AE-341: Airbreathing Propulsion

[L-T-P-D (C) – 3-0-0-0-(9)]

Spring 2020

What is propulsion ?

- Create a force to propel or move

- *The Random House College Dictionary*: propulsion as “the act of propelling, the state of being propelled, a propelling force or impulse”; and propel as “to drive, or cause to move, forward or onward” => the study of propulsion includes the study of propelling force, the motion caused, and the bodies involved – Propulsion involves an object to be propelled plus one or more additional bodies, called propellant

Approach 1 : Take mass stored in a vehicle and throw it backwards (*rocket propulsion*). Use the reaction force to propel the vehicle

Propellant	--->	burn	--->	expand through nozzle
(chem. energy)		(thermal energy)		(kinetic energy & momentum)

What is propulsion ?

Approach 2: Seize mass from the surroundings and set the mass in motion backwards. Use the reaction force to propel vehicle (*air-breathing propulsion*).

Continuously:

a) Draw in air.

b) Compress it.

c) Add fuel and burn (convert chemical energy to thermal energy).

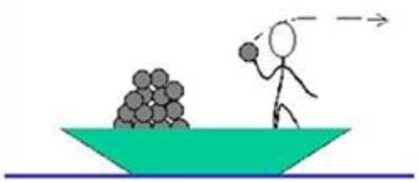
d) Expand through a turbine to drive compressor (extract work).

e.1) Then expand in a nozzle to convert thermal energy to kinetic energy & momentum (turbojet).

e.2) Or expand in a second turbine (extract work), use this to drive a shaft for a fan (turbofan), or a propeller (turboshaft). The fan or propeller impart k.e. & mom. to the air.

What is propulsion ?

A person throws rocks from a boat. At a given point in time the following parameters are known. What is the force (F) on the boat?



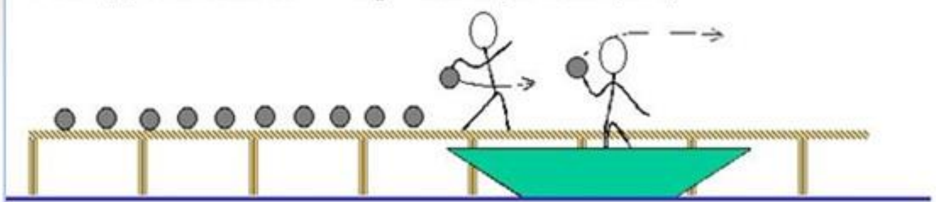
R = throwing rate (rocks/s)
m_b = mass of boat and everything in it (kg)
m_r = mass of one rock (kg)
u_r = velocity of rock relative to boat (m/s)
u_b = velocity of boat (m/s)

1) $F = Rm_r u_r$
2) $F = R(m_r+m_b)u_r$
3) $F = R(m_r+m_b)(u_b-u_r)$
4) $F = Rm_r(u_b-u_r)$
5) None of the above
6) I don't know

Force: rate of change of momentum

A person on a dock throws rocks to a person in a boat who in turn throws them into the water. What is the force (F) on the boat?

R = throwing rate (rocks/s)
m_b = mass of boat and everything in it (kg)
m_r = mass of one rock (kg)
u_{in} = velocity of rock in, relative to boat (m/s)
u_{out} = velocity of rock out, relative to boat (m/s)
u_b = velocity of boat (m/s)



1) $F = Rm_r(u_{out}-u_{in})$
2) $F = R(m_r+m_b)(u_{out}-u_{in})$
3) $F = R(m_r+m_b)(u_b-u_{out})$
4) $F = Rm_r(u_b-u_{out}-u_{in})$
5) None of the above
6) I don't know

History of propulsion

- Example: bicycle riding -> propelling against the frictional forces of the road and the aerodynamics drag force acting on the body and the bike. Paddling provides enough force or in this case torque to rotate the wheels and one moves forward

- Birds used to fly – but human society did not have the propulsive device to provide enough thrust to overcome the drag forces

- Invention of antique wheel to the modern supersonic fighters and rockets - we have come a long way. Along the way we have seen the invention of steam engines, piston engines, diesel engines etc.

