COMMAND AND STAFF TRAINING INSTITUTE

BANGLADESH AIR FORCE

Individual Staff Studies Programme (ISSP)

PROFESSIONAL SUBJECT-1 : FLYING AND AIRMANSHIP FOR PILOT
PHASE-8 : PART-I

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PHASE-8 : PART-I

First Edition : October 2011

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Approved vide Air HQ/10066/Air Trg//Vol-46/64A Date 18 Jan 2011.

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Weeks: 08 **Period: 80**

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INTRODUCTION TO THE PHASE

Scope of the Phase

1. Phase-8 Note (Part-I, ISS) is a self-contained précis. It contains part of the following subjects:

a. Airmanship

b. Meteorology

c. Basic Principles of Flights

d. Basic Principles of Helicopter Flight

e. Navigation

f. Navigation

2. The syllabus has been so designed that you would be able to co-relate and implement (most cases) your knowledge in the profession field.

TOPIC - 1 : AIRMANSHIP

Definition

1. **Aerobatics Flight**. Maneuvers intentionally performed by an aircraft involving an abrupt change in its attitude, altitude, or variation in speed.

2. **Advisory Airspace**. A generic term meaning variously, advisory areas(s) or advisory route (s).

3. **Advisory Area**. A designated area within a flight information region where air traffic advisory service is available.

4. **Advisory Route**. A route within a flight information region along which air traffic advisory service is available.

5. **Aerodrome**. A defined area on land or water (including any buildings, installations and equipment) intended to be used either wholly or partly for the arrival, departure and movement of aircraft.

6. **Aerodrome Control Service**. Air traffic service for aerodrome traffic.

7. **Aerodrome Control Service**. A Unit established to provide air traffic control service to aerodrome traffic.

8. **Aerodrome Traffic**. All traffic on the maneuvering area of an aerodrome and all aircraft flying in the vicinity of an aerodrome.
Note : An aircraft is in the vicinity of an aerodrome when it is, entering or leaving an aerodrome traffic circuit.

9. **Aerodrome Traffic Zone.** An airspace of defined dimension established around an aerodrome for the protection of aerodrome traffic.

10. **Aeronautical Information Publication.** A publication issued by or with the authority of a State and containing aeronautical information of a lasting character essential to air navigation.

11. **Aeronautical Station.** A land station in the aeronautical mobile service carrying on a service with aircraft stations. In certain instances, an aeronautical station may be placed on board a ship.

12. **Aeroplane.** A power-driven heavier than aircraft, deriving its lift in flight chiefly from aerodynamic reactions on surfaces which remain fixed under given conditions of flight.

13. **Aircraft.** Any machine that can derive support in the atmosphere from the reactions of the air.

14. **Air Defence Identification Zone (ADIZ)**. The area of airspace over land or water, extending upward from the surface, within which the ready identification, the location, and the control of aircraft are required in the interest of national security.

15. **Air Traffic**. All aircraft in flight or operating on the maneuvering area of an aerodrome.

16. **Air Traffic Advisory Service**. A service provided within advisory airspace to ensure separation, in so far as possible, between aircraft which are operating on IFR flight plans.

17. **Air Traffic Control Clearance**. Authorization for an aircraft to proceed under conditions specified by an air traffic control unit.

18. **Air Traffic Control Service**. A service provided for the purpose of :

a. **Preventing Collisions**:

(1) Between aircraft, and.

(2) On the maneuvering area between aircraft and obstructions, and.

b. Expediting and maintaining an orderly flow of air traffic.

19. **Air Traffic Control Unit**. A generic term meaning various area control centre, approach control office or aerodrome control tower.

20. **Air Traffic Service**. A generic meaning variously ; flight information service, alerting service air traffic advisory service, air traffic control service , area control service, approach control service or aerodrome control service.

21. **Air Traffic Service Unit**. A generic term meaning variously, flight information centre or air traffic control unit.

22. **Air Way**. A control area or portion there of established in the form of a corridor equipped with radio navigational aids.

23. **Alerting Service.** A service provided to notify appropriate organizations regarding aircraft need of search and rescue aid, and assist such organizations as required.

24. **Alternate Aerodrome**. An aerodrome specified in the flight plan to which a flight may proceed when it becomes inadvisable to land at the aerodrome of intended landing.
Note : An alternate aerodrome may be the aerodrome of departure.

25. **Altitude**. The vertical distance of a level, a point or an object considered as a point measured from mean sea level.

26. **Approach Control Office**. A unit established to provide air traffic control service to controlled flights arriving at, or departing from, one or more aerodromes.

27. **Approach Control Service**. Air traffic control service for arriving or departing controlled flights.

28. **Area Control Centre.** A unit established to provide air traffic control service to controlled flights in control areas under its jurisdiction.

29. **Area Control Service**. Air traffic control service for controlled flights in control area.

30. **ATS Route.** A specified route designed for channeling the flow of traffic as necessary for the provision of air traffic services.

> **Note** : The term ATS route is used to mean variously, airway, advisory route, controlled or uncontrolled route, arrival or departure route, etc.

31. **Ceiling.** The height above the ground or water of the base of the lowest layer of cloud below 6,000 metres (20,000 feet) covering more than half the sky.

32. **Clearance Limit**. The point to which an aircraft is granted an air traffic control clearance.

33. **Control Area.** A controlled airspace extending upwards from a specified height above the surface of the earth without an upper limit unless one is specified.

34. **Controlled Aerodrome.** An aerodrome at which air traffic control service is provided to aerodrome traffic.

Note : The term controlled aerodrome indicates that air traffic control service is provided to aerodrome traffic but does not necessary imply that a control zone exists, since a control zone is required at aerodromes where air traffic control service will be provided to IFR flights, but not a aerodromes where it will be provided only to VFR flights.

35. **Controlled Airspace**. An airspace of defined dimensions within which air traffic control service is provided to controlled flights.

36. **Controlled Flight.** Any flight which is provided with air traffic control service.

37. **Control Zone.** A controlled airspace extending upwards from the surface of the earth to specified upper limit.

38, **Cruising Level.** A level maintained during a significant portion of a flight.

Note : The word level, except in the expression flight level designates the vertical position, regardless of the reference data or the units of vertical distance used. In air ground communications a level will be expressed in terms of altitude height or a flight level depending upon the reference datum and the altimeter setting in use in a particular area.

39. **Current Flight Plan.** The flight plan, including changes, if any, brought about in subsequent clearances.

40. **Danger Area**. An airspace of defined dimension within which activities dangerous to the flight of aircraft may exist at specified times.

41. **Expected approach Time**. The time at which it is expected that an arriving aircraft will be cleared to commence approach for a landing.

42, **Final Approach**. That part of an instrument approach procedure from the time the aircraft has:

- a. Completed the last procedure turn , where one is specified or,
- b. Crossed a specified fix, or
- c. Intercepted the last track specified for the procedure, until it has crossed a point in the vicinity of an aerodrome from which:
  - (1) A landing can be made ,or
  - (2) A missed approach procedure is initiated.

43. **Flight Crew Member**. A crew member charged with duties essential to the operation of an aircraft during flight time.

44. **Flight Information Centre**. A unit established to provide flight information service and alerting service.

45. **Flight Information Region.** An airspace of defined dimensions within which flight information service and alerting services are provided.

46. **Flight Information Service**. A service provided for the purpose of giving advice and information useful for the safe and efficient conduct of flights.

47. **Flight Levels**. Surfaces of constant atmospheric pressure which are related to a specific pressure datum, 1013.2 mb (29.29inches), and are separated by specific pressure intervals.

Note 1 : A pressure type altimeter calibrated in accordance with the Standard Atmosphere :

a. When set to a QNH altimeter setting will indicate altitude.

b. When set QFE altimeter setting, will indicate height above the QFE reference datum.

c. When set to a pressure of 1013.2 mb (29,29 inches) ,may be used to indicate flight levels.

Note 2 : The term's height and altitude used in Note 1 above indicate altimetric rather than geometric heights and altitudes.

48. **Flight plan.** Specified information provided to air traffic services, units, relative to an intended flight or portion of an aircraft.

