AIRCRAFT PERFORMANCE (R17A2107)

COURSE FILE

II B. Tech II Semester

(2018-2019)

Prepared By

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Department of Aeronautical Engineering

MALLA REDDY COLLEGE OF ENGINEERING & TECHNOLOGY

(Autonomous Institution – UGC, Govt. of India)

Affiliated to JNTU, Hyderabad, Approved by AICTE - Accredited by NBA & NAAC – 'A' Grade - ISO 9001:2015 Certified)

Maisammaguda, Dhulapally (Post Via. Kompally), Secunderabad – 500100, Telangana State, India.

MRCET VISION

- To become a model institution in the fields of Engineering, Technology and Management.

- To have a perfect synchronization of the ideologies of MRCET with challenging demands of International Pioneering Organizations.

MRCET MISSION

- To establish a pedestal for the integral innovation, team spirit, originality and competence in the students, expose them to face the global challenges and become pioneers of Indian vision of modern society

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MRCET QUALITY POLICY.

- To pursue continual improvement of teaching learning process of Undergraduate and Post Graduate programs in Engineering & Management vigorously.

- To provide state of art infrastructure and expertise to impart the quality education.

PROGRAM OUTCOMES
(PO's)

Engineering Graduates will be able to:

1. **Engineering knowledge**: Apply the knowledge of mathematics, science, engineering fundamentals, and an engineering specialization to the solution of complex engineering problems.

2. **Problem analysis**: Identify, formulate, review research literature, and analyze complex engineering problems reaching substantiated conclusions using first principles of mathematics, natural sciences, and engineering sciences.

3. **Design / development of solutions**: Design solutions for complex engineering problems and design system components or processes that meet the specified needs with appropriate consideration for the public health and safety, and the cultural, societal, and environmental considerations.

4. **Conduct investigations of complex problems**: Use research-based knowledge and research methods including design of experiments, analysis and interpretation of data, and synthesis of the information to provide valid conclusions.

5. **Modern tool usage**: Create, select, and apply appropriate techniques, resources, and modern engineering and IT tools including prediction and modeling to complex engineering activities with an understanding of the limitations.

6. **The engineer and society**: Apply reasoning informed by the contextual knowledge to assess societal, health, safety, legal and cultural issues and the consequent responsibilities relevant to the professional engineering practice.

7. **Environment and sustainability**: Understand the impact of the professional engineering solutions in societal and environmental contexts, and demonstrate the knowledge of, and need for sustainable development.

8. **Ethics**: Apply ethical principles and commit to professional ethics and responsibilities and norms of the engineering practice.

9. **Individual and team work**: Function effectively as an individual, and as a member or leader in diverse teams, and in multidisciplinary settings.

10. **Communication**: Communicate effectively on complex engineering activities with the engineering community and with society at large, such as, being able to comprehend and write effective reports and design documentation, make effective presentations, and give and receive clear instructions.

11. **Project management and finance**: Demonstrate knowledge and understanding of the engineering and management principles and apply these to one's own work, as a member and leader in a team, to manage projects and in multi disciplinary environments.

12. **Life- long learning**: Recognize the need for, and have the preparation and ability to engage in independent and life-long learning in the broadest context of technological change.

DEPARTMENT OF AERONAUTICAL ENGINEERING

VISION

Department of Aeronautical Engineering aims to be indispensable source in Aeronautical Engineering which has a zeal to provide the value driven platform for the students to acquire knowledge and empower themselves to shoulder higher responsibility in building a strong nation.

MISSION

The primary mission of the department is to promote engineering education and research. To strive consistently to provide quality education, keeping in pace with time and technology. Department passions to integrate the intellectual, spiritual, ethical and social development of the students for shaping them into dynamic engineers.

QUALITY POLICY STATEMENT

Impart up-to-date knowledge to the students in Aeronautical area to make them quality engineers. Make the students experience the applications on quality equipment and tools. Provide systems, resources and training opportunities to achieve continuous improvement. Maintain global standards in education, training and services.

PROGRAM EDUCATIONAL OBJECTIVES – Aeronautical Engineering

1. **PEO1 (PROFESSIONALISM & CITIZENSHIP):** To create and sustain a community of learning in which students acquire knowledge and learn to apply it professionally with due consideration for ethical, ecological and economic issues.
2. **PEO2 (TECHNICAL ACCOMPLISHMENTS):** To provide knowledge based services to satisfy the needs of society and the industry by providing hands on experience in various technologies in core field.
3. **PEO3 (INVENTION, INNOVATION AND CREATIVITY):** To make the students to design, experiment, analyze, and interpret in the core field with the help of other multi disciplinary concepts wherever applicable.
4. **PEO4 (PROFESSIONAL DEVELOPMENT):** To educate the students to disseminate research findings with good soft skills and become a successful entrepreneur.
5. **PEO5 (HUMAN RESOURCE DEVELOPMENT):** To graduate the students in building national capabilities in technology, education and research

PROGRAM SPECIFIC OUTCOMES – Aeronautical Engineering

1. To mould students to become a professional with all necessary skills, personality and sound knowledge in basic and advance technological areas.

2. To promote understanding of concepts and develop ability in design manufacture and maintenance of aircraft, aerospace vehicles and associated equipment and develop application capability of the concepts sciences to engineering design and processes.

3. Understanding the current scenario in the field of aeronautics and acquire ability to apply knowledge of engineering, science and mathematics to design and conduct experiments in the field of Aeronautical Engineering.

4. To develop leadership skills in our students necessary to shape the social, intellectual, business and technical worlds.

MALLA REDDY COLLEGE OF ENGINEERING & TECHNOLOGY

II Year B. Tech, ANE-II Sem

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(R17A2107)   AIRCRAFT PERFORMANCE

Objectives:

- **To equip the students with fundamental understanding of aircraft performance in various flight regimes.**
- **To familiarize the concepts and parameters affecting flight performance.**
- **To understand the performance of rockets and missiles.**

UNIT - I
Introduction to Aircraft Performance- the Force Systems of The Aircraft: The role and design mission of an aircraft. Specification of the performance requirements and mission profile. Importance of performance analysis, estimation, measurement, operational safety and economy. The Standard Atmosphere. Off-standard and design atmosphere. Measurement of air data. Air data computers. Equations of motion for performance - the aircraft force system. Lift, drag, side force. Total airplane drag- estimation, drag reduction methods. The propulsive forces - the thrust production engines, power producing engines, variation of thrust, propulsive power and specific fuel consumption with altitude and flight speed.

UNIT - II
Cruise Performance: Maximum and minimum speeds in level flight. Range and endurance with thrust production, and power producing engines. Cruise techniques - constant angle of attack, constant Match number; constant altitude, methods- comparision of performance. The effect of alternative fuel flow laws, weight, altitude and temperature on cruise performance. Cruise performance with mixed power-plants.

UNIT - III
Climb, Descent and Manoeuvre Performance: Climb and descent techniques, safety considerations, performance analysis- maximum climb gradient, climb rate. Energy height and specific excess power, optimal climbs - minimum time, minimum fuel climbs. Measurement of climb performance. Descent performance in aircraft operations. Effect of wind on climb and descent perfomance. Accelerated motion of aircraft - equations of motion- the manoeuvre envelope. Longitudinal manoeuvres- the pull-up, push over manoeuvres. Lateral manoeuvres-turn performance- turn rates, turn radius- limiting factors. Manouvre boundaries, Manoeuvre performance of military aircraft, transport aircraft.

UNIT - IV

Take-off And Landing- Safety Requirements - Flight Planning: Estimation of take-off distances. The effect on the take-off distance wrt weight, wind, runway conditions, ground effect. Take off safety factors ,The estimation of landing distances, the discontinued landing ,baulked landing air safety procedures and requirements on performance The effect on the landing distance, of weight, wind, runway conditions, ground effect. Fuel planning, fuel requirement, trip fuel, reserve and tankering.

UNIT - V
Performance of Rockets And Missiles: Principal design features of rockets and missiles. Types, Applications, Staging, Launch and Climb. Performance in boost glide, boost sustain, long range cruise and long -range ballistic trajectories.

Outcomes:
- To make preliminary performance estimation.
- To assess various aircraft parameters and their effect of performance.
- The student will have a clear understanding of the fundamental concept leading to aircraft performance.

TEXT BOOKS
1. Eshelby, M.E., Aircraft Performance; Theory and Practice, AIAA Education Series, AIAA, 2000, ISBN: 1-56347-398-4.
2. Brandt, S.A, et. al., Introduction to Aeronautics: A Design Perspective, Second Edition, AIAA Education Series, AIAA, 2004, ISBN: 1-56347-701-7.
3. Missile Configuration Design, Chin SS, Mc Graw Hill, New York, 1961.

REFERENCES
1. Dole, C.E., Flight Theory and Aerodynamics: a Practical Guide for Operational Safety, Wiley Interscience, 1981, ISBN: 0-471-09152-9.
2. Anderson, J.D. Jr., Aircraft Performance and Design, International edition, McGraw Hill, 1999, ISBN: 0-07-001971-1.
3. McCormick, B.W, Aerodynamics, Aeronautics and Flight Mechanics, second edition, John Wiley, 1995, ISBN: 0-471-57506-2.
4. Shevel, R.S., Fundamentals of Flight, second edition, Pearson Education, 1989, ISBN: 81-297-0514-1.
5. Raymer, D.P., Aircraft Design: A Conceptual Approach, third edition, AIAA Education Series, AIAA, 1999, ISBN: 1-56347-281-0.
6. Yechout, T.R. et al., Introduction to Aircraft Flight Mechanics, AIAA Eduction Series , AIAA, 2003, ISBN: 1-56347-577-4.

Code No: R15A2106

R15

MALLA REDDY COLLEGE OF ENGINEERING & TECHNOLOGY
(Autonomous Institution – UGC, Govt. of India)
II B.Tech II Semester Regular/Supplementary Examinations, April/May 2018
Aircraft Performance
(AE)

Roll No

Time: 3 hours   Max. Marks: 75

Note: This question paper contains two parts A and B
Part A is compulsory which carriers 25 marks and Answer all questions.
Part B Consists of 5 SECTIONS (One SECTION for each UNIT). Answer FIVE Questions, Choosing ONE Question from each SECTION and each Question carries 10 marks.

PART – A   (25 Marks)

1. (a) What is the significance of off-standard atmosphere? (2M)
    (b) Write the expressions for lift, drag and side force coefficients. (3M)
    (c) What is the effect of weight on cruise performance? (2M)
    (d) Give the expressions for endurance of a jet engine and propeller engine. (3M)
    (e) What is instantaneous turn? (2M)
    (f) Write the equations of motion for accelerated flight? (3M)
    (g) What is the effect of weight of an aircraft on take-off distance?   (2M)
    (h) Define tankering (3M)
    (i) What are the types of rockets?   (2M)
    (j) What are design features of rockets? (3M)

PART – B   (50 Marks)
SECTION – I
2. Derive an equation for the total drag condition and drag reduction methods. (10M)

(OR)

3. Explain the variation of thrust, propulsive power and specific fuel consumption with flight speed. (10M)

SECTION – II
4.   Explain the effect of altitude and temperature on cruise performance. (10M)

(OR)

5. Explain the constant altitude cruise techniques and compare it with the other cruise techniques. (10M)

SECTION – III
6.   Obtain the relation for the Radius of turn and turn rate for a level turning flight.   (10M)

(OR)

7. Explain in detail, the effect of wind on climb and descent performance. (10M)

SECTION – IV
8. (a) Write the differences between discontinued landing and baulked landing. (5M)
    (b) Explain in detail about ground effect? (5M)

(OR)

9. Calculate total take off distance for Gulfstream airplane at standard sea level assuming a take-off gross weight of 80,000lb .The design features of the airplane are $s=950ft^2$,AR=7,C_{do}=0.015and K= 0.06with the added information that the wing span is 75ft .Assume that the variation of engine thrust with the velocity during takeoff is obtained with constants where k^*_1=27,700 lb k^*_2=21.28lb s/ ft^2 and k^*_3=1.117x10^{-2} lb s/ ft^2·The height of the wing above the ground during the ground roll is 6ft.Assume the runway is dry concrete ,with μ_r=0.02 (10M)

SECTION – V

10. Explain the missile performance in boost glide. (10M)

(OR)

11. Explain about long range cruise trajectory(10M)

II B.TECH II SEMESTER – AERONAUTICAL ENGINEERING
AIRCRAFT PERFORMANCE

MODEL PAPER – I
MAXIMUM MARKS: 70

Max Marks70

i.   Answer only one question among the two questions in choice.

ii.   Each question answer (irrespective of the bits) carries 10M.

1) Explain the factors to be considered in the estimation of performance of an aircraft and how the estimation is carried out

OR

2) Describe the mission of a military aircraft with the required sketches

3) Derive an expression for range and endurance for aircraft with thrust producing engines with the necessary equations

OR

4) Explain the cruising method of constant angle of attack and constant mach number and explain about the effect of alternative fuel flow laws

5) Explain the equations of motion of an aircraft with thrust producing engines in a climb .Derive the expressions for climb gradient and climb rate

OR

6) (a)Describe the phases of descending flight through a diagram and
(b) Discuss the various criteria that govern the manner in which the aircraft is flown in each phase

7) Explain the process of take –off with the help of a diagram and discuss how take-off distances are estimated

OR

8) Discuss the space available and space required for take – off performance with required sketches

9) Explain about the boost glide trajectory with graphical solution and iteration method with neat sketches

OR

10) Missiles are classified in to four general classes ,what are they explain them in detail

II B.TECH II SEMESTER – AERONAUTICAL ENGINEERING
AIRCRAFT PERFORMANCE
MODEL PAPER – II
MAXIMUM MARKS: 70

Max Marks: 70

i.   Answer only one question among the two questions in choice.
ii.   Each question answer (irrespective of the bits) carries 10M.

1) For international standard atmosphere , explain variation of temperature , pressure variation with altitude with the help of neat and proper diagram .Also define lapse rate ,stratosphere and troposphere

OR

2) Explain minimum drag speed , minimum power speed and describe their importance in aircraft performance studies

3) Derive Breguet range equation and discuss about the constant altitude , constant mach number

OR

4) Discuss the comparison of cruise methods and explain through diagrams how range function and endurance function vary with relative speed

5) What are the reasons for the maneuver performance of an aircraft to be limited by the structural strength of the airframe? Discuss the main elements of a typical maneuver envelope with the help of a schematic diagram

OR

6) Describe the equations of motion of an aircraft undergoing lateral maneuver or level turn and derive an expression for radius of turn. Discuss with the help of a diagram the maneuver boundaries for turning performance

7) Explain the process of landing with the help of a diagram and discuss the estimation of the landing distances

OR

8) Define the performance classes used to classify aircraft in meeting the requirements of certificate of airworthiness. what are the issues relating to discontinued landing

9) Explain in detail about long - range cruise trajectory

OR

10) Explain about principle design features of rockets and missiles

II B.TECH II SEMESTER – AERONAUTICAL ENGINEERING
AIRCRAFT PERFORMANCE
MODEL PAPER – III
MAXIMUM MARKS: 70

Max Marks: 70

i.   Answer only one question among the two questions in choice.

ii.   Each question answer (irrespective of the bits) carries 10M.