- Powered flight is a 20th century invention

- The era began on 17th Dec, 1903, Wright brothers flew in their aircraft which was powered by a piston engine that turned a propeller to provide thrust – 12hp reciprocating intermittent combustion engine

- This type of engine, with a propeller, provided power all manned low seed aircraft until late 1930s

History of propulsion

- The first gas turbine engines for aircraft propulsion was introduced during the second word war by German's on Me 262, but the science of gas turbine propulsion had been there for 2000 years

- At around 200 BC. Hero of Alexandria invented a device called Aeolipile which was essentially a stream turbine. But at that time the science of mechanics was not matured enough to explain its principles

- We had to wait about 1800 years and for Newton to get an explanation. Newton's laws of motion explained the working of this ancient stream turbine. Newton's second law $F = \frac{d(mv)}{dt}$ - rate of change of momentum associated with the flow of stream out of this device - generates the reaction force (Newton's third law) that turns the device in the absence of any other force

- Not much development in the science of propulsion during the dark middle ages - after the advent of industrial revolution, things started to move faster. The sciences of fluid mechanics and thermodynamics began to mature. People like Euler, Bernoulli's, Newton, Stokes, Navier, etc., formulated the fluid mechanics in a way we see it now. Similarly the science of thermodynamics also matured with the contribution of Watt, Joule, Rankine, Carrot etc.

History of propulsion

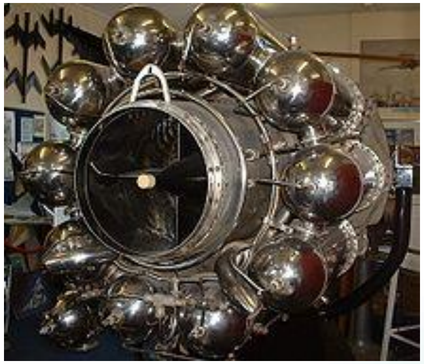
- At the beginning of 20th century there was great interest in Aerospace Science. Although airplane was invented in USA, all the major break thoughts in Aerospace Engineering came from Europe. Prandtle gave his boundary layer theory which allowed for analytic calculation of drag. Prandtle and his students developed the theory of turbulent flows

- But during that time the only engines available for aircraft propulsion was piston- propeller engines. These engines were good for low speed applications, but they were very ineffective for high speed applications (transonic & supersonic) because of formation of shock waves on the blade surface at high speeds that reduce propeller efficiency and may cause detrimental structural damage

- Pioneer of gas turbine Jet propulsion is Frank Whittle, Von Ohain

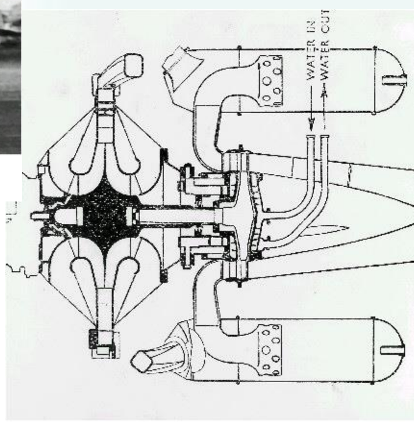
History of propulsion

Frank Whittle An engineer from England applied for a patent of his new invention, a turbojet engine, in 1930



- His idea was to drive a compressor with a turbine to produce a high speed jet stream which will produce the reaction thrust
- But the compressor of those days had very low efficiency and the experts felt that his engine will not run
- Nevertheless his patent was approved in 1935
- Later, with the help of some venture capitalist, he started a company called Power Jets in 1936 and, by 1939; he was able to demonstrate the performance of his engine to the authorities
- Finally on May 15, 1941, the first British Jet aircraft, the Gloster Meteor Powered by Whittle engine flew
- But Jet powered aircrafts were not introduced into RAF during the Second World War

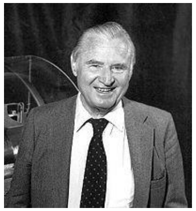
Gloster Experimental Aeroplane E28/39 at Takeoff.
(Royal Aerospace Establishment, Crown Copyright.)



Assembly of W1 Engine. (Combustion chamber details not shown.)