49. **Flight Visibility.** The visibility forward from the cockpit of an aircraft in flight.

50. **Ground Visibility** The visibility forward from the cockpit of an aircraft in flight.

51. **Heading**. The direction in which the longitudinal axis of an aircraft is pointed. Usually expressed in degrees from North (true magnetic, compass or grid) .

52. **Height**

a. The vertical distance of a level point, or an object considered as a point, measured from specified datum.

Note : The datum may be specified either in the text or in an explanatory note in the publication concerned.

b. The vertical dimension of an object.

Note : The term height may be used in a figurative sense for a dimension other than vertical, e.g. the height of a letter or a figure pointed on runway.

53. **IFR.** The symbol used to designate the instrument flight rules.

54. **IFR Flight**. A flight conducted in accordance with the instrument flight rules.

55. **IMC**. The symbol used to designate instrument meteorological conditions.

56. **Instrument Approach Procedure**. A series of predetermined manoeuvres for the orderly transfer of an aircraft under instrument flight condition from the beginning of the initial approach to a landing, or to a point from which a landing may be made visually.

> **Note**: The term instrument flight conditions are used in this definition in preference to other terms such as instrument meteorological conditions, because the later term refers to meteorological conditions necessitating under instrument flight rules. Atmosphere, but does not necessarily imply flight by reference to instruments, which is the intent of the present wording.

57. **Instrument Meteorological Conditions.** Meteorological conditions expressed in terms of visibility, distance from cloud, and ceiling, less than the minima specified for visual meteorological conditions.

58. **Landing Area**. The part of the movement area intended for the landing or take off run of aircraft.

59. **Manoeuvring Area.** That part of an aerodrome to be used for the take-off and landing of aircraft and for the movement of aircraft associated with take-off and landing.

60. **No Light Area**. Area in which aircraft may engage in night flying with displaying navigation lights or conforming to the semicircular rules. Details are to be notified to the ATCC at least two hours before the exercise begins, giving :

a. The area concerned.

b. Estimated times of entry and departure.

c. Track and altitude to be maintained.

61. **Pilot in Command.** The pilot responsible for the operation and safety of the aircraft during flight time.

62. **Prohibited Area.** An airspace of defined dimensions, above the land areas or territorial waters of a State, within which the flight of aircraft is prohibited.

63. **Reporting Point**. A specified geographical location in relation to which the position of an aircraft can be reported.

64. **Restricted Area.** An airspace of defined dimensions, above the land areas or territorial waters of a State, within which the flight of aircraft is restricted in accordance with certain specified conditions.

65. **Runway.** A defined rectangular area, on a land aerodrome, prepared for the landing and take-off run of aircraft along its length.

66. **Signal Area**. An area on an aerodrome used for the display of ground signals.

67. **Taxiway**. A defined path, on a land aerodrome, selected or prepared for the use of taxing aircraft.

68. **Terminal Control Area**. A control area normally established at the confluence of ATS routes in the vicinity of one or more major aerodromes.

69. **Track.** The projection on the earth's surface of the path an aircraft, the direction of which path at any point is usually expressed in degrees from North (true magnetic or grid).

70. **Transition Altitude**. The altitude in the vicinity of an aerodrome at or below which the vertical position of an aircraft is controlled by reference to altitudes.

71. **VFR.** The symbol used to designate the visual flight rules.

72. **VFR Flight**. A flight conducted in accordance with the visual flight rules.

73. **Visibility.** The ability, as determined by atmospheric conditions and expressed in units of distance, to see and identify prominent unlighted objects by day and prominent lighted objects by night.

74. **Visual Meteorological Conditions**. Meteorological conditions expressed in terms of visibility, distance from cloud, and ceiling equal to or better than specified minima.

75. **VMC.** The symbol used to designate visual meteorological conditions.

DIVISION OF AIRSPACE

1. Airspace is divided into the following :

a. **Flight Information Regions**. Defined areas of airspace which extend vertically from ground/sea level and normally have no upper limit, within which flight information and alerting services are provided.

b. **Controlled Airspace**. Defined areas of airspace within which Air Traffic Control Service is provided to IFR flights :

(1) **Control Area.** A controlled airspace extending upwards from a specified height above ground or wate.

(2) **Control Zone**. A controlled airspace extending upwards from ground level to a specified height.

(3) **Airway**. A control area in the form of a corridor.

c. **Advisory Airspace**.

(1) **Advisory Area**. An area within an FIR within which air traffic advisory service is available.

(2) **Advisory Route**. A route within an FIR within which air traffic advisory service is available.

d. **Air Defence Identification Zone (ADIZ).** Defined areas of airspace extending upwards from ground/sea level within which certain rules for the security control of air traffic are mandatory.

e. **Prohibited Areas**. Specified areas of airspace within which flight is prohibited.

f. **Danger Areas**. Specified areas of airspace within which there may be activities dangerous to aircraft.

g. **Restricted Areas**. Specified areas of airspace designated, other than for air traffic control purposes, as areas in which flight is restricted in accordance with certain specified conditions.

h. **No Light Areas.** Areas in which aircraft may engage in night flying exercises without displaying navigation lights or conforming to the semicircular rule. Details are to be notified to the FIC at least two hours before the exercise begins, giving:

(1) The area concerned.

(2) Estimated times of entry and departure.

(3) Track and altitude to be maintained.

Air Traffic Service

2. **Air Traffic Service is provided**

Name of Services		Unit Responsible
a. Flight Information Service	-	FIC
b. Advisory Service	-	FIC
c. Alerting Service	-	FIC
d. **Air Traffic Control Service**		
(1) Aerodrome Control Service	-	Aerodrome Control Tower.
(2) Approach Central Service	-	Approach Control Office.
(3) Area Control Service	-	Area Control Centre.

3. Flight Information Service may also be provided by other units mentioned in sub para-d above within the areas under their respective control.

Rules of the Air

4. **Rules of the Air**. The following are some of the rules laid down to reduce the hazard of collision:

a. **Giving Way.** Aircraft are to give way to each other in the following order :

(1) Airplanes and Helicopters
(2) Airships
(3) Tow and Glider combinations
(4) Gliders
(5) Balloons

b. **Converging.** When two aircraft are converging at approximately the same altitude the aircraft that has the other on its right shall give way.

c. **Approaching head on.** When two aircraft are approaching head on, or approximately so, each shall alter course to the right.

d. **Over taking.** An aircraft over taking another aircraft is to turn to the right and keep clear until all danger of collision is passed. An aircraft is said to be over taking another aircraft if it is approaching from the rear at an angle of less than 70^0 from the fore and aft axis of the aircraft in front.

e. **Landing aircraft**. An aircraft, irrespective of type, on the final stages of landing, has the right of way over all other aircraft in the air and on the ground.

f. **Approaching to land.** When to or more aircraft are approaching an aerodrome for the purpose of landing, the aircraft at the lower altitude has the right of way, but it shall not take advantage of this rule to cut in front of another which is on final approach to land, or to over-take that aircraft, however, as a matter of courtesy, Captain of light aircraft should give way to heavier types. Jet aircraft is to be given right of way over a piston engine aircraft unless the later is in final stages of landing.

g. **Emergency landing**. Aircraft in distress have right of way over all other air traffic.

h. **Aircraft preparing to take off**. Aircraft are not to taxi or take off across the path of an aircraft approaching to land or landing.

j. **Formations.** Single aircraft are to give way to aircraft flying in information.

VFR AND IFR FLYING

1. **VMC**. These are the minimum conditions of visibility, distance from clouds, and ceiling in which flight under Visual Flight Rules (VFR) is permissible:

a. Unless authorized by the appropriate authority, VFR flights shall not be operated:

(1) In Instrument Met Condition.

(2) Between sunset and sunrise, or such other period between sunrise and sunset as may be prescribed by the appropriate authority.

(3) Above flight level 150.