1) What for aircraft performance measurement is required ?Show with the help of diagrams typical military aircraft mission profiles

OR

2) Discuss aircraft force system needed for formulating the performance equations of motion

3) Derive an expression for range and endurance for aircraft with thrust producing engines

OR

4) Discuss about the effect of WAT (weight, altitude ,and temperature) on cruise performance

5) Explain about the measurement of best climb performance   (b)Discuss descent performance in aircraft operations

OR

6) (a)Explain about the transport aircraft maneuver performance and military aircraft maneuver performance

   (b) Determine the load factor, bank angle turn radius for an aircraft in a level turn at a true speed of 120km and a turn rate of 15deg/s

7) What are the phases into which the flight is divided for the purpose of flight planning ?Explain with the help of diagram the airfield distances available for take-off

OR

8) (a)Explain the effect on the take-off distances of the flight variables

   (b) Find lift to drag ratio when drag coefficient at zero lift is 0.2 density of air at 10 km is 0.4135kg/cubic meter and speed of aircraft is 300kmph.The mass of the aircraft is 5000kg area of wing plan form is 5sqm and its AR is 6, span efficiency factor is 1

9) Explain about long range - ballistic trajectories

OR

10) Explain about boost - sustain trajectory

II B.TECH II SEMESTER – AERONAUTICAL ENGINEERING
AIRCRAFT PERFORMANCE
MODEL PAPER – IV
MAXIMUM MARKS: 70

Max Marks: 70

i.   Answer only one question among the two questions in choice.

ii.   Each question answer (irrespective of the bits) carries 10M.

1) (a) Discuss vertical structure of the atmosphere and its various layers through a diagram

   (b) Explain air data computer system using a diagram

OR

2) Derive the expression for drag polar and also explain about the drag reduction methods with requires figures

3) (a) An aircraft with wing loading of 1500N/sqm is gliding from an altitude of 4 km. What is the glide angle corresponding to minimum rate of descent. If zero lift drag coefficient is 0.2? what is the equilibrium glide velocity associated with the descent

   (b) Write shortly about the climbing flight and also write short notes on weight estimation of the aircraft

OR

4) Write short note on the endurance of an aircraft and derive the expression for both turbojet and propeller driven airplanes

5) (a) An F-22 is performing a 5-g pull up at 10,000 ft and 500 kn true airspeed what is the turn rate and turn radius

   (b) Explain about the effect of wind on climb and descent performance

OR

6) Derive an expression for specific excess power

7) Explain about the take –off performance showing with the illustration of ground roll ,airborne distance and total take –off distance and also explain with the intermediate segments of the ground roll

OR

8) Calculate total take off distance for Gulfstream _like airplane at standard sea level assuming a take-off gross weight of 73,000lb .The design features of the airplane are s=950ft^2,AR=5.92,C_{do}=0.015and K= 0.08with the added information that the wing span is 75ft .Assume that the variation of engine thrust with the velocity during takeoff is

given by equation (6.74) .where k^*_1=27,700 lb k^*_2=21.28lb s/ ft^2 and k^*_3=1.117x10^{-2} lb s/ ft^2. The height of the wing above the ground during the ground roll is 5.6ft. Assume the runway is dry concrete ,with μ_r=0.04(example 6.6 in aircraft performance J.D ANDERSON)

9) Explain about fuel planning , flight planning

<p align="center">**OR**</p>

10) Explain about rate of climb in long range cruise trajectory with necessary equations

II B.TECH II SEMESTER – AERONAUTICAL ENGINEERING
AIRCRAFT PERFORMANCE
MODEL PAPER – V
MAXIMUM MARKS: 70

Max Marks: 70

i.   Answer only one question among the two questions in choice.

ii.   Each question answer (irrespective of the bits) carries 10M.

1) (a)Explain about the off standard and design atmosphere (b)Explain about the pressure height relation ship

OR

2) Derive the equations of motion for steady level flight

3) (a)Explain about the air data computers with the required sketches
   (b)Define range, endurance, the drag force, the side force and the overall drag force D

OR

4) (a)Explain about the cruising performance with the comparison of three cruise technique methods
   (b) Estimate the maximum range at 30,000ft for the gulfstream IV. Also calculate the flight velocity to obtain this range.The maximum usable fuel weight is 29,500 lb .The thrust specific fuel consumption of the Rolls Royce Tay turbofan at 30,000 ft is 0.69 lb of fuel consumed per hour per pound of thrust (example 5.19 aircraft performance J.D ANDERSON)

5) Derive the expression for maximum turn radius and maximum turn rate

OR

6) Derive the expression for rate of climb and also explain the graphical approach

7) (a)Explain about the V-n diagram with neat sketch
   (b)Explain about the landing performance with neat sketch

OR

8) (a)Explain baulked landing(b) Discuss air safety procedures and requirements on landing performance

9) Explain graphical solution in boost glide trajectory

OR

10) Explain the types of design and control of external aerodynamic configurations used for four classes of missiles with advantaged and disadvantages with neat figures

UNIT - I

# INTRODUCTION TO AIRCRAFT PERFORMANCE- THE FORCE SYSTEMS OF THE AIRCRAFT

The role and design mission of an aircraft, specification of performance requirements

- Performance can be used as a measure of the capability of the aircraft in many ways.
- Performance can be defined as a measure of the ability of the aircraft to carry out a specified task.
- In the case of a civil transport aircraft it determines an element of the cost of the operation of the aircraft and hence it contributes to its economic viability as a transport vehicle.
- In military combat operations, time, maneuver and radius of action are some of the more critical performance parameters in the overall evaluation of the effectiveness and air superiority of the aircraft.
- Performance can also be regarded as a measure of safety.
- An aircraft has an excess of thrust over drag it can increase its energy by either climbing or accelerating if the drag exceeds the thrust then it will be losing energy as it either decelerates or descends.
- In safe flight the thrust must not be committed to a decrease of energy that would endanger it so that at all critical points in the mission thrust must exceed the drag. This is a consideration of the performance aspect of the airworthiness of the aircraft.
- The design of an aircraft starts from the statement of the flight path related performance that the aircraft is expected to achieve.
- The basic statement of the performance will be concerned with the payload the aircraft will be required to carry and the mission profile it will be required to fly.
- The payload of a civil transport aircraft may be defined in the terms of no. of passengers, tonnage of freight, volume of freight or as combinations of freight and passengers.
- The definition of military aircraft mission payloads may cover a wide range of possibilities including personnel, troops, support equipment and supplies in transport aircraft and internally carried stores, externally carried stores and sensor pods on combat aircraft.
- Aircraft performance is a measurement of how well the plane flies. Many factors affect how the plane flies: its weight, the atmospheric conditions, pressure, temperature, humidity, even the runway at takeoff.

- Aircraft performance will tell you the speeds the plane can hope to achieve in different conditions. Aircraft must be able to operate safely throughout their flight regime in such a way that a safe outcome will result from specified malfunctions (e.g. power unit failure), occurring at any point throughout the flight range. Even though modern aircraft are designed and built according to strict standards which are laid down by national and international authorities due to off design conditions or some unexpected climatic changes may result in poor performance of aircraft.

- In the present study the performance will be based on flight path of aircraft in atmosphere which depends upon the mission profile of aircraft.

- Performance of an aircraft changes based upon its role and mission. In broad terms the aircraft role and mission can be classified into Civil Operations, which are commercial flights transporting passengers or cargo from one location to another, or Military Operations, which are concerned with defensive or offensive, flight operations or their associated support operations.

- Civil operations are fundamentally, intended to profit making while military operations are more concerned with the need to achieve their objectives than with the cost of doing so; this distinction points to the different performance criteria that will need to be applied to the mission.

Mission profile

- The design requirements stipulate the required performance of the new airplane. The airplane performance is critically dependent on several parameters, especially

(1) Maximum lift coefficient (CL_{max});

(2) lift-to-drag ratio L/D, usually at cruise;

(3) Wing loading W/S; and

(4) thrust-to-weight ratio T/W.
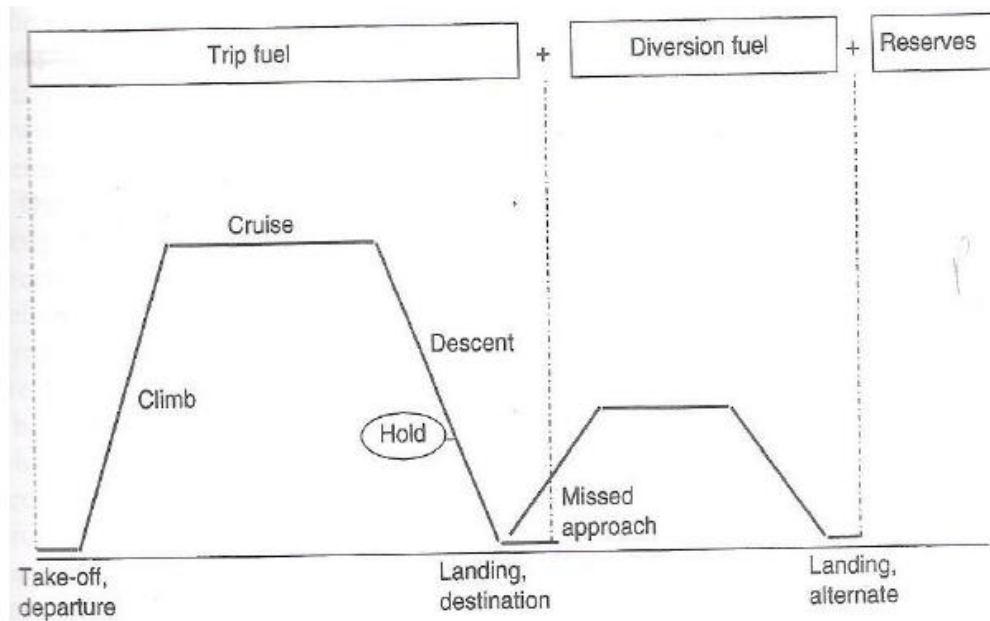
Civil transport aircraft flight profile.
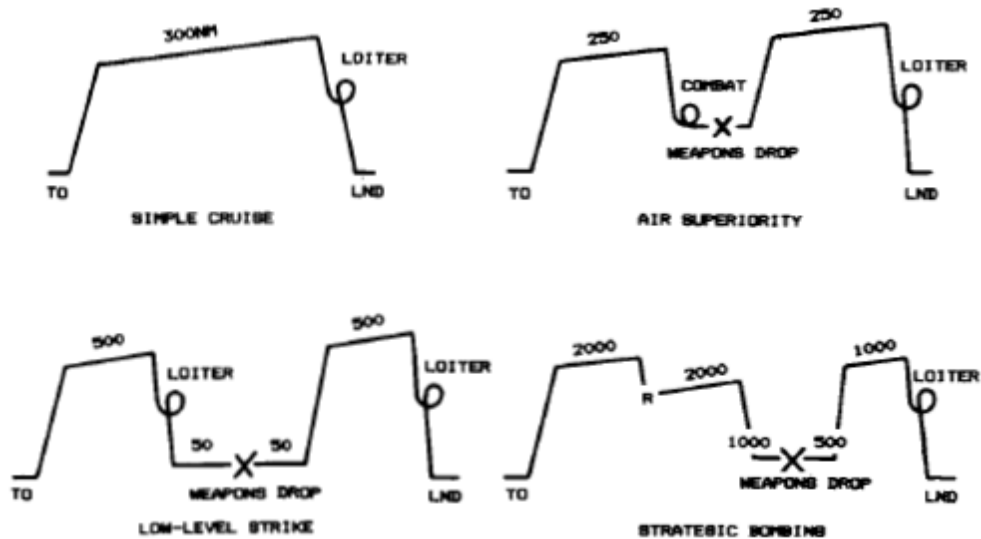
- A typical mission profile of a civil transport aircraft is shown in the above figure.

The primary mission is to fly a payload from the departure point to the destination. This requires the aircraft to takeoff from the departure point, climb to the cruising height and cruise to the destination, where the aircraft descends and lands.

- If the aircraft be unable to land the destination when it arrives, it will have to divert to an alternate airfield and the flight plan will need to include provision for the diversion.

: Military aircraft mission profiles.
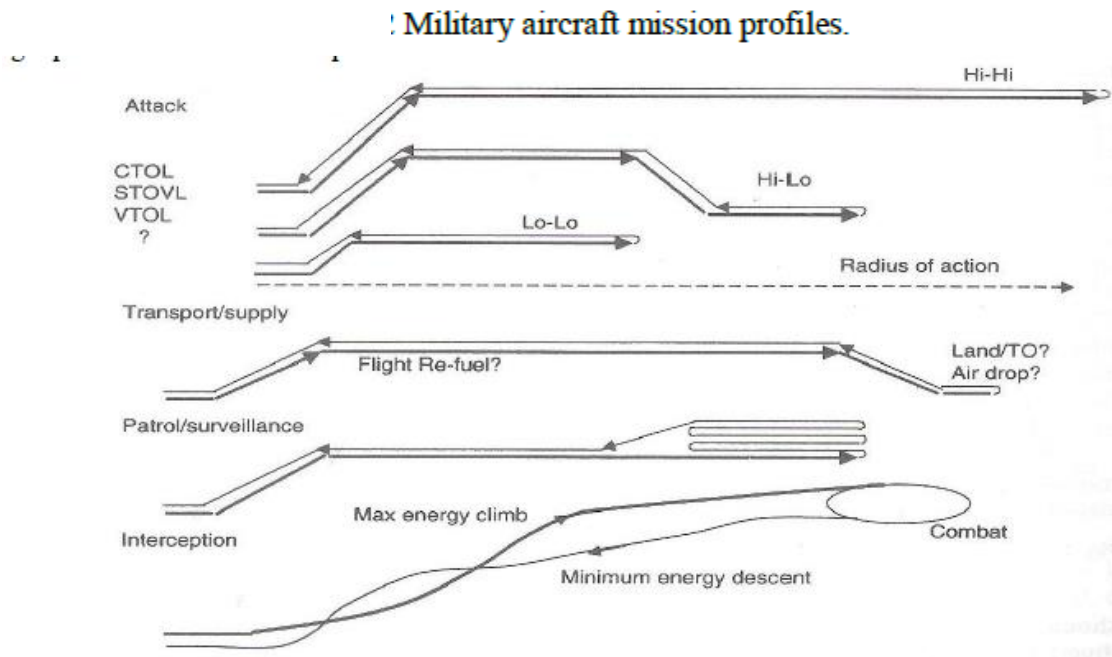
- Once the mission profile and the payload of the aircraft have been specified the design process can commence. From the performance standpoint the total design process extends from the initial project design estimations right through to the delivery of the aircraft into service.
- In the final phase the aircraft is prepared for its operational role. The overall procedure can be divided into 3 broad areas:
  - ➢ Performance estimation
  - ➢ Performance measurement
  - ➢ Operational performance

Performance estimation
- Performance estimation involves the prediction of the capabilities of the aircraft from the considerations of its aerodynamic design, power plant and operating environment.

It can be applied to

1) The design of new type of aircraft

2) Modification of existing aircraft type in respect to design changes affecting its aerodynamic characteristics or power plant or

3) To supplement or extend the full scale measured performance of an aircraft type for conditions outside those already established

- Performance estimation process begins with the proposal of some performance target.
- Initially the estimation will centre on individual elements of the flight path. Performance estimation is usually based on the assumption of a simple atmosphere model, the international standard atmosphere (ISA). This is a linearised model of the temperature atmosphere which represents the mean global atmosphere state with respect to seasonal changes and latitude and is used as the basis for aircraft design.

Performance measurement

A performance measurement is required for the three main purposes: It is required for three main purposes:

- To verify that the aircraft achieves the estimated design performance targets;

- To demonstrate that the aircraft can satisfy the safety criteria set down in the airworthiness requirements; and

- To provide validated performance data for the performance section of the flight manual.

- The performance of the aircraft is measured in development trials and compared with the estimated performance where there is difference in the characteristics of the aircraft and of the power plant can be measured and compared with those used in the models.

- As the design of the aircraft is developed and the flight trials show that it is meeting its performance targets, data was measured for submission to the airworthiness authority for the certification of the aircraft.

- As a part of the certification process validated performance data are required for the performance section of the flight manual, known as the flight performance manual or the operating data manual(ODM), which contains the information of the performance of the aircraft needed by the operator for flight planning.