History of propulsion

Hans Von Ohain

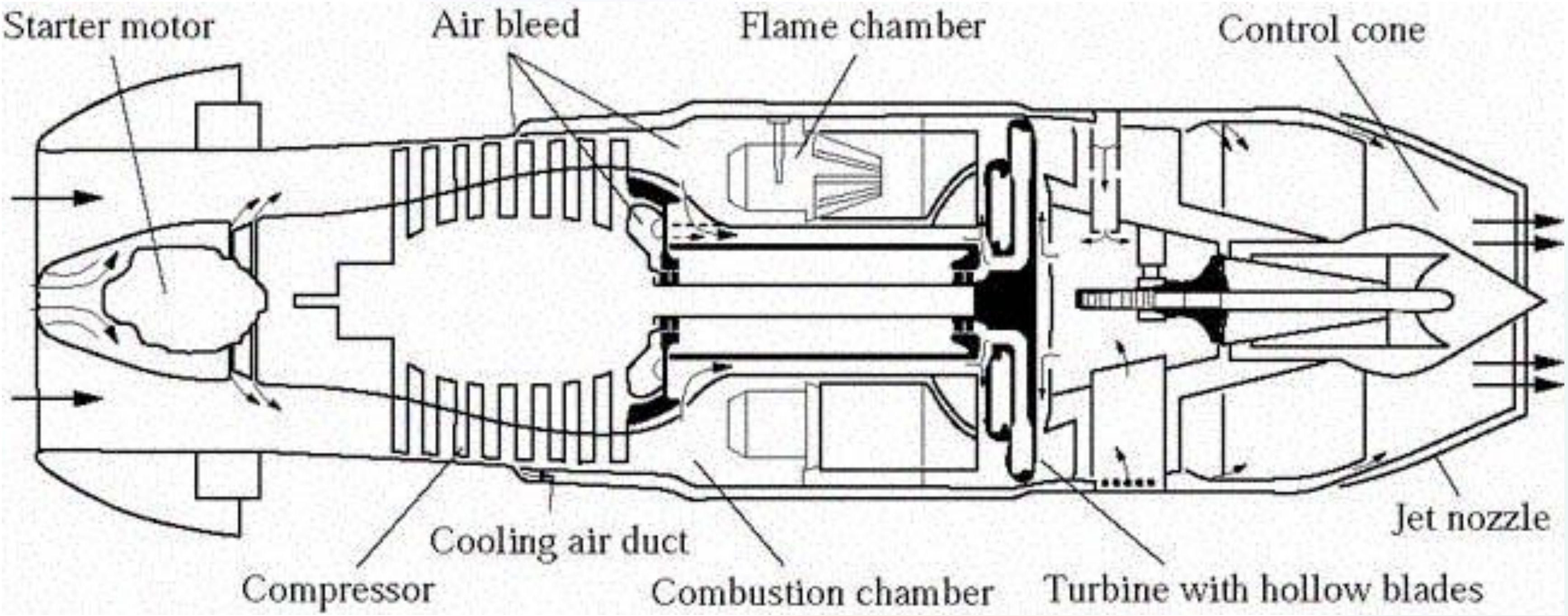


When whittle was struggling with his engine in England, Hans Von Ohain, a 23 year old PhD student in Aerodynamics at Gottingen University came up with the concept of a compressor and turbine spinning on the same shaft in 1933

- By 1934 with the help of car mechanics called **Max Hahn** he built the first prototype of his engine.
- But the combustion chamber of this engine had major flaws.
- In 1936 both Von Ohain and Max Hahn were hired by **Ernst Heinkel** of Heinkel Corporation and gave them all the necessary resources for research.
- His patent was accepted in the same year for the invention of turbojet engine
- 1937, his engine designated as He S-1 turbojet engine – tested with hydrogen fuel and produced a thrust of 250 lb @ 10000 rpm
- 1939, the first German jet engine flew in a **Heinkel He 178**.
- During the end of Second World War, Germans introduced the first jet fighter **Me262** into action.
- That aircraft was far superior than its British counterparts, the piston engined spitfire, but it was introduced so late in the war that it had no effect on the