(4) Except as otherwise authorized by the appropriate air traffic control unit for VFR flights within control zones. VFR shall be conducted so that the aircraft is flown in conditions of visibility and distance from clouds equal to or greater than those specified in the following table:

<table>
<tr><td rowspan="4">Flight visibility</td><td colspan="2">Within Controlled Airspace</td><td colspan="2">Outside Controlled Airspace</td></tr>
<tr><td>Above</td><td>At or Below</td><td>Above</td><td>At or below</td></tr>
<tr><td colspan="2">900 m (3000 ft) above mean sea level or 300 m (1000 ft) above terrain, whichever is higher*</td><td colspan="2">900 m (3000 ft) above mean sea level or 300 m (1000 ft) above terrain, whichever is higher*</td></tr>
<tr><td>8 km</td><td>8 km
[5 km**]</td><td>8 km</td><td>1500 m***</td></tr>
<tr><td>Distance from cloud:
a. Horizontal
b. Vertical</td><td>1500 m
300m (1000 ft)</td><td>1500 m
300m (1000 ft)</td><td>1500 m
300m
(1000 ft)</td><td>Clear of clouds and in sight of the ground or water</td></tr>
</table>

(5) Unless a higher plane of division is prescribed on the basis of regional air navigation agreements or by the appropriate ATS authority. ** When so prescribed by the appropriate ATS authority. *** Except that helicopters may operate with a flight visibility below 1500 m if maneuvered at a speed that will give adequate opportunity to observe other traffic or any obstructions in time to avoid collision.

(6) Except when a clearance is obtained from an air traffic control unit, VFR flights shall not take off, land at an aerodrome within a control zone, or enter the aerodrome traffic zone or traffic pattern:

(a) When the ceiling is less than 1500 feet or
(b) When the ground visibility is less than 5 miles.

2. **IMC**. Exist when weather conditions are below the minimum standard prescribed or VMC.

3. **Visual and Instrument Flight Rules**. These are the flight rules under which flight conducted and are applied as follows:

a. In IMC flight under IFR is mandatory.

b. In VMC flight may be under IFR as follows:

(1) The Captain may elect to fly under IFR.

(2) The ATC authority may impose IFR.

(3) In controlled airspace IFRs are mandatory at night.

c. Except as in b (1), (2) and (3) above flights in VMC are normally conducted under VFR.

4. **Special VFR Flights**. In special circumstances flights may enter controlled airspace in IMC without complying with IFR provided that air traffic clearance to so is obtained when filing the flight plan.

a. For operating in accordance with VFR/Special VFR the following conditions are to be fulfilled:

(1) No conflict with IFR flights.

(2) Aircraft must have radio telephone apparatus on board capable of communicating with appropriate ATS unit.

(3) Must file a written flight plan if operation is likely to be outside the vicinity of the aerodrome.

(4) For operation wholly within Aerodrome vicinity flight details is to be communicated to appropriate ATC unit prior to departure by any available means.

b. Special conditions while operating within Aerodrome Control Airspace:

(1) Select cruising level in accordance with the table of IFR cruising level except otherwise specified or instructed by appropriate ATC unit.

(2) Maintain listening watch on the appropriate air ground frequency and report position.

Semicircular System of Cruising Level

5. The cruising levels to be observed are as follows:

IFR Flights

<u>180 TO 359</u>	<u>000 TO 179</u>	
FL	FL	
40	30	
60	50	
80	70	
100	90	
120	110	
140	130	
160	150	
180	170	
200	190	
220	210	
240	230	
260	250	
280	270	
310	290	After F290 vertical separation is 2000 ft
350	330	
390	370	
430	410	
470	450	
etc	etc	

<u>VFR Flights</u>

<u>180 TO 359</u>	**<u>000 TO 179</u>**
FL	FL
45	35
65	55
85	75
105	95
125	115
145	135
165	155
185	175
205	195
225	215
245	235
265	255
285	275
etc	etc

<u>Safety Altitude Instructions (BAF)</u>

6. First three factors of the following affect the safety altitude:

a. The navigational error assumed in deciding the highest ground over which there is any possibility of the aircraft being flown:

(1) Due to the wide range of speeds and the varying accuracy of fixing aids in operation it is not possible to lay down an arbitrary figure for this error.

b. The airflow effect over high ground :

(1) An allowance of 10 percent of the height of the highest ground is to be made.

c. The altimeter setting system in force.

(1) An allowance of 1,000 feet is to be made.

d. An example of the calculation of safety altitude for an aircraft expected to fly over ground 3,000 ft high is as follows:

(1) 3,000 ft plus (2) 300 ft plus (3) 1,000 ft equals 4,300 feet (safety altitude).

e. Application of the semicircular system of cruising level where applicable will then give the minimum altitude to fly.

Altimeter Setting Procedure

7. In general the following altimeter settings are used :

a.	At all Aerodromes … …. ….	QNH
b.	Enroute … … … … … … …	1013. 2 mbs, or 29.29 inches.
c.	Control Areas and Zones -	A value of QNH as specified by the ATCC concerned.

d. Transition Level is the level at which the pilot of a descending aircraft changes to QNH from the standard setting (1013.2 mbs). This may be regarded as the lowest flight level at which an aircraft can safely proceed on the enroute altimeter setting.

e. Transition Altitude is the level at and below which QNH setting is mandatory.

f. Transition Layer is the airspace between Transition level and Transition Altitude.

g. Aircraft climbing change from QNH to 'enroute' setting after leaving transition altitude and before reaching transition level.

h. A descending aircraft when above Transition Level is to report his altitude as flight level (e.g. 6,500 ft as Fl 65; 12,000 ft as FL 120).

j. In ascent altitude is to be given in feet up to the Transition Altitude and as flight level above it.

Flight Information Service

8. A service provided for the purpose of giving advice and information useful for the safe and efficient conduct of flight.

a. **Provision of Flight Information.** The following information service is provided by FICs, ATCCs and certain aerodrome ATC units:

(1) The serviceability state of navigational aids and of aerodrome and their facilities.

(2) Meteorological information including actual forecast of weather conditions at aerodromes and enroute and warnings of unusual or dangerous weather conditions.

(3) QNH altimeter setting reports or other information to permit determination of adequate terrain clearance.

(4) Other information pertinent to the safety of aircraft.

9. **Advisory Service**

a. A service provided to ensure separation between aircraft operating outside controlled airspace. It offers a continuous separation service based on flight plans and position report to aircraft, flight on IFR flight plans within the airspace covered by the Advisory service provided aircraft are maintaining communication.

b. The procedure to be observed by pilots are not compulsory. Never the less it is obvious that advise intended to preserve separation can only be sound if it is based on accurate knowledge of the movement of all aircraft within the advisory air space and those about to join or cross it.

c. Pilots are clearly to understand that air traffic advisory service does not afford the degree of safety and does not carry the responsibility of the air traffic control service in respect of the avoidance of collisions since it gives advice only and aircraft may be operating within the advisory route or area, unknown to the unit providing the service.

10. **Flights Within Controlled Airspace**

a. **Under VFR**. Aircraft are to be flown in VMC and in accordance with the Rules of the Air.

b. **Under IFR**.

(1) **Flight plan**. File a flight plan as required.

(2) **ATC Clearance.** Before entering a controlled airspace obtain ATC clearance to do so and adhere strictly to the terms of that clearance thereafter.

(3) **Communications.** Establish two-way communication with the appropriate ATC unit and maintain continuous listening watch.

(4) **Position Reporting.** Pass position report over each specified reporting point.

(5) **Emergency.** Inform the controlling unit immediately if any emergency compels deviation from the terms of present clearance.

(6) **Communication Failure.**

(a) **In VMC:**

i. Continue to fly in visual meteorological conditions.

ii. Land at the nearest suitable aerodrome; and

iii. Report its arrival by the most expeditious means to the appropriate ATC unit.

(b) **In IMC:**

i. Continue/flying according to current flight plan, maintaining last acknowledged or assigned cruising level(s) for which clearance has been received.

ii. Arrive as closely as possible to ETA.

iii. Commence descent as nearly as possible to the last acknowledged Expected Approach Time or, if no Expected Approach Time has been acknowledged, as nearly as possible to the flight ETA.

iv. Land within 30 minutes of ETA or the last acknowledged Expected Time whichever is the later or leaves the controlled airspace before this time.

Note : Expected Approach Time calculated by ATC, this is the time at which it is expected that an arriving aircraft will be cleared to begin an approach for landing.