Operational Performance

- The basic requirements for the safe flight are that the space required for the aircraft to maneuver should never exceed the space available, and that the aircraft carries sufficient fuel for the flight these fundamental requirements form the basis of performance planning and fuel planning.
- Performance planning: It is a part of the flight plan mode in advance of the flight ensures that at any point in the flight the aircraft has sufficient performance to be able to maneuver within the space available. The space required for any given maneuver is a function of the weight of the aircraft and the space required increases as the weight increases.
- Fuel planning: It ensures that the aircraft carries sufficient fuel for the mission, taking into account reserves for contingencies, diversions and safety. Since the fuel required for the mission will depend on the takeoff weight of the aircraft the fuel planning must follow the flight planning.

Operational Safety and Economy

- Any transport operation carried out by an aircraft must be shown to be safe. The basic requirements for safe flight are that the space required for the aircraft to manoeuvre should never exceed the space available and the aircraft carries sufficient fuel for the flight; these fundamental requirements form the basis of performance planning and fuel planning.

The Standard Atmosphere, Off-standard and design atmospheres

- It is important to understand the definition of various altitudes that are usually used to analyze/compare the performance of flying vehicles in standardatmosphere.

- The International Standard Atmosphere is only a model for use in the estimation and measurement of aircraft performance. The real atmosphere encountered at any particular time and place will generally not conforms to the ISA model but will have its own temperature at datum pressure and its own temperature-height profile. The datum of the real atmosphere is usually taken to be an arbitrary height – for example, mean sea level at which the pressure will vary with time and the temperature – height profile

may range between arctic winter and tropical summer. Any atmosphere that does not confirm to the ISA profile is referred to as an off-standard atmosphere.

- The gravitational force experienced by any aircraft varies with altitude. Also, an air- craft experiences variation in aerodynamic forces with altitude. This is simply because of the fact that the atmospheric properties viz; Pressure, density and Temperature (P, ρ, T) also changes with altitude. Aerodynamic forces are strong function of these atmospheric properties (P, ρ, T). It is a necessity to specify the altitude that will help in postulating gravitational and aerodynamic forces explicitly.

- Absolute altitude (h_a) – The altitude as measured from the center of the earth
- Geometric altitude (h_g) – The altitude as measured from the mean sea level
- Geo-potential altitude (h) – The geometric altitude corrected for the gravity variation. We will discuss this later in detail.

- From Figure 1, it can be concluded that the absolute altitude is the sum of geometric altitude and mean radius of the earth. Mathematically, this relationship can be numeralized
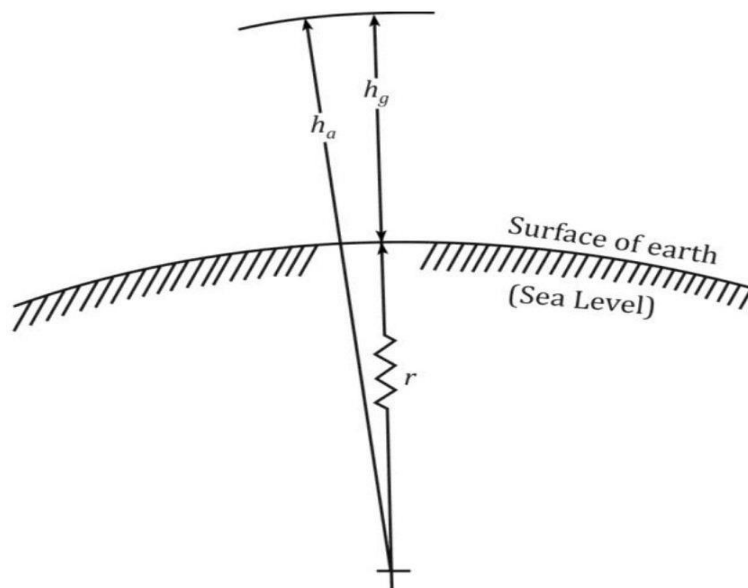

Figure 1: Schematic diagram representing geometric altitude and absolute altitude

$$h_a = h_g + r \qquad (1)$$

where, r is the mean radius of earth.

Acceleration due to gravity and altitude relationship

- Now that various concepts about altitudes are familiarized, the variations of acceleration due to gravity with altitude needs to be understood. It can be obtained using Newton's universal law of gravitation.

1. If gravitational acceleration at the sea level is g_o and the local gravitational constant is g for a given absolute altitude h_a; then the relationship between g and g_o follows

$$g = g_o \left(\frac{r}{h_a} \right)^2 = g_o \left(\frac{r}{r + h_g} \right)^2$$

Geo-potential and geometric altitudes

1. The hydrostatic equation of an infinitesimal fluid is given by
$$dP = -\rho g \, dh_g \qquad (3)$$
where, P - hydostatic pressure (Pa), ρ - fluid density

kg/m^3 and

g - acceleration (m/s^2) due to gravity corresponding to the geometric altitude h_g

2. In order to obtain the hydrostatic pressure (P) at a particular geometric altitude (h_g), the above expression has to be integrated. Density and acceleration due to gravity are functions of altitude makes integration a bit more complex/difficult.

3. In order to simplify this integration, the concept of geo-potential altitude (h) has been introduced. We will consider this concept next.

Geo-potential altitude (h)

1. It is a fictitious altitude corrected for the gravity variation, which is typically used to ease the integration process (Equation 3). In simple terms, it can be called as "gravity adjusted height". The adjustment uses Earth's mean sea level as reference.

2. Now we can rewrite the hydrostatic equation, by replacing the geometric altitude with geo-potential altitude (h).
$$dP = -\rho g_O \, dh \qquad (4)$$

where, g_o is the acceleration due to gravity at mean sea level.

3. Using the two hydrostatic equations, viz, Equation 3 & Equation 4, we can derive the relationship between geometric and geo-potential altitude

$$1 = \frac{g_o}{g}\frac{dh}{dh_g}$$

$$dh = \frac{g}{g_o}dh_g \tag{5}$$

$$dh = \frac{r^2}{(r+h_g)^2}dh_g \tag{6}$$

4. Integrating dh from sea level up to any given value of h (different from h_g) at a given point in atmosphere where geometric altitude is h_g, we get

$$\int_0^h dh = \int_0^{h_g} \frac{r^2}{(r+h_g)^2}dh_g$$

$$= \int_0^{h_g} \frac{dh_g}{(r+h_g)^2}$$

$$h = r^2 \left(\frac{-1}{r+h_g}\right)_0^{h_g}$$

$$= r^2 \left(\frac{-1}{r+h_g} + \frac{1}{r}\right)$$

$$= r^2 \left(\frac{-r+r+h_g}{r(r+h_g)}\right)$$

Thus,

$$h = \left(\frac{r}{r+h_g}\right)h_g \tag{7}$$
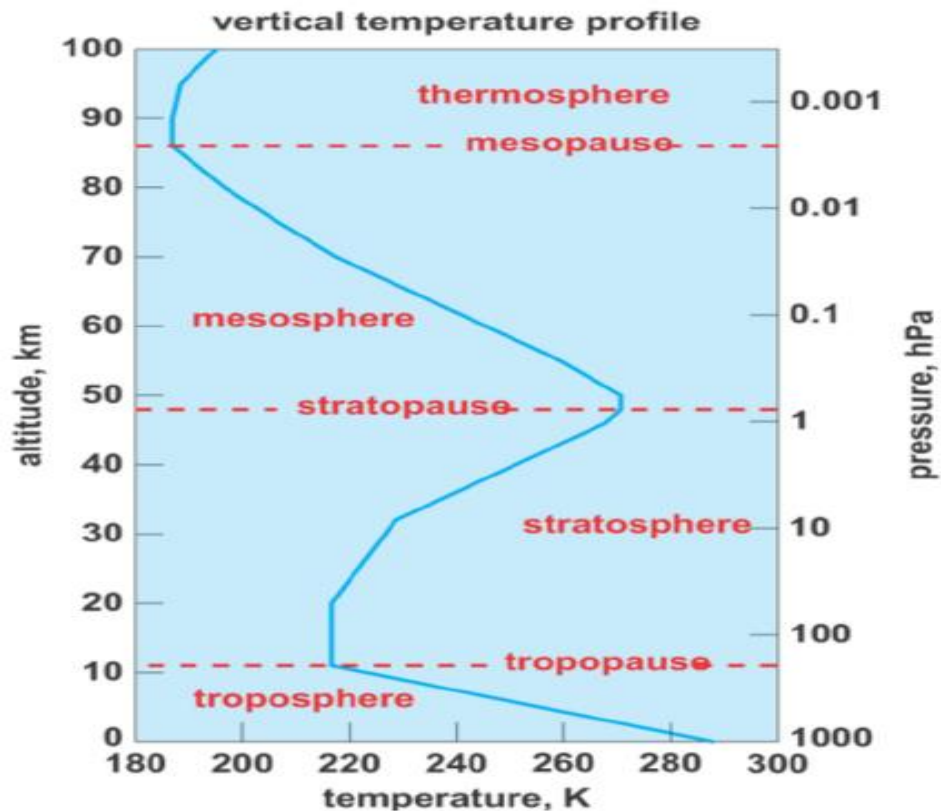
Figure 2: Plot representing variation of temperature with altitude

The troposphere: This is the region closest to the earth's surface. It is characterized by turbulent conditions of air. The temperature decreases linearly at an approximate rate of 6.5 K / km. The highest point of the troposphere is called tropopause. The height of the tropopause varies from about 9 km at the poles to about 16 km at the equator.

The stratosphere: This extends from the tropopause to about 50 km. High velocity winds may be encountered in this region, but they are not gusty. Temperature remains constant up to about 25 km and then increases. The highest point of the stratosphere is called the stratopause.

The mesosphere: The mesosphere extends from the stratopause to about 80 km. The temperature decreases to about -900 C in this region. In the mesosphere, the pressure and density of air are very low, but the air still retains its composition as at sea level. The highest point of the mesosphere is called the mesopause.

The ionosphere or thermosphere: This region extends from the mesopause to about 1000 km. It is characterized by the presence of ions and free electrons. The temperature increases

to about 0° C at 110 km, to about 1000° C at 150 km and peak of about 1780° C at 700 km (Ref.2.1). Some electrical phenomena like the aurora borealis occur in this region.

The exosphere: This is the outer fringe of the earth's atmosphere. Very few molecules are found in this region. The region gradually merges into the interplanetary space.

International Standard Atmosphere (ISA)

- Need for ISA and agency prescribing it The properties of earth's atmosphere like pressure, temperature and density vary not only with height above the earth's surface but also with the location on earth, from day to day and even during the day. As mentioned in section 1.9, the performance of an airplane is dependent on the physical properties of the earth's atmosphere.

- Hence, for the purpose of comparing (a) the performance of different airplanes and (b) the performance of the same airplane measured in flight tests on different days, a set of values for atmospheric properties have been agreed upon, which represent average conditions prevailing for most of the year, in Europe and North America. Though the agreed values do not represent the actual conditions anywhere at any given time, they are useful as a reference. This set of values called the International Standard Atmosphere (ISA) is prescribed by ICAO (International Civil Aviation Organization). It is defined by the pressure and temperature at mean sea level

Measurement of air data

- The essential requirements in the measurement of aircraft performance are first, the knowledge of the state of the atmosphere in which the aircraft is flying and secondly the relative motion between the aircraft and the air mass. This information is collected by the air data system.

- The air data system of an aircraft in fig 1.11 consists of a pitot-static installation to sense the airflow pressures from which height, airspeed and Mach number are derived. An air thermometer from which the air temperature can be determined and in some cases airflow direction detectors (ADD) which sense the local flow directions relative to the aircraft body axes are part of the system.
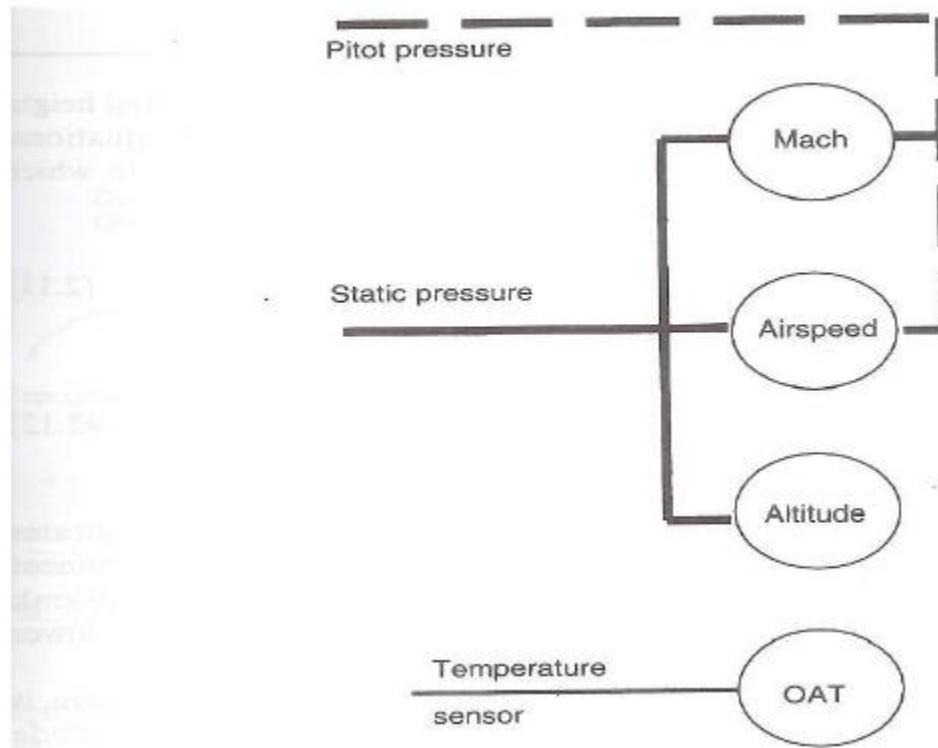
Air data system of an aircraft.

- Both the air data computer and the mechanical instruments use the same basic calibration equations to convert the measured data into a suitable form for operational use. The calibration equation will be developed in the subsequent sections. The units used in the display of air data are usually the foot for measurement of height and the knot for airspeed since international regulation requires primary flight instruments to be calibrated in these units.

Various Speeds
1. Indicated Air Speed (IAS):

- The speed indicated by the airspeed indicator in the cockpit, which is based on the Pitot - static tube attached to the airplane.

2. Calibrated Air Speed (CAS):

- The indicated airspeed correct for the position and instrument errors. In standard atmospheric conditions, this is equal to the True Air Speed (TAS).

3. Equivalent Air Speed (EAS):

- The calibrated air speed corrected for adiabatic and compressibility effects. The al- titude effects are included in this speed.

- To explain the three airspeed, let us assume that an aircraft is in cruise at an al- titude of h, where the density is ρ, dynamic pressure is q and the corresponding velocity is v. Now if we want to simulate the same dynamic pressure at mean sea level (q_O), the corresponding velocity is known as equivalent air speed.

4. True Air Speed (TAS)

   The airspeed of the airplane relative to the undisturbed air.