History of propulsion

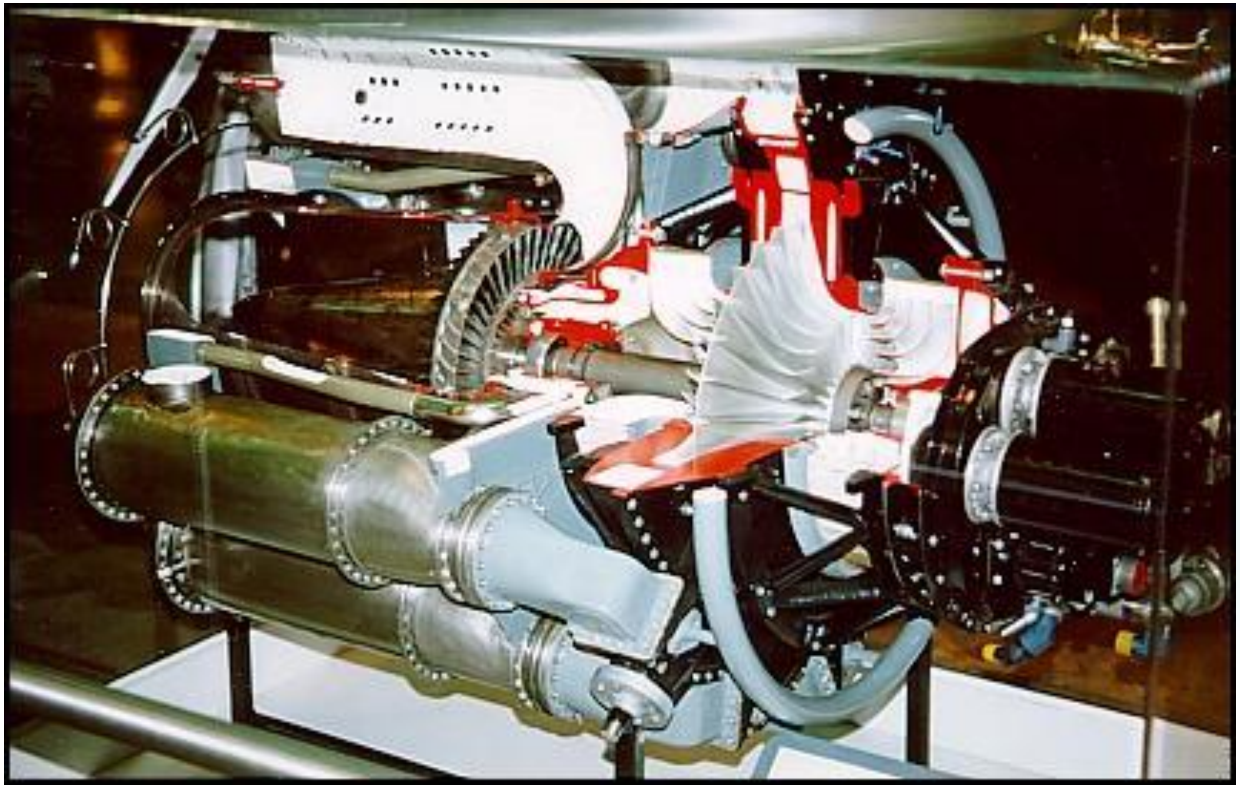
- Jet fighter Me262 is powered by two Jumo 004B turbojet engines , developed based on Von Ohain’s patent



- Axial flow compresoor, straight throughflw combustor with air-cooling of the turbine and nozzle
- Thrust ~ 2000lb @ airflow of 46.6lb/s; pressure ratio 3.14
- Turbine inlet temp: 1427°F, SFC=1.4lbm/h/lbf-thrust.
- Engine weight ~ 1650lb, dia & length ~ 30 & 152 in respectively
- η_c~ 78%, η_t~ 79.5%, η_{comb}~ 95%

History of propulsion

- Jet engine came from Britain to US in 1941
- J-31 was the first turbojet engine produced in quantity in US by GE I-A (I-16), which was a copy of highly secret British "Whittle" engine.

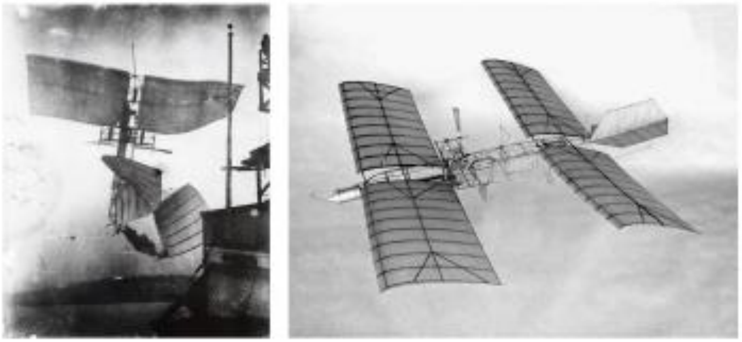


Fluid-Structure Interaction – an old problem

Little Jokers and Potomac catastrophe

Wrights' "Little Jokers" to prevent twisting of propeller blades under loads

Langley's Failure due to Torsional Divergence



Fluid-Structure Interaction – an old problem

World War I - Violent Oscillations and Lanchester's Solution

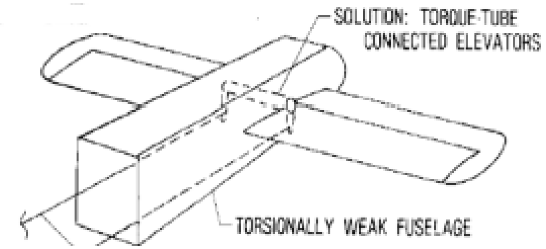
British Fighters ....