11. **Flights Within Advisory Space.**

a. Aircraft requiring Air Traffic Advisory Service under IFR within the Advisory Routes and Areas are to:

(1) File a flight Plan.

(2) Comply with reporting procedures.

(3) Maintain communication with the unit providing the service, notifying changes in cruising level track and ground speed.

12. **Joining Airways.**

a. A request for permission to join an airway is to be made on the appropriate frequency at least 10 minutes by R/T (20 minutes by W/T) before ETA at the point of entry. The selected entry point must be the Designated or on Request Reporting point most convenient to the route. The entry request is to included the following:

(1) Callsign.

(2) Aircraft type.

(3) Position, cruising level and flight conditions.

(4) ETA at point of entry.

(5) Desired cruising level on airway.

(6) Route and point of first intended landing.

(7) True airspeed.

13. **Crossing Airways**

a. Aircraft requiring to cross an airway under IFR are to :

(1) File a flight plan.

(2) Request crossing clearance 10 minutes by R/T (20 minutes by W/T) before ETA at entry point, giving :

(a) Identification

(b) Aircraft type

(c) Track (True)

(d) Place and estimated time of crossing.

(e) Desired crossing level

(f) Ground speed.

(3) Maintain two-way communication with the controlling authority.

(4) Report on entering and leaving the airway.

(5) Selected crossing points should be associated with a radio facility to assist accurate navigation and airways are to be crossed at an angle of 90 degrees to the direction of the airway, or as close to this angle as practicable.

b. **Entering Control Areas**. Procedure to enter control areas is similar to the procedure for joining airways.

14. **Position Reporting**

a. Position reports are to be passed to the appropriate ATC Unit as follows:

(1) Within control area/zone as instructed.

(2) On reaching control area/zone boundary.

(3) In ADR's and airways at each designated reporting point.

(4) Outside controlled and advisory airspace's half hourly irrespective of the weather conditions.

(5) When passing from one FIR to another.

(6) On request reporting points.

b. Position reports should be made as soon as possible after the aircraft has passed the reporting point.

c. When passing from on FIR to another the position reports to be passed to the ATC Units controlling both regions.

d. **Contents of Position Reports.** Position reports contain the following orders:

(1) Aircraft identification.

(2) Position

(3) Time of position

(4) Flight level or altitude

(5) Flight Conditions

(6) ETA at next reporting point.

15. **Pre-Flight Action.**

a. The captain and crew of the aircraft will:

(1) Have the flight authorized.

(2) Obtain a weather forecast from the meteorological office.

(3) Report to flight planning section where he/they will carry out full flight planning in accordance with Air Headquarters instruction.

(4) Compile a flight plan when required.

(5) Ensure that the air traffic control officer is notified of the flight and if a flight plan necessary that a copy is passed to him.

(6) Obtain final air traffic instructions and clearance necessary or applicable to the intended flight from the air traffic control office. At the same time notifying, the control officer of any corrections to the flight plan that may be necessary.

16. **Diplomatic Clearance and Flight by BAF Aircraft Abroad**

a. Regulations concerning flights by Bangladesh Air Force aircraft to or over commonwealth or foreign countries and details regarding diplomatic clearance are to be obtained from the Deputy Director of Air Transport, Air Headquarters, Dhaka.

b. BAF Aircraft, so far as possible and consistent with operational necessity, is to be flown in accordance with air traffic regulations issued by the countries over which they are flown.

17. When flying VMC it is the direct responsibility of the person in command of an aircraft to avoid collision with other aircraft, notwithstanding that fight is being conducted on an air traffic clearance.

18. **Diversions**

a. There are two grades of diversions, which are:

(1) **Grade 1.** This diversion is issued by the operating authority either directs or through air traffic control channels and is mandatory.

(2) **Grade 2**. This diversion may be issued either by the operating authority or by air traffic control and is advisory.

Note 1: Either grade may be issued for administrative reasons.

Note 2: The final decision on whether or nor to divert remains with the captain of the aircraft.

19. **Flight Plans**

a. A flight plan is a specified information provided to air traffic services units, relative to the intended flight of an aircraft.

b. It is the responsibility of the captain of an aircraft to ensure that flight plan is correctly complied and contains all the data relative to the intended flight.

c. No deviation shall be made from a flight plan without informing the appropriate air traffic services unit. In case any change takes place it should be in limited as soon as practicable.

d. Flight plans are to be submitted to the nearest area control centre, aerodrome control tower or air ground communications station either in person, or by telephone or radio as applicable.

e. A flight plan may be filed through intermediate stops, when required.

f. Flight plans are required in the following cases:

(1) For all IFR flights prior to operating in controlled airspaces, advisory airspaces and other areas as may be exempted by Air Traffic Services.

(2) For all international operations.

(3) For all flights prior to departure from all aerodromes in Bangladesh, with the exception of such local flights as may be exempted by Air Traffic Control.

20. **Filing of Flight Plans**

a. Flight plans are to be filed in advance. The minimum period of advance notification is as follows :

(1) **In Flight IFR Plan**. A flight plan filed from an aircraft in the air shall be transmitted at least ten minutes flying time before the intended point of entry into a controlled airspace if transmitted by radiotelephony and twenty minutes if transmitted by RadioTelegraphy.

(2) **On Ground (Bangladesh).** Flight plans will be accepted only within 45 minutes prior to departure. A flight plan for an IFR flight should be submitted at least 30 minutes prior to departure.

21. **Contents**. A flight plan shall comprise information as required to be filled in on BAF form 2919.

22. **Delay**. In case of a delay of one hour or more in the expected scheduled ground time, a new flight plan should be submitted and the old flight plan be cancelled.

23. **Changes in Flight Plan.**

a. The appropriate ATC authority is to be notified immediately, in case of any of the changes in the flight plans:

(1) **VFR Flight Plan**

(a) Cancellation.

(b) More than 30 minutes in ETD (BAF), other as in para 23 above.

(c) Route or destination.

(2) **IFR Flight Plan**

(a) Outside Controlled Airspace.

i. As in sub-para 20 a. (1) above.

ii. Height.

(b) In controlled airspace.

i. More than 10 minutes in ETD.

ii. Height, route or destination.

iii. More than 5 minutes in ETA (Bangladesh). More than 3 minutes ETA at destination over a next reporting point.

24. **Cancellation of IFR Flight Plans in Flight**

a. Pilots may cancel IFR flight plans at any time by notifying traffic control provided they are operating in VFR weather conditions when they take such action and when conditions indicate that the remainder of flight can be conducted in accordance with visual flight rules.

b. The cancellation of an IFR flight plan is only acceptable when the pilot-in-command uses the expression “Cancel my IFR Flight Plan”.

c. The fact that an aircraft reports flying VMC does not of itself constitute cancellation of an IFR flight plan and unless definite cancellation is made in the manner indicate in sub-para 24(2), the flight will continue to be regarded in accordance with the instrument flight rules.

d. If a flight plan has been cancelled and subsequent IFR operation becomes necessary, a new IFR flight plan must be filed and air traffic clearance obtained before encountering instrument meteorological conditions.

Note : Acceptance of a Flight Plan shall not constitute an ATC clearance or an authorization to depart. No aircraft shall from a controlled aerodrome without prior authorization obtained either by radio or visual signals from the Aerodrome Control Tower. ATC clearance shall be obtained or radio telephony by IFR flights prior to take-off from aerodromes located in controlled airspaces.

25. **Filing of Flight Plan (BAF)**

a. Following procedures of filing a flight will apply to BAF aircraft operating within Bangladesh. A flight plan is to be filed with the ATC of departure for all flight as specified below:

(1) **Flights in IMC/IFR.** For all transit flights planned in IMC/IFR, the flight plan is to be invariably filed in writing irrespective of distance/flying time involved.

(2) **Local Flight.** For flights in local flying area and over approved firing ranges, the flight plan can be filed on R/T. This may be done independently or in supplement to the Flying Programme supplied to ATC earlier.