True Air Speed (TAS) & Equivalent Air Speed (EAS) relation

- Suppose an airplane is flying at an altitude (h_a) and experiencing dynamic pressure (P_a). We define equivalent airspeed as that speed with which the aircraft needs to fly at sea level to duplicate the actual dynamic pressure (h_a) at a given altitude. so, we can write;

$$\frac{1}{2}\rho_a V_{TAS}^2 = \frac{1}{2}\rho_o V_{EAS}^2$$

The relationship between true airspeed and indicated airspeed is given by Equation 3.

$$v_{TAS} = v_{EAS}\sqrt{\frac{\rho_o}{\rho}}$$

Hence,

where,

ρ_O - Density of air at sea level

ρ - Density of air at a given altitude
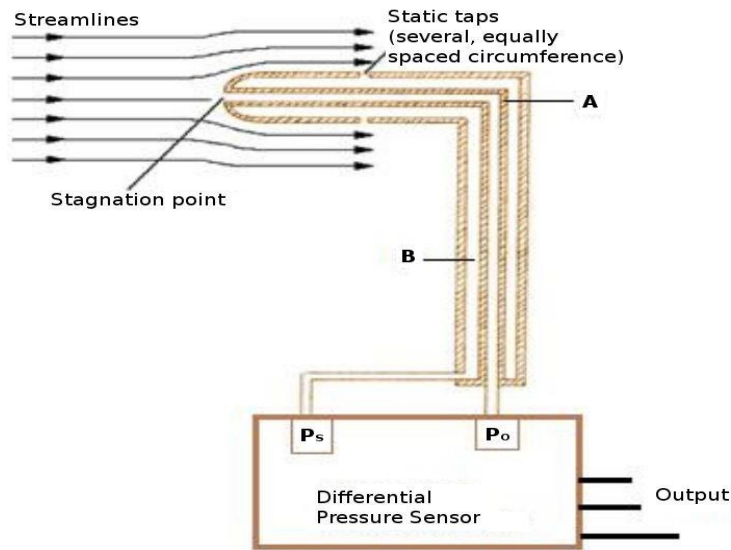
Pitot-Static tube

Figure 1: Schematic diagram representing the function of Pitot-Static tube

1. A schematic drawing of a pitot-static tube is presented in the Figure 1. It consists of two concentric tubes, say A and B.

2. The rear ends of these two tubes are connected to a differential pressure sensor. Typically a pressure sensor is a micro electro-mechanical device that is capable of measuring pressure and provides an equivalent analog output.

3. The front end of the tube A is open to free stream to trap the total pressure (P_o) during the flight.

4. Whereas tube B is a closed mouth tube having equally spaced peripheral holes to communicate with the surrounding air. Thus, tube B will be capturing the static pressure (P_S).

5. The output of the pressure sensor is usually in volts (V). In order to use this setup for velocity measurement, one has to calibrate the pressure sensor. Once the calibration chart is available for the specific pressure sensor, we can convert voltage (V) to Pascal (Pa).

Air data computers

- The measurement of the air data has been considered in terms of individual, mechanical instruments each providing an indication of one air data parameter. In many applications, the air data instruments have been replaced by an air data computer that carries out all the functions of the air data instruments. In addition it applies the known corrections to give the airspeed, altitude and air temperature in their most convenient form either for display to the pilot or to be transmitted to other systems on the aircraft.

THE FORCE SYSTEM OF THE AIRCRAFT AND THE EQUATIONS OF MOTION
The equations of motion for performance

- The equations of motion of the aircraft are statements of Newton's law, F = ma, in each of three mutually perpendicular axes. The general force F is the sum of the components of a system of forces acting on the aircraft, which results in the inertial force, ma. The system of forces acting on the aircraft can be categorized into four groups; the gravitational forces, Fg, the aerodynamic forces, Fa, and the propulsive forces, Fp, which result in the inertial forces, F1, so that the statement of Newton's law becomes,

$$F_a + F_p + F_g = F_I$$

- There will also be a system of moments acting on the aircraft but, as these do not affect the flight path directly, they do not need to be taken into account in the equations of motion for performance. Each group of forces acts in its own axis system and needs to be resolved into the velocity axis system before the equations of motion for performance.
- Each group of forces acts in its own axis system and needs to be resolved into the velocity axis system before the equations of motion can be developed. The axis systems are described in full in Appendix A and the full equations of motion for aircraft performance are developed in Appendix B. Only a summary of the characteristics of the forces and the equations of motion will be considered here.

$$- D + [T \cos(\alpha + \tau_1) \cos \beta - D_M] - mg \sin \gamma_2$$

$$= m\dot{V} + \dot{m}V$$

$$Y \cos \gamma_1 + L \sin \gamma_1 + T[- \cos(\alpha + \tau_1) \sin \beta \cos \gamma_1 + \sin(\alpha + \tau_1) \sin \gamma_1]$$

$$= mV\dot{\gamma}_3 \cos \gamma_2$$

$$Y \sin \gamma_1 - L \cos \gamma_1 + T[- \cos(\alpha + \tau_1) \sin \beta \sin \gamma_1 - \sin(\alpha + \tau_1) \cos \gamma_1] + mg \cos \gamma_2$$

$$= -mV\dot{\gamma}_2$$

(3

In these equations of motion some simplifying assumptions have already been made, three include the assumption that all engines are operating at equal gross thrust. For conventional aircraft, additional assumptions can be made to simplify the equations further, these are:

- That the rate of change of aircraft mass is negligible, $m = 0$.
- That the aircraft is in symmetric flight so that $\beta = 0$ and $Y = 0$.
- That the gross thrust acts in aircraft body axes, $\tau_1 = 0$.
- That the total net thrust Fn = $F_N = [T \cos \alpha - D_M]$, and
- That the thrust component $T\sin\alpha$ is small when compared with the lift force.

When these assumptions are made, the equations of motion reduced to a simplified form that can be used for most performance analysis takes:

$$\left.\begin{array}{r} F_N - D - mg \sin \gamma_2 = m\dot{V} \\ L \sin \gamma_1 = mV\dot{\gamma}_3 \cos \gamma_2 \\ -L \cos \gamma_1 + mg \cos \gamma_2 = -mV\dot{\gamma}_2 \end{array}\right\}$$

- The majority of performance analysis is based on the longitudinal equation of motion in which the term, Fn – D, is known as the excess thrust and provides the increase in potential energy (climb), or the increase in kinetic energy (acceleration).
- The equations of motion stated above are written in terms of aircraft with thrust-producing engines. If the ai4rcraft haspower-pr4oducing engines, which drive propellers to convert the power in to thrust, then the equations must be converted into their power form; this will be considered later in the section on propulsive forces.
- The movement of a given airplane through the atmosphere, insofar as it is responding to the four forces of flight. This movement is governed by a set of equations called the equations of motion.
- The equations of motion for an airplane are simply statements of Newton's second law, namely

F=ma

Consider an aircraft flying a curvilinear path as shown in Fig. below. To fly a curved path, a net force (Fnet), composed of force components parallel and perpendicular to the flight path, must exist. In applying Newton's 2nd law, acceleration parallel (linear) to the flight path is dV/dt— centripetal acceleration is V^2/r, where r is the radius of curvature of the curvilinear path. Lift, drag, thrust, and weight are the four forces acting on an aircraft

Aircraft flying a curvilinear path
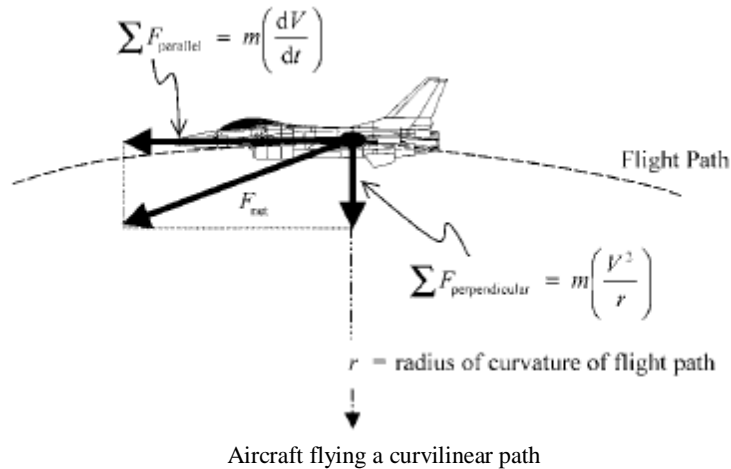
- A few points to remember about the figure:
1. Lift and drag, are the components of the aerodynamic force perpendicular and parallel to the relative wind (V_∞).
2. The x axis is a body-fixed axis, aligned with the ''reference line'' of the aircraft.
3. The aircraft's angle of attack (α) is between the x axis and the relative wind.
4. In general, the thrust vector is not aligned with the aircraft's reference line. Rather, it is displaced through an angle ϕ_T, called the thrust angle.
5. The flight path angle (γ) is the angle between the horizon and the relative wind.
6. The pitch angle (θ) is the angle between the aircraft's reference line and the horizon. It is sometimes referred to as pitch attitude or the deck angle (on transports, the cargo deck is usually taken as the aircraft's reference line).
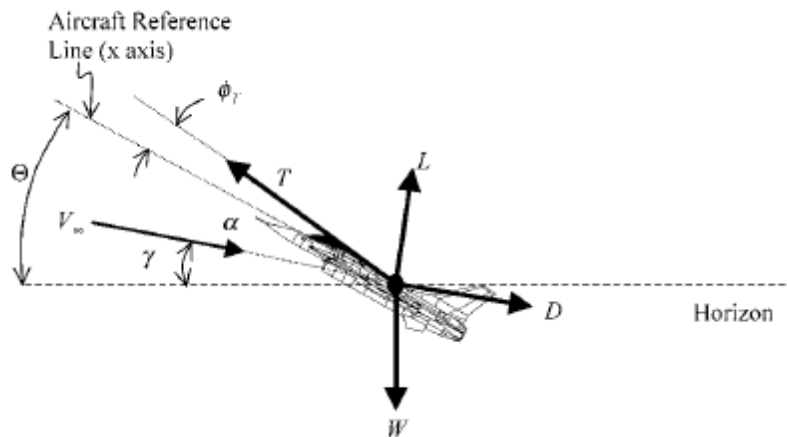
Forces and angles acting on an aircraft in flight

Summing forces, parallel and perpendicular to the flight path, yields the following.

$$\Sigma F_{parallel} = m\left(\frac{dV}{dt}\right) = T\cos(\phi_T + \alpha) - D - W\sin\gamma$$

$$\Sigma F_{perpendicular} = m\left(\frac{V^2}{r}\right) = W\cos\gamma - L - T\sin(\alpha + \phi_T)$$

The aircraft force system

- In the development of the equation of motion, the forces acting on the aircraft are represented as simple force terms and appear as constants.
- However, the forces stated in eqn (3.1) and in the equations of motion are not simple forces but depend on the performance variables, aircraft weight, airspeed (or flight Mach number) and the state of the atmosphere. In particular, the aerodynamic forces and the propulsive forces are of great importance to the performance of the aircraft. Their characteristics will define, for example, the airspeeds for best climb rate and gradient and for optimum range or endurance in the cruise part of the flight.
- Each group of forces can be considered in turn to determine how its characteristics very with the flight variables.

The inertial forces, f1

- The inertial forces arise from the mass of the aircraft and its acceleration. The accelerations may be linear accelerations or result from the combination of the forward speed of the aircraft with its rates of pitch and turn. The inertial forces act in the velocity axis system, which is discussed fully in Appendix B.

The gravitational forces, fg

- The gravitational force acts downwards in the Earth axis system and is the product of the aircraft mass, m, and the acceleration due to gravity, g. It may be referred to either as weight, W, or ass the product mg; each form of reference has its own applications within the theory and practice of aircraft performance.

The aerodynamic forces, fa

- The aerodynamic forces arise from the relative motion between the aircraft and the air mass in which it is flying; they act in the wind axis system. It will be assumed that the reader is familiar with the concepts of aerodynamics and this treatment will only consider the aerodynamic characteristics of the aircraft that are directly applicable to the study of performance.
- The dynamic pressure of the airflow, q, may be considered in terms of either airspeed or Mach number,

$$q = \tfrac{1}{2}\rho V^2 = \tfrac{1}{2}\gamma p M^2$$

- Whilst either form may be used when considering the non-dimensional aerodynamic forces, the form involving the mach number is particularly useful when considering operational performance. If the airspeed is considered in terms of the flight Mach number, then the temperature of the atmosphere is implicit in the statement of the Mach number and the atmosphere pressure can be considered independently. Since altitude is related uniquely to the static pressure of the atmosphere, the altitude becomes a basic variable of the aerodynamic forces. Therefore, the forces need to be considered only in terms of their variation with aircraft weight, flight Mach number and altitude a rather than in terms of aircraft weight, airspeed, altitude and temperature.
- The aerodynamic forces that concern performance are the lift, L, the drag, D, and the side force, Y. In the case of an air4craft, the speed of flight is relatively high and the non-dimensional flow variables that characterize the flow are,

$$R_e = \frac{\rho V l}{\mu}$$

(i) The Reynolds number,

- Typically the flight value of Re is large, 10 to 10 , and the flow can be treated as continue flow. If the aerodynamic characteristics of the aircraft have been determined from experimental sources (e.g. wind tunnels), any Reynolds number effects should have been accounted for before being used in any performance estimation process. It is unlikely that the Reynolds number will influence the analysis of the full scale flight performance of the aircraft significantly, except in extreme cases.

(ii) The Mach number, M = V/a

- This may vary from almost zero up to a typical maximum of 2.2 for conventional aircraft; higher Mach number is possible but raises special problems. Since this treatment of performance is concerned mainly with subsonic flight, the supersonic flow characteristics will not be considered in depth. Only in the transonic region, where the Mach numbers Will the effects be considered. In flight up to Mach number of 0.5 the flow can be regarded as incompressible and Mach number effects ignored; for

0.5<M<0.8 compressibility becomes significant and may lead to small changes in the lift and drag force characteristics. For most subsonic aircraft the critical Mach number occurs typically around M = 0.8; at this Mach number the local flow at points on the aircraft becomes supersonic and shock waves begin to form. This effect starts the change from subsonic to supersonic flow and affects the characteristics of both the lift and drag forces, leading to significant effects on the performance of the aircraft. March number is one of the most important variables of performance and its effect on the aerodynamic forces needs to be considered

Lift, drag, side force

$$L = \tfrac{1}{2}\rho V^2 S C_L = \tfrac{1}{2}\rho V^2 S a(\alpha - \alpha_0)$$
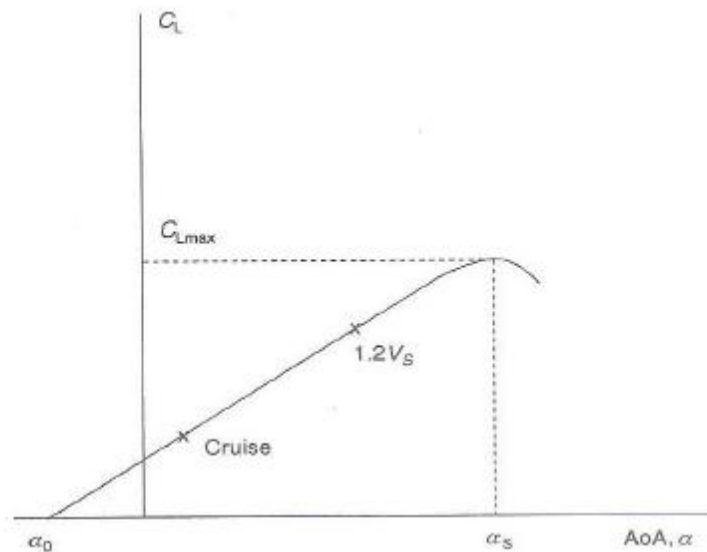
Lift Characteristic of a plain, cambered aerofoil.

- The aerodynamic force exerted on a body immersed in airflow is due to the two hands of nature which are in direct contact with the surface of the body; these two hands of nature are the pressure and shear stress distributions acting all over the exposed surface of the body. The pressure and shear stress distributions exerted on the surface of an airfoil due to the airflow over the body are sketched; pressure acts locally perpendicular to the surface, and shear stress acts locally parallel to the surface. The net

aerodynamic force on the body is due to the pressure and shear stress distributions *integrated* over the total exposed surface area.