Handley Page 0/400 Bomber

de havilland DH-9

Lanchester's 3 Page solution

- Oscillations were not the result of resonance induced by Vibratory sources but were self excited
- Increase of the torsional stiffness of the elevators by means of carry-through torque tube could eliminate the problem



Fluid-Structure Interaction – an old problem

World War I - static divergence and fatal structural failures

German Fighters ....

1. Narrow single-spar lower wing connected by a V-strut to a large upper wing

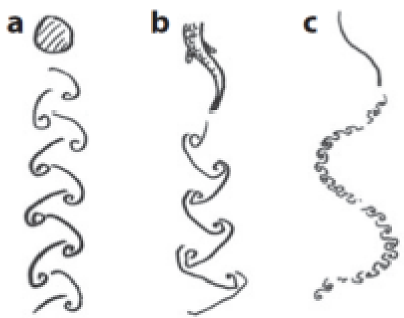
2. Because the lower wing spar was positioned too far aft and V-strut contributed no torsional stiffening to it, the wing tended to twist and wrench loose in high speed dives.

Fokker D-VIII

1. The only difference between the prototype wing, which had shown no structural deficiencies amd the production wing was a strengthening of the rear spar of the production wing
2. Although made the wing stronger, the production wing had unknowingly been made prone to aeroelastic divergence because of the shift in elastic axis.
3. This uneven deflection along the wing resulted in torsion and finally to collapse under strain during combat maneuvers.

Fluid-Structure Interaction – an old problem

Hui-Neng (638-713 AD)



Two Monks and a Flag

- Two monks argue as they watched a temple flag flutter in breeze
- One claimed "the flag flaps"
- Another "No, the wind moves"
- Hui-Neng said, "It is the mind that moves"

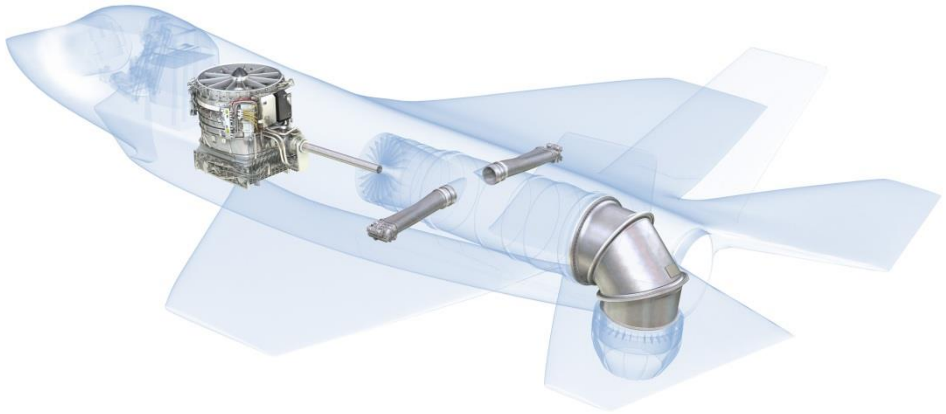
Jan Drees(1977)

In man's handiwork, aeroelastic problems of windmills were solved empirically four centuries ago in Holland with the moving of the front spars of the blades from about the mid-chord to the quarter-chord position