(3) **Training Cross Country Flights**. When proceeding on a cross country flight, is a part of an approved flying syllabus of a training unit, it is sufficient to give ATC the serial number of the training cross country on telephone or R/T, provided the cross country syllabus is held by the ATC. For other cross country flights, not involving landing out station, details of each leg are to be given; this could be done by telephone, but not by R/T.

b. When giving approval of a flight on telephone, the ATCO is to pass information about the current NOTAMS, latest weather report enroute and destination, and any other information considered necessary for the safe operation of the aircraft Weather briefing is the personal responsibility of the captain of the aircraft, and para (b) above does not absolve him of it; if the latest weather report is not available with the ATC he is to get it from the Meteorological Section.

c. ATCO on duty has the right to demand a written flight Plan whenever in his judgement the nature of flight or traffic requires it; or he considers it necessary to keep a record of the flight clearance. In all such cases he is to make the reason known to the pilot.

Note: These instructions do not apply to civil and foreign aircraft using BAF airfields; the civil aircraft will file the flight plan according to DGCA/ICAO requirement and the foreign aircraft according to ICAO and any special instructions, if issued for their operations, by Air HQ.

26. **In and IFR Flight.** When operating from within a controlled airspace, or when the point of entry into controlled airspace is within 10 minutes flying time (20 minutes when using W/D) from the point of departure, ATC clearance must be obtained prior to departure.

27. **In-flight Clearance**

a. If on an IFR flight, clearance must be obtained prior to entering to controlled airspace, or if on a VFR flight, prior to entering into IFR weather conditions within controlled airspace.

b. If at the time of requesting clearance to enter a controlled airspace, when the aircraft is flying outside the flight information region in which the entry point is situated, then sufficient time be allowed for clearance to be obtained from the FIC concerned and the ATCC with which the aircraft is in communication.

28. **Adherence to Air Traffic Control Clearance**

a. When an Air Traffic Control clearance has been obtained the pilot-in-command shall not deviate from the provisions there of unless an amended clearance is received. In case of emergency the authority is used to deviate from provision of an ATC clearance, the pilot-in-command shall notify air traffic control as soon as possible and if practicable, obtain an amended clearance.

b. Further clearance must be obtained from the controlling authority if the original flight plan is modified in any of the items as stated in sub para 24(2).

c. Pilots must keep in mind the fact that once an IFR flight has entered a control area or control zone, no deviation from the provision of a traffic clearance received shall be made unless an emergency exist, without first obtaining approval from air traffic control for such change.

29. **Air Traffic Control Instructions.** Air Traffic Control instructions are the directions issued by an air traffic control unit for an aircraft to proceed or to delay its flight in a specified manner.

30. **IFR Approach Clearances**

a. An approach clearance issued to an aircraft is approval for one approach only. If landing is not completed after one instrument approach, a pilot shall follow the specified missed approach procedure, unless otherwise instructed by air traffic control and request further clearance from air traffic control. Air traffic control will then determine whether the pilot will be cleared for another immediate attempt or be directed to stand by as a designated holding pattern at an assigned level until other aircraft in line have landed or taken off. This decision will be based upon existing traffic conditions unless an emergency situation exists. A decision to route the aircraft to an alternate aerodrome will be made by the pilot or aircraft operator involved after co-ordination, when practicable, with the air traffic control personnel concerned.

b. A new approach clearance will be required prior to commencing an additional approach. If pilot elects to proceed to the alternate aerodrome as specified in the flight plan, he must advise air traffic control and obtain a traffic clearance.

Note : If the pilot decides that he can proceed under VFR weather condition to the aerodrome of destination, he may do so by canceling his IFR flight plan and obtaining a clearance from aerodrome control when required.

TOPIC-2

METEOROLOGY

Introduction

Definition

1. Meteorology is the branch of science which deals with the earth's atmosphere and the physical processes occurring in it. It includes the study of all changing atmospheric conditions such as fog, snow, rain, thunder storms, wind – which go to make up our weather.

2. Study of weather is done in three stages:

   a. **Stage-1**. Observation of different weather elements and phenomena such as atmospheric pressure, temperature, humidity, wind, clouds, visibility, rain, thunderstorm, turbulence ice – accretion etc.

   b. **Stage-2**. To establish co-relation between changes in these elements.

   c. **Stage-3**. To forecast the future occurrences of these phenomena.

3. Need for the study of meteorology is to understand the behaviours of the ocean of air so that an aircrew can operate efficiently through it.

Aim of Study of Meteorology

4. Some weather manifestation can be-awe-inspiring. We feel uncertain when we encounter phenomena we cannot explain, but understanding breeds confidence. Moreover, the many and varied facts we need to know about the behavior of the atmosphere can be grasped more easily by understanding the physical reasons underlying them. The aim is to help you to operate with maximum efficiency, safety and confidence in all types of weather.

Value of Weather Knowledge

5. At one time, pilots though it would be possible to get above the weather by flying at about 20,000 ft. Now-a-days it is realized that even above 40,000 ft certain weather features are still important. These include; wind temperature, pressure, density, condensation trails and sometimes even thunderstorm and icing. Winds at about 30,000 ft to 40,000 ft often exceed 100 Kts in a narrow belt, and aircraft caught unprepared may be swept off their intended track or insufficient fuel to return to base.

6. Aircraft with modern aids operate regularly in weather which would once have been considered to bad for flying. In adverse weather conditions, knowledge of the weather and its forecast development is of the utmost value in helping inexperienced aircrew to avoid hazards and experienced aircrew to negotiate them confidently.

7. Accurate weather reports during flight are likely to be of value to other aircrew flying in the locality, particularly in adverse weather conditions. Apart from helping the meteorological officer to check his forecast, your reports may provide the first indication of unforeseen developments.

8. One of the best ways of acquiring useful weather information is to pay frequent visit to local meteorological office. By discussion with the forecaster one can clear up many problems and also gain an insight into his difficulties.

9. The various components which make up the weather may have widely different meanings and importance for different people. A pilot may be chiefly interested in the weather at a base and destination : the navigator may be more interested in winds and temperatures at various heights; where as the signaler is probably concerned with these areas where bad weather may interfere with communications. The forecaster caters all these varied requirements on request, but to use thee service efficiently you must know what facilities are available, as well as the limitations of the service and be able to understand weather charts on technical terms.

PRESSURE PATTERN AND ASSOCIATED WEATHER

Isobars

10. An isobar is a line joining points having the same barometric pressure at the same level. (The level generally used on surface weather maps is mean sea level).

11. **Straight Isobars**. It has been accepted that all isobars form closed curves when they are drawn over a sufficiently extensive area. However, they appear as straight lines over hundreds of miles and sometimes even over thousands of miles.

12. It has been found by experience that although the configuration of isobars may be variable and complex, they often make up certain well defined patterns to which special names have been given.

Low or Depression

13. A depression is a part of the atmosphere where pressure is lower than the surroundings. It is bound by a series of close isobars. The wind speed in any part of this area does not exceed 38 mph (33 kts). The deficiency of pressure at the centre is of order of 3-4 mbs.

14. Some depressions are deeper than others. The terms ‘Shallow Depression’ and ‘Deep Depression’ are therefore used. A shallow depression is one in which the pressure at the centre is not very much lower than the surroundings. It is sometimes also called a low or an area of low pressure. A deep depression is one in which the pressure is very much lower near the centre than on the outside (as compared with a depression) and/or winds reported from different parts of the depression may reach as high value as 38 mph.

15. The depressions of temperate latitudes generally move from west to east and have well marked sectors with air masses of different origins and properties.

16. In depression of tropical areas the air masses in different sectors are not easily distinguishable from each other. They move, at least in their initial stages, from east to west. Isolated weather is occasionally met with in the disturbed weather area of such depressions.

17. The winds in all types of depression which affect the countries blow in counter clockwise direction round their centres.

Tropical Storms

18. The natures of a tropical depression and a tropical storm are essentially alike, but the wind force associated with tropical storm exceeds 38 mph and may go upto 73 mph (63 kts).

19. On the basis of wind speed associated with the tropical storms two terms are used.

20. **Tropical Storm**. When wind speed in any part of its closed circulation (Observed or in its absence inferred from isobaric gradient) is 39 mph (34 kts) to 54 mph (59 kts).