$p = p(s)$

$\tau = \tau(s)$

(a) Pressure distribution (schematic only; distorted for clarity)

(b) Shear stress distribution
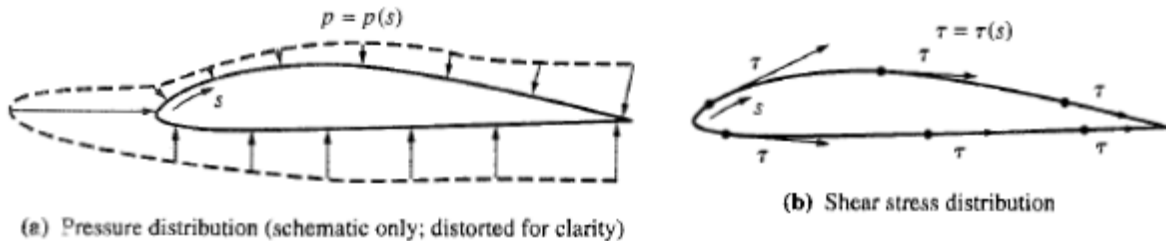
The component of R perpendicular to the free-stream velocity is the *lift* and the component of R parallel to the free-stream direction is the *D.* The force perpendicular to the other two is called the **side force**. The side force concept is mostly used in connection with turning aircraft.
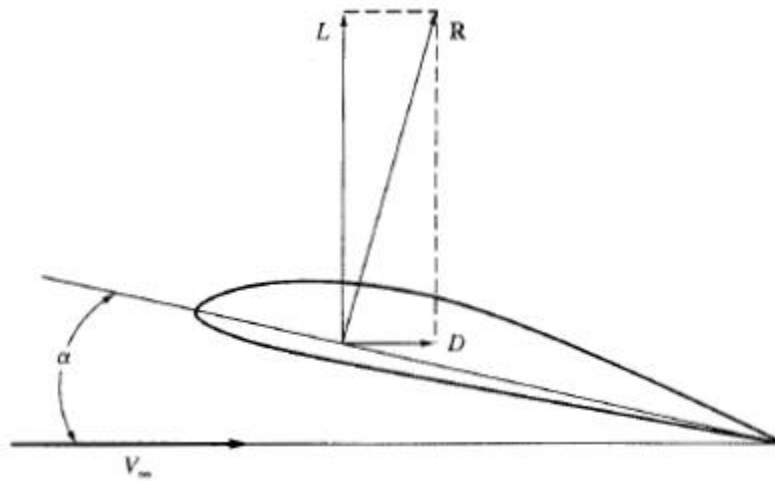

Total airplane drag- estimation, drag reduction methods.

- Drag is simply force that opposes the motion of an aircraft through the air. However it does have separate components that comprise it.

- **Total Drag** produced by an aircraft is the sum of the **Profile** drag, **Induced** drag, and **Parasite** drag. Total drag is primarily a function of airspeed. The airspeed that produces the lowest total drag normally determines the aircraft best-rate-of-climb

speed, minimum rate-of-descent speed for autorotation, and maximum endurance speed.

- **Profile Drag** is the drag incurred from frictional resistance of the blades passing through the air. It does not change significantly with angle of attack of the airfoil section, but increases moderately as airspeed increases.

- **Induced Drag** is the drag incurred as a result of production of lift. Higher angles of attack which produce more lift also produce increased induced drag. In rotary-wing aircraft, induced drag decreases with increased aircraft airspeed. The induced drag is the portion of the **Total Aerodynamic Force** which is oriented in the direction opposing the movement of the airfoil.

- **Parasite Drag** is the drag incurred from the non lifting portions of the aircraft. It includes the form drag and skin friction associated with the fuselage, cockpit, engine cowlings, rotor hub, landing gear, and tail boom to mention a few. Parasite drag increases with airspeed.

- The graphic illustrates the different forms of drag versus airspeed:

DRAG/AIRSPEED RELATIONSHIP
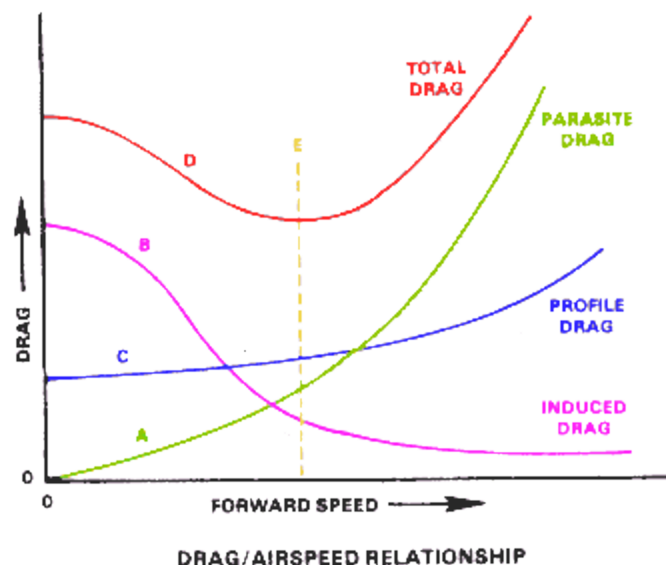
- Curve "A" shows that parasite drag is very low at slow airspeeds and increases with higher airspeeds. Parasite drag goes up at an increasing rate at airspeeds above the midrange.

- Curve "B" shows how induced drag decreases as aircraft airspeed increases. At a hover, or at lower airspeeds, induced drag is highest. It decreases as airspeed increases and the helicopter moves into undisturbed air.
- Curve "C" shows the profile drag curve. Profile drag remains relatively constant throughout the speed range with some increase at the higher airspeeds.
- Curve "D" shows total drag and represents the sum of the other three curves. It identifies the airspeed range, line "E", at which total drag is lowest. That airspeed is the best airspeed for maximum endurance, best rate of climb, and minimum rate of descent in autorotation.

(Total drag) = (parasite drag) + (wave drag) + (induced drag)

- For the subsonic transport, the elements labeled wing, body, empennage, engine installations, interference, leaks, undercarriage, and flaps are the contributors to the zero-lift parasite drag; that is, they stem from friction drag and pressure drag (due to flow separation). The element labeled lift-dependent drag (drag due to lift) stems from the increment of parasite drag associated with the change in angle of attack from the zero-lift valve, and the induced drag. Note that most of the drag at cruise is parasite drag, whereas most of the drag at takeoff is lift-dependent drag, which in this case is mostly induced drag associated with the high lift coefficient at takeoff.
- For the supersonic transport, more than two-thirds of the cruise drag is wave drag-a combination of zero-lift wave drag and the lift-dependent drag (which is mainly wave drag due to lift). This dominance of wave drag is the major aerodynamic characteristic of supersonic airplanes. At takeoff, the drag of the supersonic transport is much like that of the subsonic transport, except that the supersonic transport experiences more lift-dependent drag. This is because the low-aspect-ratio delta wing increases the induced drag, and the higher angle of attack required for the delta wing at takeoff (because of the lower lift slope) increases the increment in parasite drag due to lift.

The propulsive forces - the thrust production engines, power producing engines,

- There are two basic forms of power plant used for aircraft propulsion
- ➢ The thrust-producing power plant, which produces its propulsive force directly by increasing the momentum of he airflow through the engine, and
- ➢ The power-producing power plant, which produces shat power that is then turned into a propulsive force by a propeller.

- ➢ Each form of power plant has different characteristics and needs to be considered separately.

The thrust-producing power plant

- ➢ The usual from of thrust-producing engine is the turbojet or turbofan, although rocket could be included in this category.
- The turbojet or turbofan engine uses atmospheric air as its working fluid and, with the addition of fuel, burns the air to increase its energy.
- The high-energy air is then expelled through a nozzle with increased momentum to produce the thrust force.
- In simplified terms, the turbojet engine can be considered to produce thrust by increasing the momentum of its internal flow stream. The net propulsive force, Fn, is the difference between the stream force entering the engine and the stream force exiting the engine. The thrusts produced at the exit plane of the nozzle is known as the gross thrust, Fg, and is equal to the rate of change of momentum of the exhaust gas flow, Fg = mVj. The flow into the intake also contributes to the engine thrust. In this case, the momentum of the flow is lost as the air enters the engine.
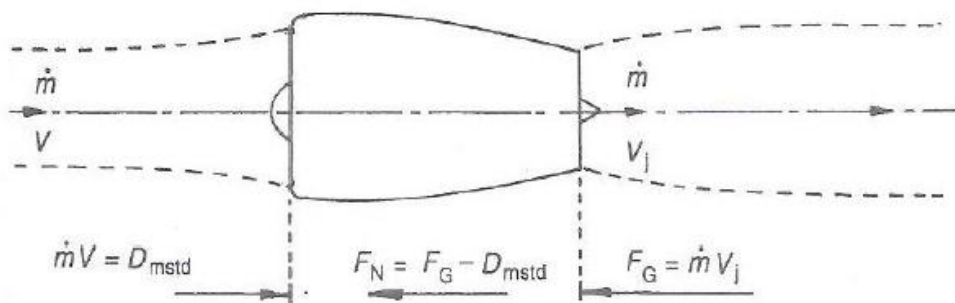

Fig 1.24 The thrust-producing power plant

- The force due to the intake flow, known as the momentum drag, Dm, is equal to the rate of change of momentum in the intake airflow, Dm = mV. The net propulsive thrust is given by

$$F_N = F_G - D_m = \dot{m}V_j - \dot{m}V$$

- The net thrust of the power plant will be affected by the flight Mach number and altitude. It is not possible to postulate any precise function that will relate thrust to Mach number or altitude for all thrust-producing power plants. However, simple relationships can be developed that will enable the general characteristic of the thrust variation with Mach number and altitude to be deduced. From above eqution the net thrust can be expressed as,

$$F_{\mathrm{N}} = \dot{m}(V_{\mathrm{j}} - V)$$

The power-producing power plant

- The power-producing power plant delivers its power through a rotating shaft to a propeller that converts the power into propulsive thrust. The power plant may be either a piston engine or a gas turbine that converts the energy of its gas flow into shaft-power rather than into thrust. In either case the shaft-power output is not greatly affected by airspeed and, to a first-order approximation, the power can be regarded as independent of airspeed.
- The shaft-power, P, is converted into thrust, T, by the propeller. In the process, losses occur and the thrust-power produced will be less than the shaft-power delivered. The propeller efficiency, n, is the ratio of the thrust-power output to the shaft-power input so that,

$$\eta P = TV$$

Where V is the true airspeed.

This implies that the propulsive thrust increases as airspeed decreases at constant engine power and that the thrust will become infinite at zero airspeed. In practice, the propeller efficiency will vary with airspeed and a constant engine shaft-power produces a finite thrust at zero airspeed, known as the Static Thrust, which decreases as the airspeed increases. The propeller efficiency, n, is a characteristic of an individual propeller and depends on the Advance ratio, J, of the propeller, and the Power coefficient, Cp, of the engine.

- The propeller Advance ratio is given by $\qquad J = V/nD$
- And the engine Power coefficient by,

$$C_{\mathrm{P}} = \frac{P}{\frac{1}{2}\rho n^3 D^5}$$

Where n is the rotational speed in rad/s and is the propeller diameter.

- The propulsive thrust is a function of airspeed, eqn. The equation is now written in the form.

$$\frac{\eta P}{V} = D + W \sin \gamma_2 + m\dot{V}$$

Or, rearranging and writing in terms of equivalent airspeed gives

$$\eta P \sqrt{\sigma} - DV_e = WV\sqrt{\sigma}\left[\sin\gamma_2 + \frac{V}{g}\right]$$

- Thrust is the propulsive force which moves an aircraft through the air. Thrust is used to overcome the drag of an airplane, and to overcome the weight of a rocket. Thrust is generated by the **engines** of the aircraft through some kind of propulsion system.

- Thrust is a mechanical force, so the propulsion system must be in physical contact with a **working fluid** to produce thrust. Thrust is generated most often through the reaction of accelerating a mass of gas. Since thrust is a force, it is a vector quantity having both a magnitude and a direction. The engine does work on the gas and accelerates the gas to the rear of the engine; the thrust is generated in the **opposite direction** from the accelerated gas. The magnitude of the thrust depends on the amount of gas that is accelerated and on the difference in velocity of the gas through the engine.

- To accelerate the gas, we have to expend energy. The energy is generated as heat by the combustion of some fuel. The thrust equation describes how the acceleration of the gas produces a force. The type of propulsion system used on an aircraft may vary from airplane to airplane and each device produces thrust in a slightly different way. The four principal propulsion systems: the propeller, the jet engine, the ramjet, and the rocket.

- Reciprocating engine is the rotating crankshaft-this is the means by which the engine's power is transmitted to the outside world-a wheel axle in the case of an automobile, or a propeller in the case of an airplane. The power output of the engine is directly proportional to the *rpm.* Third, the amount of force applied by the burned gas on the face of the piston after combustion will affect the work performed during each power stroke. Hence, the higher the pressure in the cylinder during the power stroke, the

larger will be the power output. An average pressure which is indicative of the pressure level in the cylinder is defined as the *mean effective pressure* P_e. Therefore, we can state that the power output from the engine to the crankshaft, called the *shaft brake power P,* is

$$P \propto dp_e RPM$$
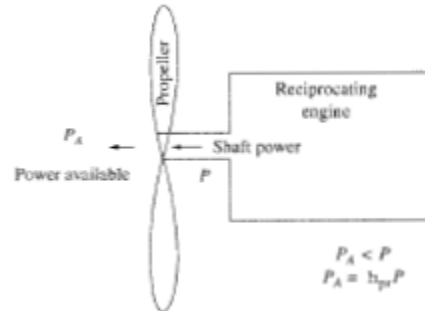
- The thrust generated by the engine is due to the net resultant of the pressure and shear stress distributions acting on the exposed surface areas, internal and external, at each point at which the gas contacts any part of the device. The calculation of jet engine thrust is carried out infinitely more simply by drawing a control volume around the engine, looking at the time rate of change of momentum of the gas flow through the engine, and using Newton's second law to obtain the thrust.

$$T = (\dot{m}_{air} + \dot{m}_{fuel})V_j - \dot{m}_{air}V_\infty + (P_e - P_\infty)A_e$$
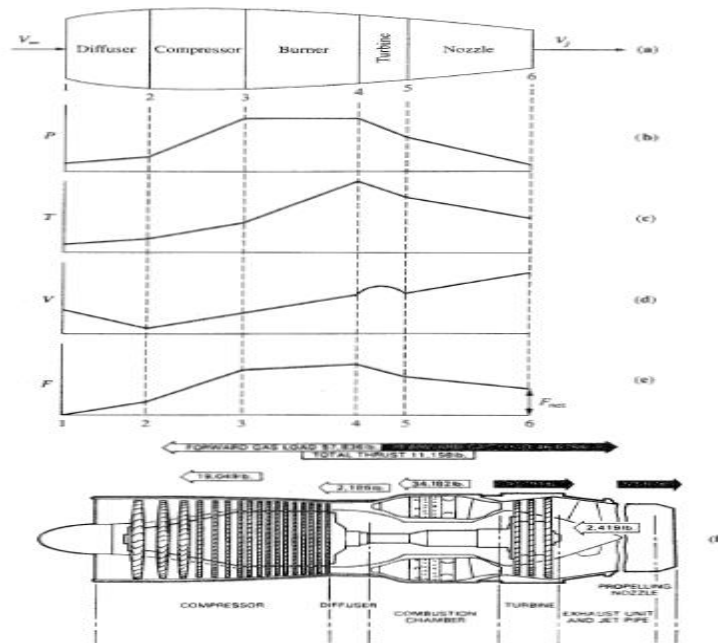
- The measurable primary output from a jet engine is thrust, whereas that for a piston engine is power. Therefore, for a turbojet the specific fuel consumption is based on thrust rather than power; to make this clear, it is frequently celled the *thrust* specific fuel consumption. We denote it by c_t, and it is defined as

c_t = weight of fuel burned per unit thrust per unit time

variation of propulsive power and specific fuel consumption with altitude and flight speed.