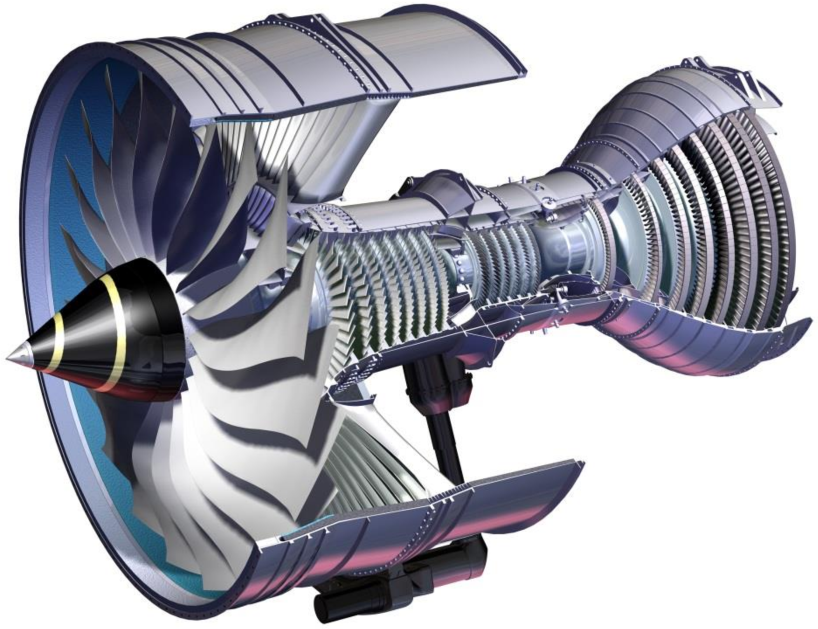
15-16th century windmills of Holland

Innovations in Aircraft Gas turbine engines

- Multispool configuration: (P&W)
- Variable stator (GE)
- Transonic compressor
- Low-emission combustor
- Turbine cooling
- Exhaust Nozzles
- Modern material and manufacturing techniques



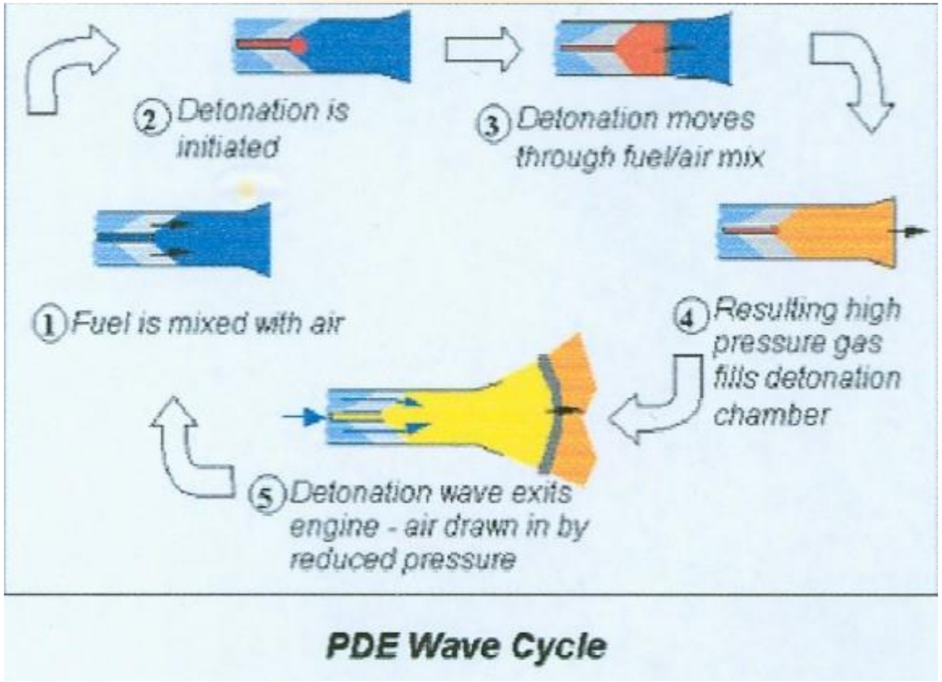
Propulsion laye out of F-35 joint strike fighter by Rolls-Royce



Trent 1000 by Rolls-Royce

New engine concepts

- Wave rotor topping cycle : Humphrey cycle Vs Brayton cycle
- Pulse detonation engine (PDE)
- Multi-meter Scale Gas turbine engines : triumph of MEMS
- Combined cycle propulsion: engines from takeoff to space

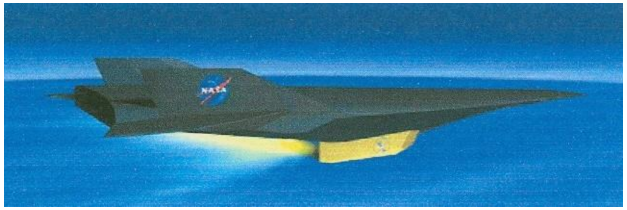


New vehicles

Northrop-Grumman X-47 “pegasus”

Boeing X-36

Boeing X-45A UCAV



NASA X43-A Mach 10 air breathing technology demonstrator

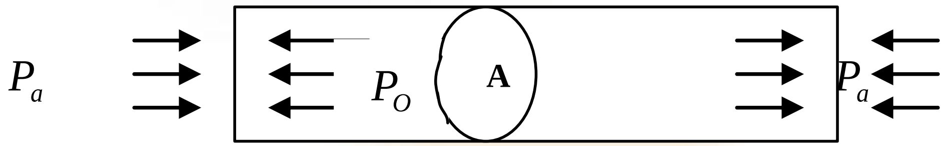
NASA X43-B technology demonstrator

NASA X43-C technology demonstrator

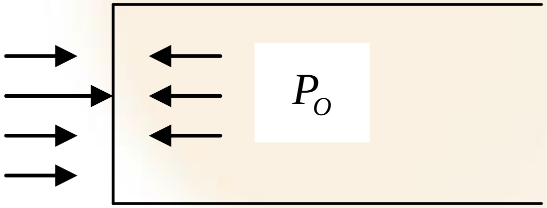
How it works ?

