**Introduction to Aerospace Propulsion**

**By**

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**Lecture – 1**

**Prof. Bhaskar Roy:**

This is a course on introduction to Aerospace Propulsion. This course is intended for the junior years of the Undergraduate Program in Aerospace Engineering and this course introduces the various issues in fundamental engineering related to Aerospace Propulsion. The course will be taken by two of us. I am Prof. Bhaskar Roy from the dept. Of Aerospace Engineering, IIT Bombay. The course will be taken by Prof.A.M.Pradeep who is also from Aerospace Engineering, IIT Bombay and throughout this course we will be sharing various lecture modules presented through this programme. It actually involves lot of topics. We will be presenting these topics to you in various lecture formats and an idea of various lecture formats is given.

We will start off with Introduction to Propulsion which I(BR) will be taking. We will start off this with certain amount of history and the development of science what we call propulsion. When it started it was not called propulsion, but today we call it propulsion. So how whole science of making human beings fly developed is some of the things we will first try to look at in the history of Propulsion. Then how the concept of how jet engines came about and the various formats of the jet engines that we have today were not there when jet engines first appeared. We will have a look at the various forms of jet engines developed in the last 50 years and later on we will get into the science & technology of those developed engines.

**Prof. Pradeep:**

I along with Prof. Bhaskar Roy will be taking up this course on Introduction to Aerospace Propulsion. I would be covering some aspects of this propulsion course which I shall explain in next few minutes. We will start with the basic concepts of Thermodynamics Aerospace propulsion Devices. We shall start with the basic concepts of thermodynamics and why thermodynamics is the important part of Propulsion. Then some of the other important aspects like definition of System-Boundary, Surroundings and how do you define certain Thermodynamic System which are very important for analysing Propulsion Systems. We will define various equilibrium states and the State Co-ordinates and its parameters, the intensive and extensive parameters. Subsequently we are going to look at Energy Interactions and different types of energy interactions like work and heat interactions and as well as quasi static as well as Reversible Process followed by Non-Reversible and Ir-Reversible Processes. This is where we are going to start with Thermodynamic Principles and we will continue with defining the laws of thermodynamics which also plays an important role in analysing thermodynamic systems.

We will start with the Zeroeth Law of Thermodynamics which is the governing principle for defining the Temperature Scale as we shall see later on. Subsequently we shall look about the First law of Thermodynamics and its significance which is the Conservation of Energy. The terminology we shall come across several times throughout this course is Internal Energy which is the outcome of the 1st Law of Thermodynamics. After this we shall 2nd Law of Thermodynamics and a very important property which we come across as an outcome of this 2nd law is the Entropy and the Absolute Temperature Scale. Followed by this we shall look about the 3rd Law of Thermodynamics and Absolute Entropy. The thermodynamics of simple equilibrium, simple compressible Systems, the State Postulates and the fundamental Principles associated with that will be covered. The thermodynamic potentials and the Jacobian and the Legender Transformations which lead to the Maxwell’s Equations will be covered subsequently to the definition of thermodynamic systems. The derivation of thermodynamic Properties which are followed by the Maxwell’s Law will be taken up. In terms of application of Thermodynamics we will be looking at closed and open systems, Polytropic processes and Cyclic processes. In Cyclic Processes we are going to talk about different thermodynamic systems, basically Power Cycles, gas and Vapour power cycles. We shall talk about various gas and power cycles which shall talk about the fundamental power cycles that are used in the thermodynamics systems. Further we shall discuss about the Mixture of gasses and vapours and a little bit of details about 1-D Compressible Flow, Isentropic Flow, Flow with Friction and Heat transfer, Normal Shock flows. These are the various topics that are required for understanding the various Propulsion Systems.

Prof. Roy is also going to discuss about some of the cycles in detail which we had seen earlier like the Otto Cycle which is the basic Cycle required for the Spark Ignition Engine, the different IC Engines which are used for Aircraft Applications. We shall also be discussing about the Reciprocating Engine Performance, Supercharging and the Propeller Speed Control mechanism and Gear Box. Propeller Fundamentals and Blade theory will also be covered by Prof. Roy. Prof. Pradeep, I will be taking up the Cycle Analysis for Propulsion Systems, the ideal Cycle analysis for Propulsion Systems basically the Joule’s and the Brayton’s Cycle which are the basic cycles of different Air Breathing Aircraft Engines. Introduction to Missiles & Rockets will be taken up by Prof Roy. He shall be talking about Ramjets and Pulsejets, fundamental principles and the working of Rockets and missiles and the various Space Propulsive Devices and their Operating Principles.