- Consider the engine mounted on an airplane. As the airplane velocity V_∞ is changed, the only variable affected in power Eq. is the pressure of the air entering the engine manifold, due to the stagnation of the airflow in the engine inlet. (Sometimes this is called a *ram effect.)* In effect, as V_∞ increases, this "ram pressure" is it is reflected as an increase in P_e in Eq. which in tum increases P via Eq. For the high-velocity propeller-driven fighter airplanes of World War II, this effect had some significance. However today reciprocating engines are used only on low-speed general aviation aircraft and the ram effect can be ignored. Hence Power is reasonably constant with V_∞. Similarly SFC is also constant with V_∞.

variation of thrust and specific fuel consumption with altitude and flight speed.

- Consider the mass flow of air m_{air}. The mass flow of air entering the inlet is $\rho_\infty A_1 V_\infty$, where A_1 is the cross-sectional area of the inlet. As V_∞ is increased, V_j stays essentially the same; the value of V_j is much more a function of the internal compression and combustion processes taking place inside the engine than it is of V_∞. Hence, the difference $V_j - V_\infty$ tends to decrease as V_∞ increases. From thrust eq with V_∞ increasing but V_j staying about the same, the value of T is decreased. These two effects tend to cancel in thrust eq, and therefore we might expect the thrust generated by a turbojet to be only a weak function of V_∞.

- Here the thrust for a typical small turbojet is given as a function of flight Mach number for two altitudes, sea level and 40,000 ft, and for three different throttle settings (denoted by different compressor rpm values) at each altitude. Note that, especially at altitude, T is a very weak function of Mach number.

- There is a strong altitude effect on thrust, as can be seen by examining thrust eq. Again, we note that $m_{air} = \rho_\infty A_1 V_\infty$; hence m_{air} is directly proportional to ρ_∞. As the altitude increases, ρ_∞ decreases. In turn, from thrust eq where T is almost directly proportional to m_{air}, thrust also decreases with altitude. Indeed, it is reasonable to express the variation of T with altitude in terms of the density ratio ρ / ρ_0, where p is the density at a given altitude and ρ_0 is sea-level density.

UNIT - II

CRUISE PERFORMANCE

Introduction

- The cruise performance of an aircraft is one of the fundamental building blacks of the overall mission.
- In the cruising segment of the mission, both height and airspeed are essentially constant and the (airspeed) aircraft is required to cover distance in the most expedient manner.
- Usually, the majority of the fuel carried in the aircraft will be used during the cruise.
- The distance that can be flown, on the time that the aircraft can remain aloft, on a given quantity of fuel are important factors in the assessment of the cruise performance

Maximum and minimum speeds in level flight

- By definition, the thrust available curve is the variation of T_A with velocity at a given throttle setting and altitude. For the throttle full forward, $(T_A)max$ is obtained. The maximum thrust available curve is the variation of $(T_A)max$ with velocity at a given altitude. For turbojet and low-bypass-ratio turbofans, we have seen that at subsonic speeds, the thrust is essentially constant with velocity. Hence, for such power plants, the thrust available curve is a horizontal line, as sketched in Figure below.
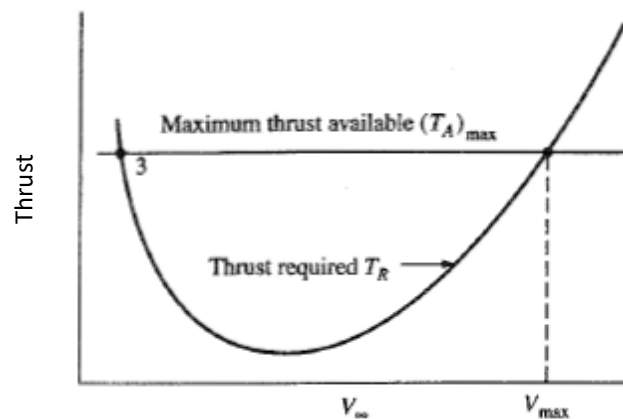
- In steady, level flight, the maximum velocity of the airplane is determined by the highspeed intersection of the thrust required and thrust available curves.
- Finding V_{max} from the intersection of the thrust required and thrust available curves, as shown in above Figure, is a graphical technique. An analytical method for the direct solution of V_{max} follows from the velocity Eq through thrust required. For steady, level flight, $T_R = T_A$.

For flight at V_{max}, the thrust available is at its maximum value. Hence,

$$T_R = (T_A)_{max} \text{ ---- 2.1}$$

In Eq., replacing V_∞ with V_{max} and T_R with $(T_A)_{max}$, and taking the plus sign in the quadratic expression because we are interested in the highest velocity, we have

$$V_{max} = \left\{ \frac{\left[\frac{(T_A)_{max}}{W}\right]\left(\frac{W}{S}\right) + \left(\frac{W}{S}\right)\sqrt{\left[\frac{(T_A)_{max}}{W}\right]^2 - 4C_{D,o}K}}{\rho_\infty C_{D,o}} \right\}^{1/2} \text{ --- 2.2}$$

- The above equation allows the direct calculation of the maximum velocity. Moreover, being an analytic equation, it clearly points out the parameters that influence V_{max}. Note in Eq. 2.2 that depends on (1) the maximum thrust-to-weight ratio $(T_A)_{max}/W$, (2) wing loading W/S, the drag polar via $C_{D,o}$ and K, and altitude via ρ_∞.

From this equation we see that
1. V_{max} increases as $(T_A)max$, W increases.
2. V_{max} increases as W / S increases.
3. V_{max} decreases as $C_{D}.o$ and/or K increases.

When the aircraft is cruising in trim the equations of motion of a conventional aircraft

$$F_N - D - mg\sin\gamma_2 = mv$$
$$L\sin\gamma_1 = mv\gamma_3\cos\gamma_2$$
$$-L\cos\gamma_1 + mg\cos\gamma_2 = -mv\gamma_2$$

The above equations can be reduced to the simple statements

$$F_N = D$$
$$L=W$$

Range and endurance with thrust production, and power producing engines

Definitions of range and endurance
- Range (R) is the horizontal distance covered, with respect to a given point on the ground, with a given amount of fuel. It is measured in km.
- Endurance (E) is the time for which an airplane can remain in air with a given amount of fuel. It is measured in hours.

Cruising efficiency can be measured in terms of either the range or the endurance of the aircraft.

The Specific Air Range (SAR) is defined as the horizontal distance flown per unit of fuel consumed and the Specific Endurance (SE) is defined as the time of flight per unit of fuel consumed.

The distance travelled, x, in still air is given by the time integral of the true airspeed, V, so that

$$V = dx/dt$$

And in cruising flight the true airspeed is usually quoted in knots, or nautical miles per hour (nm/hour)

In addition, during cruise, fuel is burned and the fuel mass flow, Qf, will determine the rate of change of mass of the aircraft,

$$Q_f = -dm/dt$$

- The above definition of range is very general and terms like safe range and gross still air range are commonly used. These terms include details of the flight plan and are explained in the subsequent subsections.

The fuel mass flow is usually quoted in kg/hour and is negative since the mass of the aircraft decreases with time as fuel is burned.

- Cruising efficiency can be measured in terms of either the range or the endurance of the aircraft. The specific Air Range (SAR) is defined as the horizontal distance flown per unit of fuel consumed.

$$SAR = -\frac{dx}{dm} = V/Q_f \text{ ---- 2.3}$$

Where *V=dx/dt* is the velocity and *Qf =-dm/dt* fuel burned during cruise

The Specific Endurance (SE) is defined as the time of flight per unit of fuel consumed.

$$SE = -\frac{dt}{dm} = 1/Q_f \text{ ---- 2.4}$$

If the aircraft is powered by thrust producing engines the fuel flow is seen to be a function of engine thrust which in cruise is equal to drag.

$$L=W$$

$$F_N = D$$

The specific fuel consumption, C is defined as the fuel flow per unit thrust

$$C = Q_f/F_N \text{---- 2.5}$$

By using steady level flight equations and eq 2.5 in SAR and SE equation with suitable integration we get

$$SAR = \frac{V}{C}\frac{L}{D}\frac{1}{W} \text{---- 2.6}$$

$$SE = \frac{1}{C}\frac{L}{D}\frac{1}{W} \text{---- 2.7}$$

If the aircraft has power-producing engines which produce shaft power with negligible residual thrust, the power is converted into propulsive thrust by a propeller. In this case, the performance equation is written in terms of thrust power available and drag power required for cruising flight,

$$\eta P = DV \text{---- 2.8}$$

Where η is propeller efficiency

The specific fuel consumption is defined in power terms as

$$C = Q_f/P \text{---- 2.9}$$

$$SAR = \frac{V}{CP} = \frac{\eta}{C}\frac{L}{D}\frac{1}{W} \text{---- 2.10}$$

$$SE = \frac{1}{CP} = \frac{\eta}{CV}\frac{L}{D}\frac{1}{W} \text{---- 2.11}$$

Cruise method 1
Constant angle of attack, constant Mach number

- In this method, the air pressure must be allowed to decrease to allow for the decrease in air craft weight as fuel is consumed, thus

$$W = \frac{1}{2}\gamma P M^2 S C_L \text{---- 2.12}$$

- This implies that the aircraft must be allowed to climb during the cr4uise to maintain the parameter W/p constant and the method is known as the Cruise-Climb technique. Since the angle of attack is constant throughout the cruise the lift coefficient, and hence lit-drag ratio. L/D, will be constant. The constant Mach number implies flight at constant true airspeed.

- Let the range under cruise method 1 be then from above equation,

$$R_1 = \frac{V}{C} \frac{L}{D} \int_{W_i}^{W_f} \frac{dW}{W}$$

This becomes,

$$R_1 = \frac{V}{C} \frac{L}{D} l_n \omega$$

- This expression is the best known expression for the range of an aircraft and is known as the Breguet Range expression.
- Although it offers the optimum performance in terms of distance flown on a given fuel load there are practical reasons that make its application to flight operations difficult, and further consideration of this cruise method is necessary.
- As weight decreases during the cruise the variables on the right side of above equation has to compensate. So, by using three variables (Pressure, Mach number and Coefficient of lift) thus three methods can be considered to compensate reduction in weight by varying one variable with other two constants.

Cruise method 2: Constant angle of attack, Constant altitude

- In this case, the Mach number, or true airspeed, must be reduced during cruise, so that

$$\frac{W}{M^2} = \frac{1}{2} \gamma P S C_L$$

- This implies that the lift coefficient and lift-drag ratio, will be constant during the cruise and that substituting for airspeed in SAR equation then range under cruise method 2 is

$$R_2 = \frac{1}{C} \left(\frac{2}{\rho S C_L} \right)^{\frac{1}{2}} \frac{L}{D} \int_{W_i}^{W_f} \frac{dW}{W^{\frac{1}{2}}} \qquad \text{----- 2.18}$$

$$R_2 = \frac{1}{C}\left(\frac{2W_i}{\rho S}\right)^{\frac{1}{2}} \frac{C_L^{\frac{1}{2}}}{C_D} 2(1 - \omega^{-\frac{1}{2}}) \quad \text{---- 2.19}$$

- The endurance of the aircraft in cruise method 1 is same as cruise method2.

Cruise method 3: Constant Mach number, Constant altitude

- In this case, the angle of attack must be allowed to decrease as the weight decreases to maintain constant W/C_L

$$\frac{W}{C_L} = \frac{1}{2}\gamma PSM^2$$

- Assuming that the aircraft is cruising at a speed greater than its minimum drag speed, then the decrease in lift coefficient during the cruise will cause the drag coefficient and hence the drag force to decrease. This will require a progressive decrease in the thrust required to maintain the Mach number or true airspeed constant. Since the lift-drag ratio will not be constant, the range will need to be found by integrating the drag over the weight change during cruise.

$$R_3 = \frac{V}{C}\int_{W_i}^{W_f} \frac{dW}{D}$$

Now for an aircraft with a parabolic drag polar.

$$D = qSC_{Dz}^{\cdot} + \frac{KW^2}{qS}$$

where $q = \frac{1}{2}\rho V^2$.

- Substituting in above equation and integrating gives,

$$R_3 = \frac{V}{C}\frac{1}{(KC_{Dz})^{\frac{1}{2}}}\left\{\tan^{-1}\left[\frac{W_i}{qS}\left(\frac{K}{C_{Dz}}\right)^{\frac{1}{2}}\right] - \tan^{-1}\left[\frac{W_f}{qS}\left(\frac{K}{C_{Dz}}\right)^{\frac{1}{2}}\right]\right\}$$

Now

$$\frac{W_i}{qS}\left(\frac{K}{C_{Dz}}\right)^{\frac{1}{2}} = \frac{C_{Li}}{C_{Lmdi}} = \frac{V^2_{mdi}}{V^2_i} = \frac{1}{u^2_i}$$

And, similarly,

$$\frac{W_f}{qS}\left(\frac{K}{C_{Dz}}\right)^{\frac{1}{2}} = \frac{1}{u^2_f}.$$

Methods- comparison of performance

- It has been possible to write the range and endurance attained by each method of cruise in the form of a product of a range factor and a range function, and of endurance factor and endurance function, giving

$$R = \left[\frac{V_{mdi}}{C} E_{max}\right]\{f_R(u_i,\omega)\} \quad \text{----- 2.22}$$

$$E = \left[\frac{E_{max}}{C}\right]\{f_E(u_i,\omega)\} \quad \text{----- 2.23}$$

- The range functions are compared for a fuel ratio of 1.5 and shows that the cruise-climb is the optimum method which gives 10% better range than the other methods.
- The comparison between the cruise methods for endurance shows less disparity but favours the constant angle of attack methods.
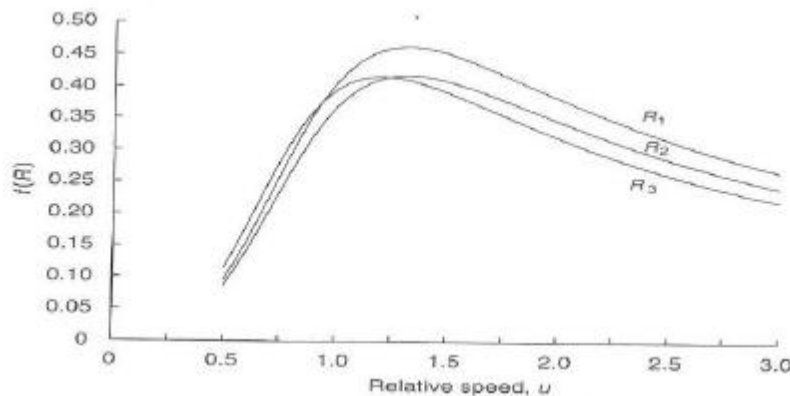
Comparison of cruise methods for range.

The effect of alternative fuel flow laws

- The range and endurance functions developed above have used the simple fuel flow law, above equation which assumes that the fuel flow is proportional only to net thrust. It was accepted that this fuel flow law is idealized, probably not full describing the characteristics of the engine, and that a more realistic law should be applied. If an alternative fuel flow law is considered, for example above equation then it may produce different optimum operating airspeeds.

Above equation states a fuel flow law of the form:

$$i.e \ C = C_2 \theta^{1/2} M^n$$

where n may vary from 0.2 for a turbojet to about 0.6 for hybass ratio turbofan.