Basic idea of Jet Propulsion

Consider a tube having area A is closed from all the sides and filled with a gas at a pressure P_o and let P_a is the ambient pressure



Initially, the pressure forces are balanced at all direction and there is not net Thrust.

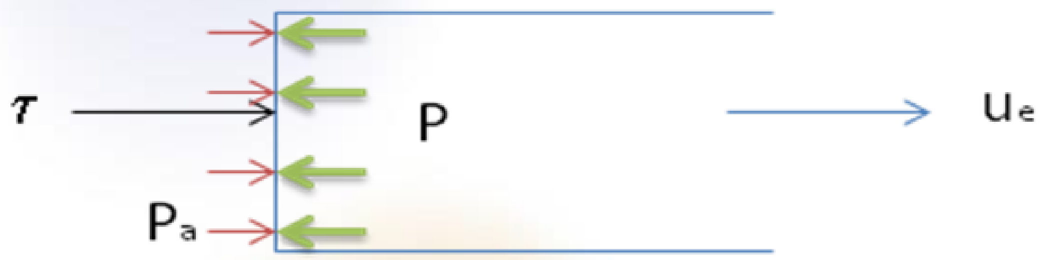


Say at t = 0, the right side of the tube is removed. Then, in order to keep the left side stationary, we need to apply a force τ to the right, such that

$$\tau = (P_O - P_a)A$$

This force τ is the instantaneous thrust.

Basic idea of Jet Propulsion



After a small time increment, the gas starts to leave the tube at a velocity U_e and the pressure drops to P. Then the thrust is

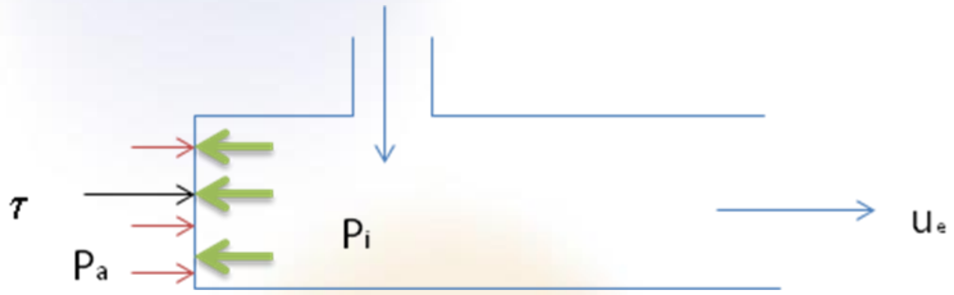
$$\tau = (P - P_a)A$$

As $P \rightarrow P_a$ $\tau \rightarrow 0$

i.e., as the pressure inside the tube attains equilibrium with the ambient, the net thrust reduces to zero as there is no imbalance of force at mechanical equilibrium.

But, if additional fluid a supplied to the tube at the same rate at which it leaves the tube, then a steady thrust can be maintained

Basic idea of Jet Propulsion



If the pressure inside the tube can be maintained at a constant value of P_i then the thrust will be equal to

$$\tau = (P_i - P_a)\, A$$

This shows that if we know the pressure distribution inside the thruster, we can calculate the thrust.