**Text Books :**

1. Engineering Thermodynamics by P.K.Nag, Tata McGraw Hill.
2. Advanced Classical Thermodynamics by Emmanuel G, AIAA Ed. Series.
3. Mechanics and thermodynamics of Propulsion by Hill Philip, Peterson Carl.
4. Aircraft Propulsion by Bhaskar Roy
5. Elements of Propulsion- Gas Turbines and Rockets, J.D.Mattingly, AIAA Education Series.

More Reference Materials will be prescribed as the course progresses.

**Prof. Bhaskar Roy:**

Basic sciences involved in the field of propulsion are :

1. **Laws Of motion:** are associated with the motion of Aircraft which is the important thing in this course
2. **Laws of Thermodynamics:** the creation of Motion and the propulsion systems are based conceptually on the laws of thermodynamics. Thermodynamics is the matrix on which the entire field of Propulsion is Concentrated on. So we need to know a lot about thermodynamics which will be covered by Prof. Pradeep.
3. **Principles and theories of Aerodynamics:** Prof Pradeep will be covering the Aerodynamics. We need to know Aerodynamics because a lot of Proulsion we deal in this course is based on Aerodynamics. Various Aerodynamics Laws, Principles & Mathematics need to be known. Many of the components of Propulsion or Propulsive Devices works on the principles of Aerodynamics and many of them are called Aerodynamics Machines. So many of the propulsive devices are known as Aero-Thermodynamics Devices. So we need to know both these sciences very well.
4. **Mechanical Sciences:** Deals with the mechanical Issues and a lot of Mechanical engineering in making propulsive devices and engines which basically are Mechanical Entities.
5. **Material Sciences:** Issues related to Material and Metallurgical Sciences are dealt here. The propulsive devices use the Material Sciences of the highest order.
6. **Control Theory:** Most of the devices of Aircraft Propulsion and Rocket Propulsion need to be controlled. These theories are extremely involved and they are the sciences by themselves. Some of the issues of Control of the propulsive devices will be dealt here. These propulsive devices need to be embedded with the modern control theories and control systems.

**MOTION:**

The propulsive devices that are created are trying to impart a continuous motion to the aircraft or spacecraft and not just a motion for a few seconds. Its continuous motion that is required, so some fundamental sciences are required to apply to these Propulsive Devices which govern the motion of various bodies. Newton’s laws of Motion codified various concepts of creating continuous motion and these motions are what we are concerned about in this course. Before the Newton’s Laws of Motions came into being, the concept of creating motion through various kind of understanding of motion was actually applied. For example: paddling the oars to make the boats move in water uses instinctive understanding of basic principles without the application of the laws of motion. The question of understanding the motion has been there for more than thousands of years and Newton codified those laws in the form of Physics or Mathematical Laws and making it easy for us to create Propulsive devices using the sciences and laws.

**TYPES OF MOTIONS:**

**Perpetual Motion:** It is not physically possible but it has been possible because of the various laws of Physics and Mathematics that has existed and they have proved that it’s not really possible to create Perpetual Devices. We have to have devices that create motion on continuous basis. A motion cannot be sustained on a continuous basis but a device has to be created that on a continuous basis of producing perpetual motion. In our case it deals with the creation of Perpetual motion. And this continuous production of force is what is necessary we have to provide through the propulsive devices. This course deals with whether a continuous force can be provided for continuous flying motion.

Some of the earlier methods that used to provide continuous forces for providing continuous motion started some 2000 years back.