If SAR and SE equations are written in terms of Mach number and the alternative fuel flow substituted they give,

$$SAR = \frac{a_0 \theta^{1/2}}{C_2 \theta^{1/2}} M^{1-n} \frac{L}{D} \frac{1}{W}$$

$$SE = \frac{1}{C_2 \theta^{1/2} M^n} \frac{L}{D} \frac{1}{W}$$

When these expressions are differentiated, they give the airspeeds for maximum SAR and SE to be,

$$V_{max}SAR = \left[\frac{3-n}{1+n}\right]^{1/4} V_{md} \quad V_{max}SE = \left[\frac{2-n}{2+n}\right]^{1/4} V_{md}$$

The effect of weight, altitude and temperature on cruise performance

- For a given final weight of the aircraft, the increase in initial weight implies an increase in the fuel available for the cruise; it is this that extends the range not the weight of the aircraft itself.
- An increase in air temperature increases the range since the TAS (True Air Speed) is increased and the aircraft flies further in given time, during which it burns the same quantity of fuel. If the specific fuel consumption is a function of air temperature then the effect of the temperature may be lessened and the range may even decrease as temperature increases.
- Increasing altitude will produce an increase in the range as the ambient relative pressure decreases. In the troposphere, the effect will be reduced by the accompanying decrease of temperature with altitude and further affected by any dependency of the SFC on air temperature.

Cruise performance with mixed power-plants.

- Turboprop is the engine which converts the turbine shaft power into thrust by using propeller and the exhaust gases convert into thrust using nozzle.
- By using cruise-climb range expressions for thrust and power producing engines cruise performance of mixed power plants in terms of Range can be obtained as

$$R = E_{max} \left[\Pi \frac{\eta}{C_p} + (1 - \Pi) \frac{uV_{md}}{C_T} \right] \left\{ \frac{2u^2}{u^4+1} \right\} l_n \omega \quad \text{----- 2.28}$$

- Where Π is the proportion of the thrust derived from the shaft power in the overall thrust of the power plant and C_P and C_T are the specific fuel consumptions based on the shaft power and net thrust respectively.

UNIT - III

CLIMB, DESCENT AND MANOEUVRE PERFORMANCE

Climb and descent techniques

- Climb is a phase in the overall mission of the aircraft in which the aircraft increases its height to the required cruising level from takeoff and in a descent phase the aircraft decreases its height from the end of the cruise to the landing. Climb performance is important from both economic and flight safety point of view. The descent is less critical than the climb economically since the aircraft will be operating at low thrust and hence low fuel flow.

- In these phases of flight, the difference between the propulsive thrust and the airframe drag is used to change the potential and kinetic energy of aircraft. If the thrust exceeds drag the aircraft will climb and if drag exceeds thrust then aircraft will descend.

- The fuel required to climb to a given height can be minimized by the use of the correct climb technique. A climb or a descent will usually be performed with reference to an indication either of airspeed or of Mach number.

- The constant EAS climb implies, as the aircraft climbs, the ambient air density will be decreasing and the true airspeed will be increasing thus the aircraft will be accelerating throughout climb.

- A constant Mach number results in a constant TAS and there is no acceleration.

- Steady state climb and descent can be measured in terms of rate or gradient. The rate of climb is the vertical, dH/dt. The gradient of climb is γ_2 is defined by

$$\gamma_2 = \sin^{-1}\left[\frac{dH/dt}{V}\right] \qquad ---- 3.1$$

- Where the height, H, is geopotential height.

Climb and descent performance analysis

- The power plant of the aircraft may be thrust producing or power producing. Thrust-producing engineers, turbojets and turbofans, produce thrust that is relatively constant with small change of airspeed in subsonic flight. Power-producing engines, piston engines or turbo-shaft engineers, produce shaft power, which is relatively constant with change of airspeed, and which needs to be converted into propulsive thrust by a propeller. The differing characteristics of these power plants lead to different criteria for optimum climb performance and each need to be considered separately.

Safety Considerations

- The safety of the aircraft depends on its ability to climb above obstructions at all points on the flight path. Sufficient excess thrust must be available to ensure that the aircraft can meet certain minimum gradients of climb in any of the safety critical segments of the flight. Several safety-related considerations will affect the choice of the flight path in the descent. Among them are the attitude of the aircraft, the rate of change of cabin pressure and the need for the engines to supply power for airframe services.

Performance analysis- Aircraft with Thrust producing engines

- The equations of motion of an aircraft with thrust-producing engines in a climb or descent can obtained using equation 1.1. In a straight, wings level, climb in which the flight path gradient is constant the equations of motion can be written as

$$F_N - D = W sin\gamma_2 + m\dot{V}$$

$$L = W cos\gamma_2$$

- If the aircraft has a normal takeoff thrust-to-weight ratio of about 0.3 then the rates of climb will be low enough to assume that the acceleration associated with the rate of climb is negligible. The climb can then be assumed to be made either at constant airspeed or constant Mach number. Also the gradient of climb and descent will be low enough to allow the assumption that $cos\gamma_2$=1 and the equation can be simplified as

$$F_N - D = W sin\gamma_2$$

$$L = W$$

- The excess thrust [F_N-D] provides the gradient of climb,

$$[F_N - D]\left(\frac{1}{W}\right) = sin\gamma_2$$

- If the thrust is constant the best gradient of climb will be obtained by flying at the minimum drag speed. Using eq 3.1 in 3.6 leads to an expression for the best rate of climb,

$$[F_N - D]\left(\frac{V}{W}\right) = \frac{dH}{dt}$$

- The above equation indicates that the airspeed for the best rate of climb occurs when the excess thrust power$[F_N V]$, over drag power, $[DV]$ is a maximum. Since the ideal thrust power increases linearly with true airspeed, the best rate of climb is predicted to be at airspeed greater than the minimum drag speed.

- The climb and descent performance can best be analysed in a general manner by considering a dimensionless form of the performance equation

$$\tau - \frac{1}{2}[u^2 + u^{-2}] = E_{max} sin\gamma_2 = E_{max}\left(\frac{v}{u}\right) \qquad \text{---- 3.8}$$

- Where $\tau = F_N/D_{min}$ and the dimensionless $v = \frac{dH/dt}{V_{md}}$

Maximum Climb Gradient

- By differentiating eq 3.8 the relative airspeeds for best climb or descent performance can be found. From eq 3.8 the gradient of climb is given by

$$E_{max} sin\gamma_2 = \tau - \frac{1}{2}[u^2 + u^{-2}]$$

- For maximum gradient $\frac{d\gamma_2}{du} = 0$, which occurs when u=1 if τ is constant, and confirms that the steepest climb occurs at the minimum drag speed. In the special case of gliding flight, in which $\tau = 0$, flight at the minimum drag speed will give the shallowest glide angle, which will give the greatest range of glide; this speed is used when cruising between thermals. The minimum glide angle will be

$$\gamma_2 = sin^{-1}[1/E_{max}]$$

Climb Rate

- From eq 3.8 the rate of climb is given by
$$E_{max}v = \tau u - \frac{1}{2}[u^3 + u^{-1}]$$

- For maximum rate of climb $\frac{dv}{du} = 0$ and the relative airspeed for best rate of climb is found to be a function of dimensionless thrust,

$$u = \frac{1}{\sqrt{3}}\left[\tau \pm (\tau^2 + 3)^{1/2}\right]^{1/2}$$

- In gliding flight, the minimum sink rate is attained by flying at a relative airspeed of $u/\sqrt[4]{3}$ which is the minimum power speed of the aircraft. Flying at this speed will maximize the time (or endurance) of gliding flight and is the speed used for climbing in thermals.

Performance analysis- Aircraft with Power producing engines

- The generalized performance equation for climb and descent is given from equations of motion for aircraft with power-producing engines as

$$\frac{\lambda}{u} - \frac{1}{2}[u^2 + u^{-2}] = E_{max} sin\gamma_2 = E_{max}\left(\frac{v}{u}\right) \qquad \text{---- 3.13}$$

Where λ is the dimensionless power given as $\lambda = \eta P / D_{min} V_{md}$

From eq 3.13 the gradient is given by

$$E_{max} sin\gamma_2 = \frac{\lambda}{u} - \frac{1}{2} [u^2 + u^{-2}] \text{ ----- 3.14}$$

and the rate of climb is given as

$$E_{max} v = \lambda - \frac{1}{2} [u^3 + u^{-1}] \qquad \text{---- 3.16}$$

Climb performance in aircraft operations

- One of the usual ways of determining the best climbing performance is by partial climbs. This technique consists of flying a number of short climb segments through a datum height. Each of the climbs is flown at a different airspeed around the predicted speed for best climb performance. The measured rates of climb are corrected for change of aircraft weight due to the consumption of fuel during the series of climbs. So that the performance relates to a common standard aircraft weight. The measured climb rate and climb gradient can then be plotted against airspeed to give the actual airspeeds for best performance under the weight, altitude and temperature conditions of the test. From these measured data the airspeeds at which optimum climb performance is achieved can be found.
- An alternative method is to measure the maximum excess thrust or power by level accelerations. In this technique, the aircraft is flown as slowly as possible in level flight; maximum thrust or power is selected and the airspeed recorded in a level acceleration to maximum airspeed. From the acceleration, the excess thrust or power can be deduced and thus so can that speeds for best climb performance.
- The level acceleration method is best suited to aircraft with thrust-producing engines and the partial climb method is best suited to aircraft with power producing engines since the best climb speeds tend to be towards the lower end of their speed range.

Minimum fuel climbs

- The fuel consumed in the climb can be expressed in terms of the specific climb, SC, as

$$SC = \frac{dH/dt}{Q_f} \text{ ----- 3.17}$$

- If the fuel flow is measured during the flight trails to determine the optimum climb speed, then the specific climb function can be formed to give the airspeed for a minimum fuel climb.

Descent performance in aircraft operations

- If the propulsive thrust is less than the airframe drag then the aircraft will decelerate or descend. The aircraft has wide range of descent flight paths like shallow descent, steep descent which occurs by changing thrust and drag. In the special case of gliding flight, in

which there is no propulsive thrust, the descent will be determined based on lift-drag ratio.

- A descent can be produced by flying at airspeed less than the minimum drag speed; the aircraft will not have a stable flight path. The stability of flight path occurs when the flight path gradient can be controlled by the use of elevator control only. If the aircraft is flying at airspeed greater than the minimum drag speed then the flight path gradient of descent can be increased (steepened) by increasing airspeed. This is achieved by nose down pitch change with no adjustment in engine thrust setting. The optimization of the descent is not straightforward as the optimization of the climb.

- In transport operations it would be undesirable to make a very steep, high airspeed descent since this would entail a steep nose-down attitude that could be uncomfortable, if not dangerous to persons in the cabin. In addition the rate of increase of cabin pressure during descent must be kept to a reasonably low value to prevent discomfort due to the re-pressurization of the passenger's ear passages. The rate of change of cabin pressure should not exceed the equivalent of 300 ft/min at sea level. This implies that, if the cabin pressurized to the equivalent of 8000 ft pressure height, the descent to sea level should not take less than 24 min regardless of the pressure height from which the aircraft descends. An exception to this general rule is the emergency descent following the loss of cabin pressure. In this case, the aircraft must descend to a safe altitude as quickly as possible and the highest rate of descent must be used.
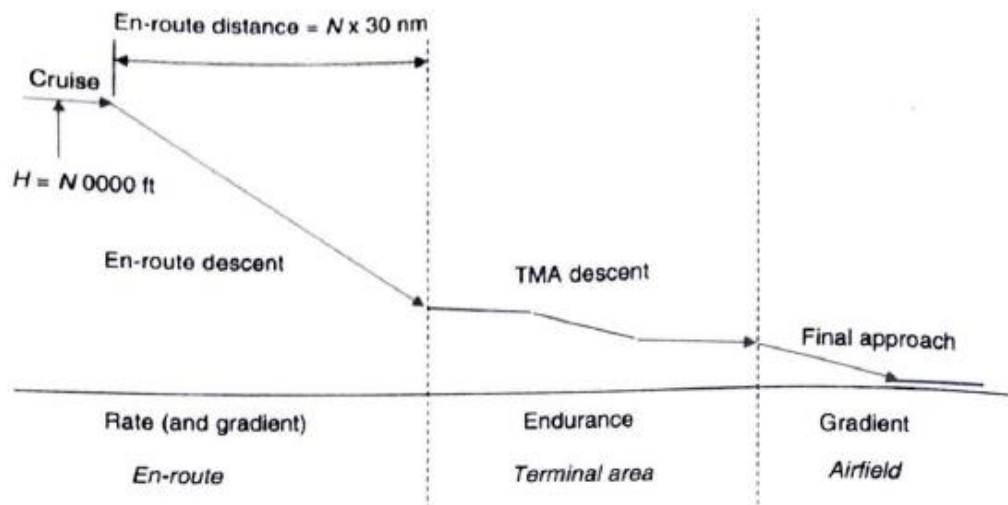
Phases of descending flight.

- There are several phases of a typical descent flight path from cruising altitude down to landing. Each phase of the descent has different criteria that govern the manner in which the aircraft is flown. Figure above shows the phases of atypical descent.

Effect of wind on climb and descent performance

- Wind is the relative velocity between the general air mass and the ground. Wind can be assumed to have only a horizontal component of velocity but due to ground profile vertical velocity components are also to be considered where sloping or undulating ground occurs. So, in the present case the aircraft will be taken to be operating over ground level so that only horizontal component will be considered.
- The performance relative to the ground will be affected by the wind which is known as perceived performance seen by the observer, from either the aircraft or ground and which affects the ability of the aircraft to clear ground-based obstructions.
- An extreme case of the wind effect on the flight path is that of *Wind-Shear,* in which the rate of change of wind velocity is very large. Wind-shear is caused by severe meteorological conditions associated with rainstorms that create very strong local downdraughts, known as a microburst, which spread out rapidly as they contact ground. This results in localized changes in wind speed and direction that may be large and occur very suddenly. Wind shear risks aircraft final approach or after takeoff climb. To recover to its original position need a quick response in both engine thrust and angle of attack. Wind shear warning systems are used to make early response which will minimize the effect of wind shear encounter.

Effect of wind on climb gradient
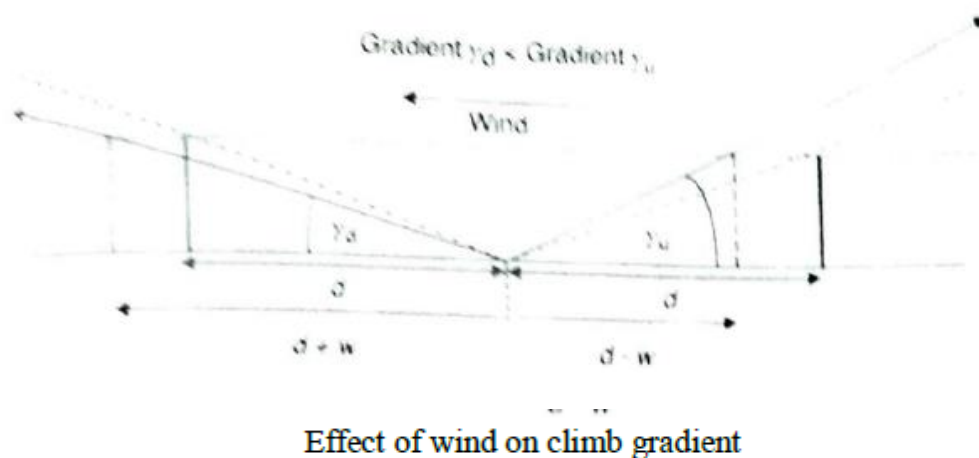
Accelerated motion of aircraft - equations of motion- the manoeuvre envelope

- An aircraft can be said to be in manoeuvring flight when its flight path is in a continuous change of state and in which there is an inertial force due to acceleration.

Longitudinal manoeuvres- the pull-up, push over manoeuvres.