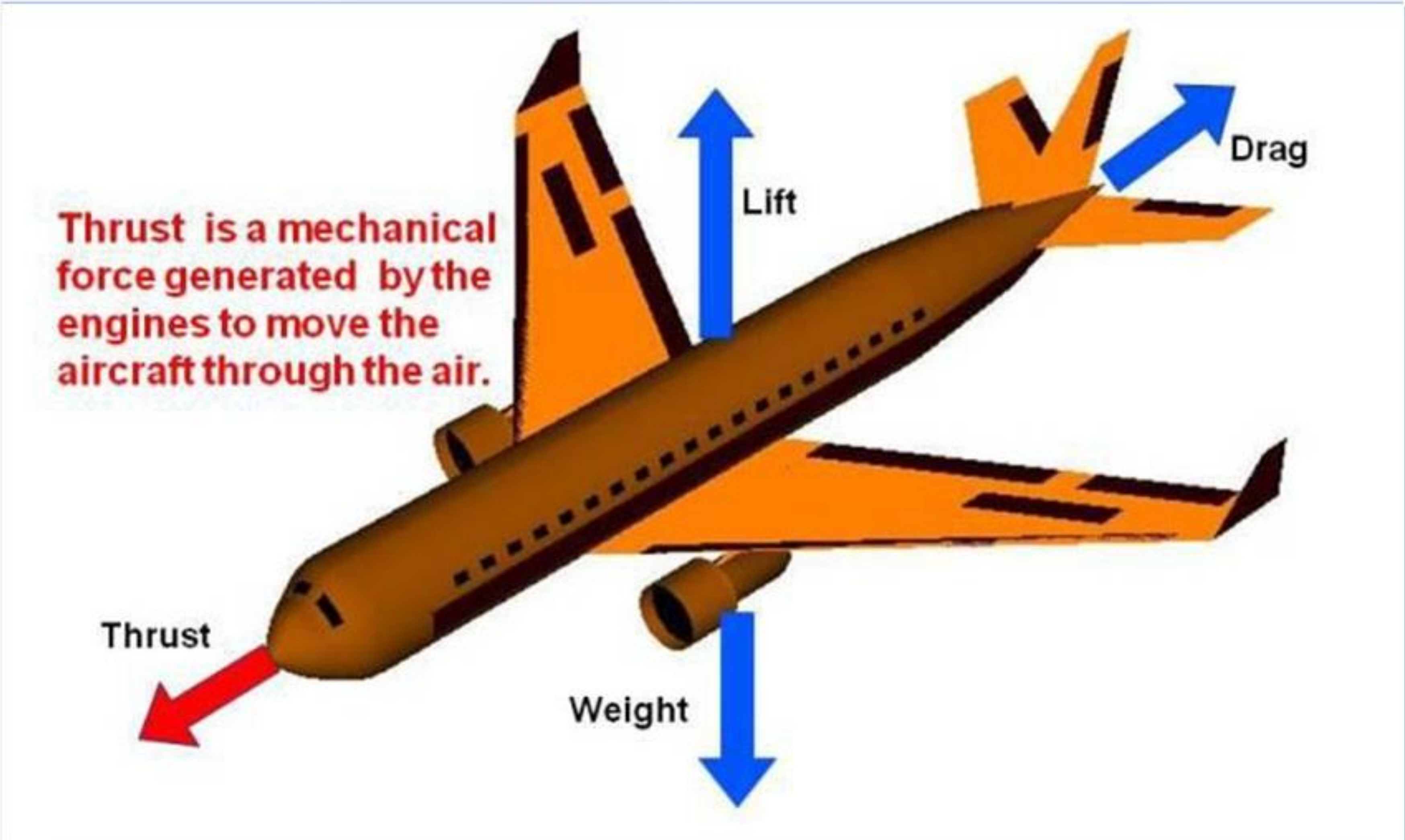
But that is not always possible because of the complex geometry and the frictional losses. However, there is an easier way to estimate the steady state thrust. We will see later in this course that

$$\tau = \dot{m}.U_e$$

$\dot{m} =$ Mass flow out of the engine

$U_e =$ Velocity of exhaust gases

Thrust



Thrust is a mechanical force generated by the engines to move the aircraft through the air.
Lift
Drag
Thrust
Weight

Thrust equation

Thrust is a force.

Force = change in momentum with time

$$F = \frac{([mV]_2 - [mV]_1)}{(t_2 - t_1)}$$

$\dot{m}$ = mass flow rate = mass / time

$\dot{m} = r \times V \times A$ where r = density, V = velocity, A = area

If $p_e \neq p_0$: $F = \dot{m}_e V_e - \dot{m}_0 V_0 + (p_e - p_0) A_e$

If $p_e = p_0$: $F = \dot{m}_e V_e - \dot{m}_0 V_0$

Classification of Propulsive devices for Aerospace applications

AERO-ENGINES

- AIRBREATHING ENGINES
  - •Piston-Propeller
  - •Turbojets
  - •Turbofans
  - •Turbo-Props
  - •Turbo-Shafts
  - •Ramjets
  - •Scramjets
- ROCKET ENGINES
  - •Chemical Rockets
    - •Solid Propellant
    - •Liquid Propellant
  - •Electric Rockets
  - •Solar Sails
  - •Nuclear Thrusters, etc.

Carries the fuel. Atmospheric air is used as the oxidizer.

No interaction with the atmosphere (except the interaction of the nozzle flow with the ambient pressure). Carries both the fuel and oxidizer.