1. One of the devices that were developed was **Aeolepile** designed by Hero in 2nd century BC. He demonstrated a particular device in which if steam is put in and allow the steam to come out through Jets in Opposite Direction, then continuous motion can be created of a ball. This ball can be held on together on the both sides which can provide a rolling motion to the ball. This was called Aeolepile. About 1800 years after this, William Avrey designed this Ball which is shown in the picture on the right side. During the time of Hero, there was no Newton’s Law to develop this idea. Hero developed this Aeolepile based on his instinctive understanding.
2. Around 13th Century, the Chinese Scholar Wan Hu decided to try and create a Flying Motion. Since China is very good in making **Gun Powder and Fireworks**, they had the concept of making small rockets through the Fireworks could be made to fly. Wan Hu as a scholar thought was that if number of rockets were put together and fired them up together, then the object could be made to fly. He made a chair which consisted of number of rockets attached to the under of the chair and fired them up together so that a vertical flying motion was produced. It was one of the first attempts to make human being go up in the air in the 13th century. But we do not know if that story is true because the picture shown is an artist’s drawing.
3. The next invention was from Leonardo Da Vinci, who is regarded as the genius of the millennium. Around 16th century he created what is now known as a **Chimney Jack**, which the hot air rising up from the chimney creates a motion of the turbine and this rotating turbine was used to drive number of elements like Gear Box, Belt and Pulley Drive and other motions. He used the hot gas of a chimney to make a Turbine. This was one of the first methods developed conceptually to make a turbine through the hot gas or hot air. Subsequently around that Wind Turbines were being created around the world which used the natural air to rotate the Turbine. However, the most important contribution of Leonardo Da vinci was the **Ornithopter** which is a machine that actually could make human beings fly. His idea was to create a small platform in which the human being can sit or lie down and it would have something like a Helicopter which will have a Vertical Motion similar to a Screw Motion and the whole device would rise up in the air using the Screw Motion of the air. This was his concept of ornithopter which he never made but was only conceptualised by him. Da Vinci also created the **Flapping Wing concept** which is actually a copy of the motion of Birds Flying. Da Vinci thought if we could imitate the Mechanical Motion of the Bird Flying then human beings could also fly like birds. He noticed as an avid scientist and as an engineer that flapping wing contributes to the flying motion of the birds. So he created a small conceptual machine in which he thought could have flapping wings which if could be flapped could aid the motion of this craft. The Picture shown represents Da Vinci’s Ornithopter. Whether the machine was made is not sure. As a concept nothing was wrong with it and today lot of people talk about the flapping wing concept as one of the modern aids of making a new aircraft or a small aircraft.
4. The problem was not just making an aircraft but also powering the aircraft. In order to power an aircraft, it is necessary to have Engines. When we talk about Propulsive Devices, we are talking about having Engines embedded inside it. This engine works on the principle of thermodynamics as we have seen, but Mechanical Sciences also come in the process of propulsive devices involve number of elements. Nearly 400 years back, Giovanni Branca came up with the idea of a **Jet Turbine**. Those days creating Steam was a known thing. So if we boil a large beaker and create Steam and allow the Steam to come out like a Jet impinging upon a turbine which is held on a vertical shaft to create a Rotary Motion. This Rotary Motion can be transferred through the Gears to the Shaft. This Shaft can be used to run the Propeller. The entire device is geared towards producing a Rotary Motion which is connected to a Propeller to run the propeller. It is then this propeller which produces the power to the aircraft to fly through the air. This was the concept of Jet Turbine. At this particular time the people were more bothered about creating an engine in which the propeller could be powered and supplied with continuous power thereby allowing the propeller to produce continuous Propulsive Force which would aid the aircraft to fly on a continuous basis. This was one of the 1st devices that were able to produce continuous motion.
5. Then came the Newton’s concept **Steam Wagon** which is shown in the picture. His concept was if you just create a Steam jet out of a large Beaker which is heated out from the bottom by means of some heating device. If the steam that comes out is made to come out of a Nozzle like part, then the Steam jet would aid the process of movement of wagon. This was Newton’s Steam Wagon. This was just a sketch and was never made. This would actually never work because the amount of force required moving the wagon would have been impossible to create through such Steam Wagon. However as a sketch and as a concept it provided some ideas to the people who came down the line. We will be talking about the Newton’s Law of Motion in a few minutes from now.
6. Then the ideas of creating Steam and using the Steam to create a Continuous Motion was followed up by Barber and he created **Steam Driven Compressor Turbine**. This is the precursor to what we call Jet Propulsion today. He created this model about 200 years back as a whole in the backyard using a Chain pulley System. This was one of the 1st contraption in which engineering was used along with the concept of Steam Force which is used to create a Continuous Power generating unit.