21. **Severe Tropical Storm.** When the wind speed in some part of its field reaches 55 mph (48 kts) to 73 mph (63 kts).

Cyclone

22. The cyclone is a tropical storm of great intensity. The diameter is sometimes less than 25 miles and sometimes as great as 600 miles. The minimum pressure at the centre is sometimes lower than 900 mbs, but usually of the order of 950 mb. The winds in the centre are nearly calm but round the calm centre there is a ring of high winds reaching 73 mph or more. When the cyclone reaches phenomenal intensity and the wind speed cannot ordinarily be measured it is called a Severe Cyclone.

Western Disturbance (Extra Tropical Depression)

23. Disturbed weather conditions moving towards the country from the west are term “Western Disturbance”. They usually approach as waves of low pressure of shallow depression in the temperate latitude, weather systems originating from Mediterranean Sea or the Middle East. At times they are 3 to 4 mbs deep, when they may be called “Western Depression'. Such Western Disturbances are most frequent in the winter and spring seasons and are sometimes associated with well-marked warm and cold fronts.

Trough of Low Pressure

24. It is an outward extension from a cyclone in which the isobars are either U-shaped or V-shaped. It becomes V-shaped only when it is traversed by a front and is then known as V-shaped depression. The pressure is low within the trough and increases outward.

25. In frontal type, ie a V-shaped trough marked change of wind and deterioration of weather generally occurs which are same as in fronts. Increased clouds with showers or other precipitation may be expected. Behind the trough weather usually improves rapidly.

Secondary Depression

26. It is a small depression within the circulation of a larger one. It circulates around the primary depression with the general air stream. Sometimes the secondary becomes well developed, when the primary get filled up.

27. In winter intense secondary depressions cause much rain or snow, and also severe gales on the side away from the parent depressions. In summer most secondaries over land often give thunderstorms.

Anti-Cyclone

28. When the isobars close around a central high pressure region, the pattern is called an anti-cyclone. In an anti-cyclone pressure decreases outward from the centre.

29. In an intensifying anti-cyclone air tends ton subside and clouds disappear. This explains the common association between high pressure systems and good weather. Although appreciable rain is unlikely near the centre of an anti-cyclone, good flying conditions do not invariably occur; for example, poor visibility is frequently experienced because light winds and stable air retard the dispersal of smoke and dust.

Ridge of High Pressure

30. It is an outward extension from an anticyclone towards the low pressure. Pressure is highest in the central region and decreases outward.

31. The weather in it is nearly always fair or fine, and there are rarely extensive cloud sheets such as appear in many anti-cyclones. However, the good weather is usually for short duration owing to rapid movement of the system. Radiation fog may occur near the centre of the ridge rarely persists.

Col

32. The ‘Col’ is a saddle shaped region between two cyclones and two anti-cyclones arranged in such a way that the two cyclones (or anticyclones) are diametrically opposite to each other. Near the ground level the wind blows towards ‘Col’ region from the two anti-cyclones and outward from the ‘Col’ towards the two cyclones.

33. Sometimes fronts traverses the ‘Col’. Such fronts are usually very slow-moving. Very slow moving, and clouds or precipitations may therefore persist for long periods. Very light winds or calm occur in a Col, but otherwise the weather depends largely on circumstances. Over the land a Col is often associated with thunderstorms in summer, and with fog or low cloud in autumn and winter.

The Significance of Pressure System

34. When weather maps comprising a sequence at, say 6 hourly intervals, are compared, the patterns made by isobars, although tending to retain their identity, are usually found to change in shaped and also to move progressively across the maps from one map to the next. Depressions are said to deepen or intensify or to decay or fill up.

35. The change of shape particularly the movements of pressure systems are more marked in high than in low latitudes. This is because thee atmospheric pressure does not change much from day to day near the equator.

36. The various types of isobars configurations are in general associated with particular types of weather. Hence the highs and lows, troughs and ridges etc are particularly important features of the weather maps of middle and high latitudes, because these pressure systems tend too retain their identity and to carry their associated weather with them wherever they good. Their identification is therefore a considerable aid to forecasting.

VISIBILITY AND ITS RESTRICTIONS

Introduction

1. Although modern developments in radio and radar have made flying possible without ever looking outside the cockpit, still visibility remains a factor of great importance in all ordinary aircraft operations both civil and military. Visibility is a measure of the degree of transparency of the atmosphere. A pilot's interest in visibility arises because he wants to know how far he will be able to see various things, land marks, targets, obstructions, beacon lights, other aircraft, runway etc, while in flight or when he is about to make an approach for landing. A pilot should be thoroughly familiar with the prevailing visibility in different seasons over the airfields on which he operates and the incidents of phenomena which render visibility poor.

Aim

2. To know about visibility and its restrictions.

Definition

3. Visibility is defined as the greatest distance at which an object of specified characteristics can be seen and identified with the unaided eye in any particular circumstances, or in the case of night observations, could be seen and identified if the general illumination were raised to the normal daylight level. Lower visibilities are expressed in meters or yards and higher visibilities in kilometers or miles. Reports generally refer to a visibility based on all directions; where there is marked variation with direction, the lowest visibility is recorded for synoptic purposes, with an appropriate entry in a 'special phenomena' group.

4. 'Visibility objects' by day are ideally confined to black or nearly black objects which appear against the horizon sky. Night visibility objects comprise mainly unfocused light of moderate and known intensity at known distances.

Types of Visibility

5. There are three types of visibility that affect aviation, shown in Figure 1. They are:

a. **Horizontal Surface Visibility**. Horizontal surface visibility refers to the ability of an observer on the surface to see other objects on the surface.

b. **Air-to-Air or Flight Visibility**. Air-to-air visibility refers to the ability of an observer aloft to see other objects aloft. This is reported by pilots.

c. **Oblique or Slant Visibility**. Oblique visibility, or 'slant visibility' is the greatest distance at which a given object can be seen and identified with the unaided eye along a line of sight inclined to he horizontal. Oblique visibility in a downward direction, an important element in aircraft operation, is generally different from the visibility measured at the earth's surface due:

(1) To height variations of atmospheric Extinction Coefficient[1] in the layer concerned. In relation to Visibility, scattering is much the more important of the two extinction processes.

(2) To the fact that objects are then viewed against a terrestrial background.

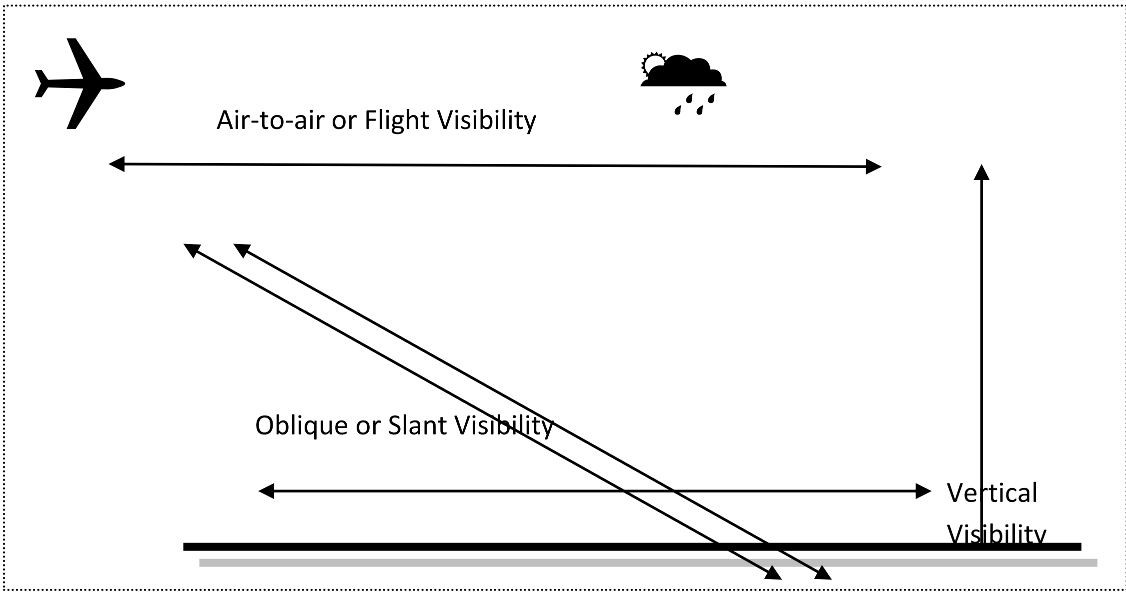


Figure1: Different types of visibility.

d. **<u>Vertical Visibility</u>**. The greatest distance at which a given object can be seen and identified in the vertical plane of the observer. This element, required in synoptic observations on occasions when the sky is obscured by fog, etc. may be measured by pilot balloon and theodolite, the vertical visibility being taken as *h.cosecE* where h is the height of the balloon and E its angular elevation at the moment of its disappearance from view.