- Consider an airplane initially in straight and level flight, where L = W. The pilot suddenly pitches the airplane to a higher angle of attack such that the lift suddenly increases. Because L > W, the airplane will arch upward, as sketched in Fig. below. The flight path becomes curved in the vertical plane, with a turn radius R and turn rate dθ/dt. This is called the pull-up maneuver.
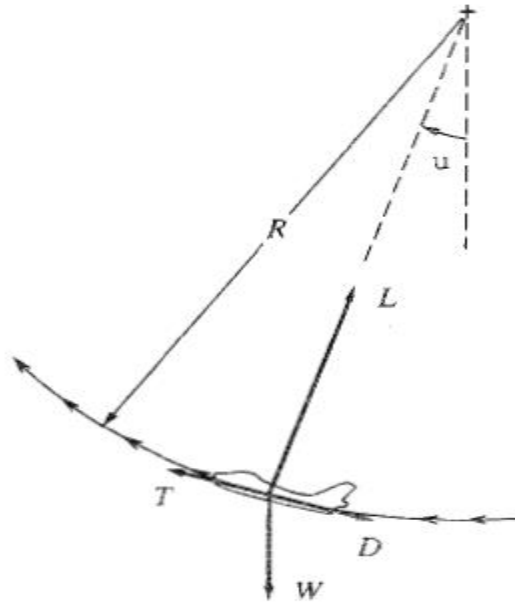
Pull up maneuver

$$m\frac{V_\infty^2}{R} = L - W\cos\theta \qquad \text{----3.18}$$

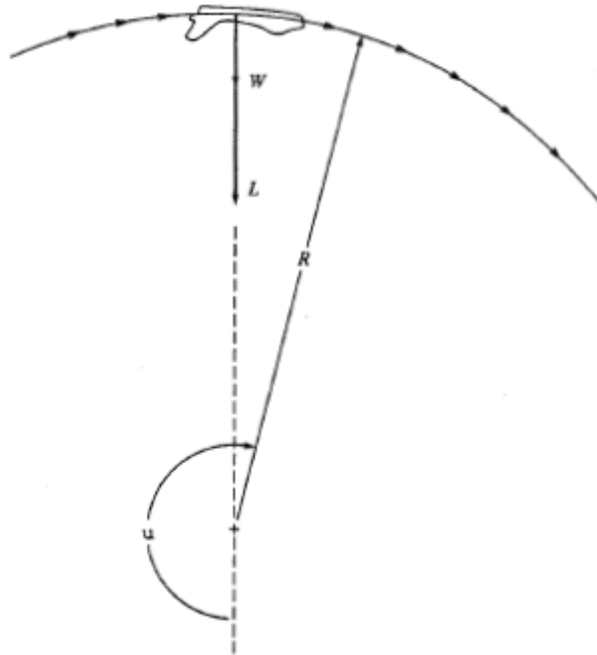- Assuming instantaneous pull-up is initiated from straight and level horizontal flight; this corresponds to θ=0.

$$m\frac{V_\infty^2}{R} = L - W \qquad \text{----3.19}$$

- The instantaneous turn radius is given by

$$R = \frac{mV_\infty^2}{L-W} = \frac{WV_\infty^2}{g(L-W)} = \frac{V_\infty^2}{g(L/W-1)} = \frac{V_\infty^2}{g(n-1)} \qquad \text{---- 3.20}$$

- The instantaneous turn rate is

$$\omega = \frac{g(n-1)}{V_\infty} \qquad \text{----- 3.21}$$

Pull down maneuver

An airplane initially in straight and level flight is suddenly rolled to an inverted position, such that both L and W are pointing downwards.

- The instantaneous turn radius is given by

$$R = \frac{mV_\infty^2}{L+W} = \frac{WV_\infty^2}{g(L+W)} = \frac{V_\infty^2}{g(\frac{L}{W}+1)} = \frac{V_\infty^2}{g(n+1)} \qquad \text{-----3.22}$$

- The instantaneous turn rate is

$$\omega = \frac{g(n+1)}{V_\infty} \qquad \text{-----3.23}$$

Lateral manoeuvres- turn performance- turn rates, turn radius- limiting factors.

- The flight path and forces for an airplane in a level turn are sketched in Fig. Here, the flight path is *curved,* in contrast to the rectilinear motion. By definition, a *level* turn is one in which the curved flight path is in a horizontal plane parallel to the plane of the ground; that is, in a level turn the altitude remains constant. The relationship between forces required for a level turn is illustrated in below fig. Here, the airplane is banked through the roll angle ф. The magnitude of the lift *L* and the value *of* ф are adjusted such that the vertical component of lift, denoted by *L* cosф, exactly equals the weight, or

$$Lcos\phi = W \text{ ---- 3.24}$$
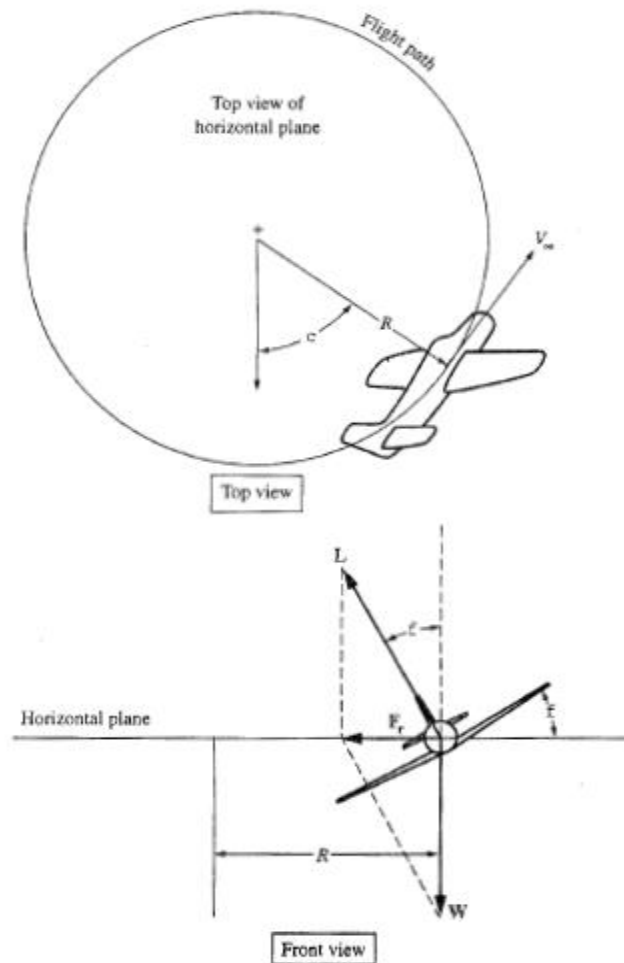
Level turn

- Under this condition, the altitude of the airplane will remain constant. Hence, Eq. applies only to the case of a level turn; indeed, it is the *necessary condition for a level turn.*

- For a level turn, the governing equation of motion is

$$m\frac{V_\infty^2}{R} = L sin\phi \quad \text{----- 3.25}$$

- The two performance characteristics of greatest importance in turning flight are

1. The turn radius *R.*
2. The turn rate $\omega = d\psi/dt,$ where ψ is defined in Fig. The turn rate is simply the local *angular* velocity of the airplane along the curved flight path.

For a level turn

$$cos\phi = \frac{W}{L} = \frac{1}{L/W} \quad \text{---- 3.26}$$

the ratio *L/ W is* an important parameter in turning performance; it is defined as the *load factor n,* where

$$n \equiv \frac{L}{W} \qquad \text{---- 3.27}$$

$$\phi = Arccos\frac{1}{n} \qquad \text{---- 3.28}$$

- To obtain an expression for the turn radius, insert *m = W/g* in Eq. and solve for *R.*

$$R = \frac{mV_\infty^2}{Lsin\phi} = \frac{W}{L}\frac{V_\infty^2}{gsin\phi} = \frac{V_\infty^2}{gnsin\phi} \quad \text{------ 3.29}$$

- By trigonometric calculations we get

$$R = \frac{V_\infty^2}{g\sqrt{n^2-1}} \quad \text{----- 3.30}$$

To obtain the smallest possible *R,* we want
1. The highest possible load factor (i.e., the highest possible *L* / W).
2. The lowest possible velocity.

To obtain an expression for the turn rate *ω,* return to Fig. and recall from physics that angular velocity is related to *R* and *V∞* as

$$\omega = \frac{d\psi}{dt} = \frac{V_\infty}{R} \quad \text{----3.31}$$

- Substituting R in above equation

$$\omega = \frac{g\sqrt{n^2-1}}{V_\infty} \quad \text{-----3.32}$$

To obtain the largest possible turn rate, we want
1. The highest possible load factor.
2. The lowest possible velocity

- Structural design limits of a given airplane represent a practical, mechanical constraint on the load factor. Stalling velocity is a constraint on the minimum value of *V∞* for R and *w.*
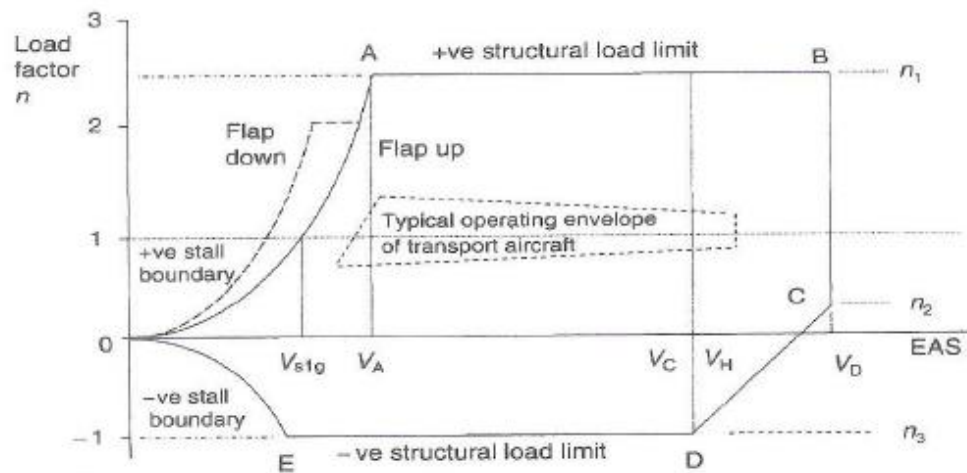
Maneuver boundaries, Manoeuvre performance of military aircraft, transport aircraft.

- The effect of manoeuvres on the flight path performance of civil transport aircraft is generally not very significant. They spend only very low proportion of their time in turning flight and, since the maximum bank angle is typically 20^0 the turns are generally low rate. The only case in which the effect of turning would be significant to a transport aircraft in terms of its effect on flight safety is a turn made with marginal excess thrust available.

- Military transport aircraft may be required to manoeuvre more aggressively than civil aircraft and sustained turning performance may be significant in the operational profile of the mission. Requires higher rate of pitch and fuel consumption during manoeuvres. The design criteria for such aircraft should be sustaining high g manoeuvres with high rate of turns. Complex manoeuvres combing turning with pull-ups and acceleration will also need to be considered to establish the limits of aircraft in air – air combat situations.

The Maneuver envelope

- The maneuver performance of the aircraft will be limited by the structural strength of the airframe; there are two basic reasons for this.
- The pressure loading produced by the dynamic pressure of the airflow increases with the square of the airspeed and with it the air loads on structural com opponents of the aircraft. This is particularly obvious in the case of the deflection of devices such as flaps or landing gear into the airstream. The design maximum dynamic equivalent airspeed, EAS.

- The normal acceleration associated with maneuvering flight produces structural loads in the airframe. The maximum allowable load factor in a maneuver is determined by the load bearing capability of the airframe structure.
- These limitations do not always apply universally. Since the configuration of the airframe may be changed for certain parts or the flight, for example by the lowering of the landing gear or the deflection of flaps, the structural loading and strength limits may be affected. Therefore, different maximum airspeed and load factor limitations may exist for each configuration. The design maneuver envelope, or n-V diagram, describes the design limitations on airspeed and load factor.
- The structural strength of the airframe must be capable of sustaining the structural loading generated by flight maneuvers and gusts at a given air4raft weight5 and by the dynamic pressure of the airflow at the maximum permissible airspeed. The load factor limits and maximum airspeeds depend on the role of the aircraft.

- A military combat aircraft requires a high level of maneuverability and, therefore, the capability of sustaining a high load factor. In addition, it will be called upon to perform the maneuvers over a wide range of airspeeds. These requirements lead to the need for a strong airframe to withstand the combined aerodynamic and maneuver loading; this implies that the airframe will be relatively heavily constructed.

- A large, subsonic, transport aircraft need only low maneuverability and can meet the entire maneuver and gust loading requirements with a relatively low load factor.

The maneuver envelope

- The airspeed is likely to be limited by a sub sonic Mach number, which may enable a relatively low maximum EAS to be scheduled. These considerations lead to a much lower structural strength requirement and, consequently, a lighter airframe construction.
- Fig above shows the main elements of a typical maneuver envelope. Although the maneuver envelopes for civil and military aircraft differ in detail, the definitions of the boundaries and the principal airspeeds are similar enough to be generalized.

Transport aircraft maneuver performance

- The effect of maneuvers on the flight path performance of civil transport aircraft its generally not very significant. They spend only a very low proportion of their time in tur4ning flight and since the maximum bank angle used in the turn is typically 20*, the turns are generally of very low rate. The effect of such turns on the overall performance is minimal. En-route turns, which are generally associated with heading changes, are usually made through angles of less than 900. If the aircraft is stacked in the hold during the descent to landing it is required to fly an oval flight path, with a 180* turn at each turn, known as the holding pattern. The holding pattern turn is flown at Rate1, or 3*/s, and takes one minute. This is probably the most sustained turn that the aircraft will be

required to carry out in normal operations and will be flown at a speed commensurate with flight safety and air traffic control considerations. This speed should be losing to the maximum endurance speed if possible.

- The rate and radius of the turns made by aircraft with differing airspeeds can be used to advantage in control of air traffic. The smaller _regional' aircraft, often turbo-props, can fly at lower speeds than the big jets and can use bank angles up to 30* compared with the normal maximum of 20* in the case of the big jets. This enables the regional aircraft to turn at a higher rate and with a smaller radius. These differences in performance can be used to aid the separation and flow of traffic in airport terminal areas.

- The only case in which the effect of turning would be significant to a transport aircraft, in terms of its effect on flight safety, is a turn made with marginal excess thrust available. For example, during the after-take-off climb with one engine inoperative, the additional drag due to the turn may decrease the already small gradient of climb. Similarly, the sustained pull-up is not a maneuver associated with civil transport operations. The most significant pitching maneuvers, other than the transition at take-off and the flare on landing, will be transient maneuvers between the limb and cruising states or between cruising and descending flight.

Military aircraft maneuver performance

- Military transport aircraft may be required to maneuver more aggressively than civil aircraft and sustained turning performance may be significant in the operational profile of the mission. Although pure pull-ups are still unlikely to be more than transient maneuvers in path, they may extend, in the case of tactical transport aircraft, to pop-up' maneuvers from low-level flight that would demand a higher rate of pitch than the simple gradient changing maneuver. The increased fuel burned due to the turning maneuvers may need to be accounted for in the analysis of the fuel requirement for the mission.

- The combat aircraft (or the aerobatic aircraft) spends a significant proportion of its mission time in maneuvering flight and the design criterion for the aircraft is that it will be capable of sustaining high-g maneuvers with high rates op turn. In the design phase of the development of the aircraft, estimates will be needed of the thrust required to achieve the design target maneuvers combining turning with pull-ups and acceleration will also need to be considered to establish the limits of the aircraft in air-to-air combat situations. The performance in these maneuvers will be part of the design specification of the aircraft. However, in service combat maneuvers will be developed from combinations of the three basic maneuvers to take advantage of the performance equalities peculiar to the aircraft. It is unlikely that such maneuvers could be foreseen at the design stage, but their development in service through experience of the aircraft, is a necessary phase of the maintenance of the aircraft air superiority.