**NEWTONS LAWS OF MOTION:**

These laws of motions govern any motion that occurs on earth like the motion of an aircraft or the motion of an automobile. They have to conform to these laws of motion and when these crafts are created they are made to conform to these laws of motion.

**NEWTON’S 1ST LAW:**

It states that “an object at rest will remain at rest unless acted upon by an external force. An object in continuous motion with the same speed and in the same direction unless acted upon by an external force”. This law is often called as the **Law of Inertia**.

This means that the body maintains the state of Inertia which could be the State of Rest or the State of Motion and it will continue in the state of rest or motion unless acted upon by some external force. This external force needs to be applied. This external force is very essential to aid the continuous motion of an aircraft. If continuous source of Power and force is not available then continuous motion is not possible either in air or anywhere else. This law is established within the Newtonian Frame of Reference which means that we are talking about the Newtonian Bodies and the motion we are talking about are Newtonian Motion. We have to understand from the point of view that some of the concepts here may not be exactly accurate if you bring in the modern Theory of Relativity. In Theory of Relativity the State of Rest and the State of Motion are defined slightly differently. So we are entirely concerned with the Newtonian Motion only and not the Theory of Relativity in this entire Lecture Series. Even for a Spacecraft, we will not be talking about the motion of a body using Theory of Relativity as a law of Physics. We will always be in the Newtonian Frame of Reference.

**NEWTON’S 2ND LAW:**

It states that “acceleration is produced when the force acts on a mass. The greater the mass of the object being accelerated the greater the amount of Force needed to accelerate the object”.

Creation of the motion is itself a kind of acceleration. When you are starting from a state of rest, you need some force and that itself is a first acceleration that you need to produce and it is codified simply as:

**F = M\*A**

where,

M- Rest mass(definition of Rest mass is different from Newtonian Mechanics to the Relativity theory)

So this mass to be accelerated needs a force and this is what the 2nd law motion states. Our work in Propulsion is to create this Force such that the motion can be created.

**NEWTON’S 3RD LAW:**

It states that “for every action there is an equal and opposite re-action”.

This law is very well known of all the laws and this is the important law on which the propulsive system is based on. This law tells that if you create an action then there is bound to be an equal and opposite re-action. As the diagram illustrates, if an action is created to push a body then some amount of material is ejected from the rear which the diagram illustrates. The act of releasing the material from the rear is the Action and the reaction is the force that propels the body forward. This is the concept on which most of the Aircraft and the spacecraft is based on. This action of releasing some material from the rear of the body which we want to move is the 1st principle on which the propulsive devices are created on. Newton’s 3rd law serves as one of the basis on which the propulsive devices are created. This was developed conceptually long back.

**For example**:

Shown in the picture, if you fill a up balloon and then hold the balloon in one hand and take your hand off and release the compressed air or pressured air from within the balloon to suddenly come out through the open lip, then it will create a nozzle as we saw in the illustration of the 3rd law. This nozzle effect will immediately create a Re-action. So the Action created by the release of air from inside through the open lip creates a force and that Re-action makes the balloon move forward. If you do this experiment by yourselves in a room, you will find that the balloon is moving in a Zigzag motion. This is not because anything has gone wrong with the balloon or the release of the balloon. The point is the balloon is always moving as a re-action to the action instantaneously through that lip. So the instantaneous Re-action direction and the magnitude creates the instantaneous motion of the balloon. So the Zigzag motion you see is the correct Motion based on the instantaneous vector of the action that is created. Re-action always occurs opposite to that vector.

This is shown in the lower diagram in the Aircraft example. If you are flying an aircraft and if you create an Action which throws something towards the back and this something we shall see more and more is actually the air in which the aircraft is supposed to be flying. If you create an action of throwing the Air actually backwards then the aircraft experiences the Re-action which is the motion forward. Our work in this course is to see how this action can be created through various devices on a Continuous basis in a Controlled Manner, so that in a controlled manner we have the reaction and motion of the aircraft. We cannot allow the aircraft to move in a Zigzag manner as we see in the balloon. We have to have a **continuous, controlled, smooth motion** of the aircraft and this smooth motion of the aircraft needs to be done in a controlled manner. This controlled Action and Re-action needs to be created through the Propulsive Devices and there is a question of integration of these propulsive devices with the aircraft. We shall be talking about more and more issues relating to this as we enter into the subject matter.

