1842)
The change in wave frequency during relative motion between the source of the wave (f_0) and the observer (f_a) is known as the Doppler effect. The apparent difference between f_0 and f_a gives the value of the frequency changed.

Solving difficulties in aerodynamics:

- how do we overcome the sonic barrier?

To overcome fluid resistance, the degree of propulsive force available for the aircraft should be great enough so as to allow the projectile to pass through the critical speed range. The transition range, that is, the spectrum connecting the subsonic and the supersonic speed ranges is relatively difficult to fly in than an airplane solely flying in the supersonic speed domain.

The possibility of powered flight | the Wright brothers
Aviation pioneers, Orville Wright and Wilbur Wright, first brought about the concept of powered flight which was assisted by a light engine with ample propulsive power. Ramjets (can work between Mach 3 and Mach 6) and rockets have been able to surmount the sonic barrier, but there are four downsides associated with such level flights;
I) They are uneconomical
II) They consume a lot of fuel
III) Their period of flight is ephemeral, and
IV) Gas turbines and afterburners (combustion components used to increase thrust with the aid of additional fuel) might have to be used withal

Subjugating the complications posed above might provide a plausible solution to truncate the effects wielded by the sonic wall and other undesirable resistances which might fall in the way of flight.

Discussion:
A note on fuel storage (cryogenic propellants or "*cryogens*") and usage.

Liquid hydrogen (LH_2) is known to be the second coldest liquid on Earth, with a temperature of -253 °C (-423 °F). The oxidizer it is paired up with is LO_2 or LOX, which has a temperature of -183 °C (-297 °F). The combustion takes place at a temperature of 3000 K, with the reactants being water molecules, which possess a temperature of 3,588.7 K. These numerical values are higher than the melting point of iron even! Rocket fuels are more combustible than jet fuels as they have to undergo quicker ignition. The expeditious change in temperature leads to an expansion of N_2 and water vapour, which eventually escapes, resulting in a lift-off.

Prior to usage, the propellants are stored in tanks. They are stored under pressure with minimized sloshing and vortexing. The propellants are loaded in to the combustion chamber through pipes, turbopumps and valves when the time arises. The IPRC, which is a government-owned company, helps ISRO with affairs pertaining to storable liquid propellants which are used in launch vehicles, satellite programmes and various other Indian space missions.

RP-1 is used by many orbital rockets to power their first-stage boosters. It is a dense, highly-refined form of kerosene. The fuel's propensity to be stored at room temperature, makes it the most favoured selection for many launch providers.

References:

[1]. Culler, G. J., & Fried, B. D. (1957). Universal gravity turn trajectories. Journal of Applied Physics, 28(6), 672–676. https://doi.org/10.1063/1.1722828
[2]. Yan, X., Xu, R., Nie, H., Yan, Q., Liu, J., & Sun, Y. (2023). Mechanism of Interaction between Ammonium Perchlorate and Aluminum. The Journal of Physical Chemistry A, 127(31), 6532–6540. https://doi.org/10.1021/acs.jpca.3c03935
[3]. NASA Glenn Research Center. (2023a, November 20). Rocket Thrust Equation | Glenn Research Center | NASA. Glenn Research Center | NASA. https://www1.grc.nasa.gov/beginners-guide-to-aeronautics/rocket-thrust-equation/
[4]. Sun, H., Hu, C., Tian, Z., & Deng, Z. (2016). Experimental investigation on mass flow rate measurements and feeding characteristics of powder at high pressure. Applied Thermal Engineering, 102, 30–37. https://doi.org/10.1016/j.applthermaleng.2016.03.142
[5]. Von Kármán, T. (2004). Aerodynamics: Selected Topics in the Light of Their Historical Development. Courier Corporation. ISBN 0-486-43485-0
[6]. The Editors of Encyclopaedia Britannica. (1998, July 20). Shock wave | Definition & Facts. Encyclopedia Britannica. https://www.britannica.com/science/shock-wave
[7]. Elert, G. (2023). Shock waves. The Physics Hypertextbook. https://physics.info/shock/
[8]. Wessels, W. (2023, August 1). How cryogenic fuels are kept cold before and during a rocket launch. Headed for Space. https://headedforspace.com/how-cryogenic-fuels-are-kept-cold/
[9]. ISRO Propulsion Complex, Mahendragiri. (n.d.). https://www.iprc.gov.in/