6. Except in periods of overall clear weather, the three types of visibility that affect aviation function independently of each other. Horizontal surface visibility may be good at a time when cloud conditions limit air-to-air and air-to-ground visibility. At other times, horizontal surface visibility and air–to–air visibility may be good in an area where cloud layers limit air–to–ground visibility. A particular airport may be closed so that aircraft do not arrive or depart because of bad horizontal surface visibility, while air–to-air visibility may be excellent a short distance above the surface.

7. The stability of air largely determines the type and intensity of restrictions to visibility near the ground. Stable air, which resists vertical movement, does not break up and spread out restrictions to visibility. However, unstable air produces vertical currents which tend to break up and separate fog, and to spread haze and smoke both vertically and horizontally. Precipitation in sable air tends to continue without stopping, precipitation in unstable air does not usually cover large areas, nor does it usually continue a long time. Thus we can say, stable air will have a characteristic of poor visibility, and unstable air, good visibility.

[1] The term *Extinction Coefficient* is reserved as a measure of the combined effects of 'Absorption' and 'Scattering' of wavelength within the 'Visible Spectrum'. Extinction coefficient has the dimension L^{-1}: its value in the atmosphere varies from about 10 per km in thick fog to 0.01 per km in air of very good visibility.

8. As the earth and lower layers of air become warm during the day, air that was stable during the early morning hours may become unstable. For this reason visibility usually improves as temperatures rise. If cloud layers aloft keep the sun's heat from reaching the ground, visibility improvement is usually slow.

9. **Runway Visual Range (RVR).** A pilot's interest in visibility arises because he wants to know how far he will be able to see the runway markings and edge lights etc. during landing and take-off. Hence the term Runway Visual Range (RVR) is commonly used in aviation more often than meteorological visibility. RVR is defined as the maximum distance in the direction of take-off or landing at which the runway or the specified lights or markers delineating it can be seen from a position above a special point on its centre-line at a height corresponding to the average eye level of the pilot at touchdown. As per ICAO recommendations, the pilot's eye level position is taken as 5 metres above the runway surface when the aircraft is on the runway. The RVR is based on the following factors:

a. The atmospheric transparency.

b. Background luminance.

c. Runway light intensity RVR is not an observation or measurement of a meteorological parameter like surface wind, temperature etc. but it is an assessment based on calculations taking the above factors into consideration. The purpose of RVR is to provide pilots and other aeronautical users with information on runway visibility conditions during periods of low visibility due to rain, snow, fog or dust storm. RVR is required to allow as assessment to be made as to whether conditions are above or below the specified operating minima.

Visibility/RVR Observations Required

10. Visibility observations should be made on all runways intended for use during periods of reduced visibility and in particular on:

a. Precision approach runways.

b. Runways used for take-off and having high intensity edge lights and/or centre line lights.

The RVR observations should be made and reported throughout any period when either the horizontal visibility or the RVR is observed to be less than 1500 meter.

Descriptive Terms of Visibility

11. Visibility in terms of range is classified as:

a.	Poor visibility	:	1,500m or less.
b.	Moderate visibility	:	More than 1,500m but <5km.
c.	Good visibility	:	More than 5km but <9km.
d.	Very good or excellent visibility	:	More than 10km.

Causes of Atmospheric Obscurity

12. The distance at which an object can be seen depends on the position and characteristics of the observer and the object, as well as on the obscurity of the atmosphere

between the two. The condition determining the obscurity may be classified as follows:

a. Fog and mist caused by water droplets. Cloud and precipitation caused by water droplets or ice crystals or both.

b. Wind blown spray from sea caused by water droplets.

c. Smoke caused by solid impurities from combustion.

d. Dust and smoke also caused by solid impurities thrown out from active

e. volcanoes or by raised dust or sand from ground on desert or semi desert regions in dry season.

Common Weather Phenomena Reducing Visibility

13. Common weather phenomena which reduce visibility are given below:

Weather Phenomena	Visibility (m)
Haze	1000-5000
Mist	1000-5000
Fog	30-1000
Drizzle	<1000
Rain	<1000
Snow	<300
Blowing snow	<50

Conclusion

14. Visibility is a measure of the degree of transparency of the atmosphere. A pilot's interest in visibility arises because he wants to know how far he will be able to see various things, land marks, targets, obstructions, beacon lights, other aircraft, runway etc, while in flight or when he is about to make an approach for landing. It is the greatest distance at which a black object, during day, or unfocused light, during night, of suitable dimension or if illumination were raised to normal daylight level, can be seen and recognised with normal eyesight. The distance at which an object can be seen depends on the position and characteristics of the observer and the object, as well as on the obscurity of the atmosphere between the two. The lowest visibility is to be reported for operational purposes. There are 4 types of visibility as horizontal surface visibility, air-to-air visibility, oblique visibility and vertical visibility. Fog, rain and drizzle are the main weather phenomenon for reducing the visibility.

FOG, MIST AND HAZE

Introduction

1. Bangladesh is influenced by four seasons in the light of meteorology. The seasons are summer or south-west monsoon, winter or north-east monsoon, pre-monsoon and post-monsoon. The average duration of the summer and winter seasons are 4 months each, and pre-monsoon and post-monsoon seasons are 2 months each. This paper is confined to the winter season specially the winter weather fog. Poor visibility condition without precipitation prevails in fog in winter. Decrease in temperature on earth's surface to dew point temperature and increase in stability in the lower troposphere by forming inversion layer are the main causes for the formation of fog. Different type of fog, such as radiation fog, advection fog, upslope fog, steam fog etc will be discussed in the following paragraphs. How one can anticipate fog by observing previous day's surface and upper air charts, and how fog influences the military air operations are important of this attempt.

Aim

2. To provide knowledge on fog, mist and haze.

Definition

3. **Fog**. Fog is a visible aggregate of minute water droplets or ice crystals or both from 0.01 mm to 0.1 mm in diameter suspended in the air. It reduces surface visibility to less than 1000 meter. If it is lifts up to a height of 50 ft or more then it is said to be cloud. In fog, Relative Humidity (RH) remains more than 90%. In industrial area, fog may be mixed with smoke and smog may be formed.

4. **Mist**. Mist is a suspension in the air of microscopic water droplets or wet hygroscopic particles, reducing the visibility at the earth's surface. Note that in the International Codes for weather reports, the term 'mist' is used when the hydrometeor mist or fog reduces the horizontal visibility at the earth's surface to *not less* than 1 km. In mist RH remains more than 75%.

5. **Haze.** Haze is a suspension in the air of extremely small dry particles invisible to the naked eye and sufficiently numerous to give the air an opalescent appearance. It may also be defined as the suspension of dust particles that reduces surface visibility from 5 to 8 km irrespective of the presence of cloud in the sky. If RH is less than 80% (generally less than 65%) and visibility is in between 1km and 5km that is in mist range, we can call the atmospheric obscurity as Haze. Haze is of two types:

a. **Dust Haze**. Dust haze is a suspension in the air of dust or small sand particles, raised from the ground prior to the time of observation by a dust storm or sandstorm.

b. **Moist Haze**. Occasionally a haze layer is found in a position which would be occupied by cloud if the air were sufficiently humid of it indicates a layer previously occupied by cloud which has been evaporated by descent and adiabatic warming.