**NEWTON’S 1ST LAW:**

Let’s get into the Newton’s 1st law in detail because that is what is going to create bedrock for our Subject.

It states that, “if the vector sum of all forces acting on the object is zero then the velocity of the object is constant”. This means that if the object is in a state of rest it will be in its state of rest and if the object is in its state of motion then it will remain in its state of motion without experiencing any change in its motion. There will be **no acceleration, no change in velocity and no change in direction**. For changing any one of the three mentioned previously, you would need to apply force and this force will need to be applied in a certain direction. So the Vector Sum of all the forces is what we need to have our eyes on, so that the motion can be created in a particular direction giving it a particular magnitude.

So creation of Motion is the 1st thing in Newton’s law and giving it a direction is the next thing. We need to keep our eyes open on both the issues that is creating the motion, magnitude of the force we apply and the direction in which the force is applied because the Re-action will be based on both the magnitude and the direction of the action that is created. Reaction will be opposite to that magnitude and direction.

**NEWTON’S 2ND LAW:**

The second law states that “the net force on a body is equal to the time rate of change of its linear momentum M in a specified reference of frame for the inertial motion under interest”.

The second law is mathematically codified as :

For a constant mass system we get,

where,

M- Linear Momentum in a particular direction.

m – Rest mass

V- Instantaneous velocity

The 3rd equation above constitutes what we call as Force is the product of mass (m) and acceleration (derivative term) that was written down earlier. This signifies that for moving a certain body of mass (m), a certain amount of acceleration is to be given which produces a Linear Momentum change thereby creating the Force of Action and the Re-action is the motion of the aircraft forward.

Any mass that is gained or lost by the system will cause a change in momentum. That is not because of the external force. A different equation is necessary for **Variable-Mass Systems.** This is the issue one has to talk about. The mass that we considered earlier was a fixed mass. If we have a Variable Mass System (eg.) : Spacecraft, when the mass stored in the spacecraft is used and the mass changes with respect to time. So finally the mass flow will be different for a variable mass system and the equation of Newton’s Law will also be different for a Variable Mass System. Most of the time we will be dealing with constant mass system, but if variable mass system is used then necessary equations are to be used.

Consistent with the Law I, the time derivative of the momentum is non-zero when the momentum changes direction, even if there is no change in the magnitude. This motion is associated with the Circular Motion. This happens because the Instantaneous Velocity of the motion is always Constant, but it is continuously changes its direction. This direction change requires a continuous application of an External Force. This is what is done when an aircraft or a Spacecraft is taken a turn on its flight which may be either circular or non-circular. But the forces are to be applied to bring this change in Direction. The propulsive devices are needed to bring a change in the direction of action, so that the reaction force makes the craft to change its direction. This implies the **Conservation of Momentum.** When the net force on the body is zero, the momentum of the body is constant (zero or non-zero). The Net force is therefore equal to the Rate of Change of the Momentum assuming there is no loss of energy anywhere. This is the fundamental principle on which the action- reaction works and this is what is required when we create the propulsive devices.

**Concept of Propulsive Forces of Flying Vehicles:**

Newton’s 2nd Law is the conceptual basis of the Propulsive Forces of all Flying Vehicles. Newton’s 2nd law is the law that is activated more inside the Propulsive Device to create all the motions and the physics involved in creating the propulsive force. At very high speeds, the concept that the momentum is the product of Rest Mass and Velocity is not accurate because we are talking about the motion of object around the speed of light according to the theory of Relativity. These motions are not considered for the propulsive devices creation. We will be dealing with the propulsive devices that depends on the Newton’s Laws, Newtonian Fluid and the Newton’s motion.

**Impulse:**

Impulse is the corollary of the force. It is defined as the force that acts over an interval of a small time dt and is given by,

This type of Impulsive force makes the Rockets, missiles and Space Vehicles move through the Space.

**NEWTON’S 3RD LAW:**

It states that “all forces are interactions between different bodies and thus there is no such thing as a unidirectional force or a force that acts on only one body”.

The law states that every force has a Counter Force. The reaction force is very much important because it is the force that makes the craft move. If a body A exerts a force on body B, body B simultaneously exerts a force of the same magnitude on body A then both the forces will be acting on the same line. This represents the action-reaction concept of Newton’s 3rd Law.

**Next lecture**: Propulsive Devices created over the past century.