Conditions for the Formation of Fog

6. The main requirement for the formation of fog is to fall the surface temperature below the dew point temperature of the air aloft. As such the relative humidity presents as the thick fog or reduced visibility prevails in the morning or late night, clear night allows terrestrial radiation to fall surface temperature. The anticyclone over the Head Bay or North Bay at lower levels helps to surge the moisture to the coastal districts and it results thick fog. Light wind makes surface layer turbulent which acts like a triggering action for formation of fog. A large number of condensation nuclei are favourable for formation of fog with even less relative humidity. Radiation fog, advection fog or sea fog, upslope fog or mountain fog and steam fog or sea smoke are discussed in the following paragraphs.

Types of Fog

7. There are mainly four types of fog according to the place of origin. They are:

a. Radiation fog.

b. Advection fog.

c. Upslope fog.

d. Steam fog or sea smoke.

Wet fog and ground fog are the other types of fog.

Radiation Fog

8. If the temperature falls over a certain land area by terrestrial radiation through night to a value near dew point or below it with respect to air aloft then radiation fog forms. The favourable conditions for formation of radiation fog are:

a. High relative humidity so little cooling is required to reach the saturation.

b. Clear night so that heat is lost by radiation.

c. Light wind (2-8 knots) so that cooling is confined to the surface layer.

9. Lowest temperature is observed in the early morning even after the sunrise. Thick radiation fog occurs about an hour after the sunrise because when there is a light wind instead of calm, turbulence spreads the cooling through a deeper layer. If the wind speed increases then fog disperses. During radiation fog there is a high possibility of forming temperature inversion, fog then disperses after the break down of inversion layer by sunshine. Deeper inversion layer causes longer duration of radiation fog. Thicker radiation fog occurs over grassy ground and it also prevails longer duration to dissipate.

Advection Fog

10. When warm air moves to a place of underlying cold surface then advection fog forms. Advection fog forms near the coastal districts even near the ponds. If temperature falls down to dew point after reaching from one place to another place then thick advection fog forms if RH is sufficient to a great depth. Wind is the main driving force to move the moist air but if it exceeds 8kts then advection fog is dropped and cloud forms. Sometimes warm air over sea moves to another place of underlying cold sea surface the sea fog then forms.

Upslope Fog

11. Sometimes stable air moves up slopping terrain or hills or mountains and cools adiabatically resulting upslope fog or mountain fog. This fog lays lee side of the terrain.

Steam Fog or Sea Smoke

12. During winter when cold dry air passes from land to over comparatively warm ocean water. It cannot hold evaporating moisture by cold dry air, therefore, condensation takes place just above the evaporating water surface and appears as “steam” rising from the water surface. If the condensation takes place to a certain height cloud then forms. We observe steam fog over ponds and sea smoke over sea with the sweep of cold wave.

Smog

13. The term Smog, contraction for ‘smoke and fog’ which signifies a Fog in which smoke, or other form of atmospheric pollutant besides playing an important part in causing the fog to form and to thicken, for example by acting as condensation nuclei, has unpleasant or dangerous physiological effects.

Advection-Radiation Fog

14. Advection-radiation fog is a radiation fog that occurs with nigh time cooling of air brought in by advection from warm, moist seas. It occurs a short distance inland from coasts. It is also common around the great lakes. It is likely to form in the fall when the waters are warm and night time radiation over the land has begun to strengthen.

Visibility Limits in Fog and Clouds

15. The surface visibility in fog may be reduced to below 50 meters. The visibility in clouds may vary from even less than 10 meter in Cb or Cu clouds to more than 1,000 meter in Ci cloud. The smaller and numerous the water droplets, the lesser the visibility, and vise-versa.

16. The visibility limits in Cb or Cu cloud and fog may be same but rainfall in usual in clouds and drizzle is seldom in fog. The growing of water droplets by collision and coalescence is rare in fog due to a little vertical depth.

Flying Hazards in Fog

17. Fog envelops the ground, low building and trees; therefore, the pilot in the sky cannot detect the underlying place. Again the fog forms in winter so there is a great chance of aircraft icing which reduces the performance of aircraft and forces to bring down the aircraft. Long route transport aircraft may fall in accident in fog.

Usefulness of Fog

18. Fog may camouflage aircraft and equipment on the ground, troops, detachment, and as such enemy forces cannot effectively attack. During winter moisture is less in the atmosphere and this fog is only the source of moisture, which balances the moisture content and dominates the growing of different crops. During pre-monsoon period fog may cause formation of clouds and result rain or Nor’wester.

Precaution in Fog

19. Instrumental landing system and de-icing facilities must be used if any. By increasing the surface temperature fog may be dropped.

Feeling Cold in Fog

20. With the same minimum temperature whether foggy day is colder can easily be explained. If fog prevails and light wind blows then water droplets will come in contact with the skin of body. The fog particles will evaporate on warm skin by absorbing the latent heat from the skin of the body. Temperature of bare skin will then be reduced. Thus the man and women will feel and notice colder in foggy morning than the other days with the same minimum temperature.

Conclusion

21. Fog, mist and haze reduce visibility and specially fog hinders the flying actively during landing and take-off. Different types of fog form on different formation places. Decrease in surface temperature to or near dew point temperature, clear night allows terrestrial radiation and light wind helps surface layer turbulent are the main favourable conditions for the formation fog. Fog has both merits and demerits in military air operations. Fog obscures the runway and ground objects, as such pilot can not land or take-off in fog. It also camouflages aircraft, equipment and troops etc on the ground; therefore enemy forces cannot effectively attack during war.

TOPIC-3

BASIC PRINCIPLES OF FLIGHTS
AERODYNAMIC FORCES

Introduction

1. In aerodynamics, as in most subjects, there are a number of conventional symbols used. These are given below, together with a list of the more frequently used expressions.

Symbols and Definitions

2. **Symbols**

a. **Density**

(1) Density at any unspecified point = ρ (Rho)
(2) Density at ICAO MSL = ρ_o = 1.2250 kg per m^3
(3) Relative density = σ (Sigma) = $\frac{\rho}{\rho_o}$

b. **Velocity**

(1) Equivalent air speed (EAS) = Ve
(2) True airspeed (TAS) = V, Then Ve = $V\sqrt{\sigma}$

c. **Pressure**

(1) Static pressure at any unspecified point = p
(2) Free stream static pressure = p_o
(3) Dynamic pressure = q = ½ ρV^2 or ½ $\rho_o Ve^2$
(4) Total head pressure or stagnation pressure = H or Ps

d. **Angle of Attack**

Aerofoil	**Wing**
(Two dimensional flow)	(Three Dimensional flow)
α_o (alpha)	α
or	
α_{1o} (zero lift angle of attack)	

e. Coefficients.

	Aerofoil	Wing
(1) Lift	C_1 $\frac{\text{lift/span}}{\text{q.c}}$	C_L $\frac{\text{lift}}{\text{q.S}}$
(2) Dr	$\frac{\text{drag/span}}{\text{q.c.}}$	C_D $\frac{\text{drag}}{\text{q.S}}$

Whe c = chord

(3) F

$$\frac{\text{pressure differential}}{\text{dynamic pressure}} = \frac{p - p_o}{q}$$

f. Aircraft Body Axes – Notation (See Table 1)

3. **Definitions**

a. **Free Stream Flow.** Air in a region where pressure, temperature and relative velocity are unaffected by the passage of the aircraft through it. Sometimes called relative airflow (RAF).

Table 1 Aircraft Body Axes - Notation

	Designation	*Longitudinal*	*Lateral*	*Normal*
Axis	Symbol	x	y	z
	Positive Direction	Forward	To Right	Down
Force	Symbol	X	Y	Z
Moment	Symbol	L	M	N
	Designation	Rolling	Pitching	Yawing
Angle of				
Rotation	Symbol	ϕ (phi)	θ (theta)	Ψ (psi)
Velocity	Linear	u	v	w
	Angular	p	q	r
Moment of				
Inertia	Symbol	A	B	C

b. **Total Reaction (TR)**. The resultant of all the aerodynamic forces acting on the wing or aerofoil section.

c. **Lift.** That component of the TR which is perpendicular to the flight path or RAF.

d. **Drag.** The component of the TR which is tangential to the flight path, ie parallel to the RAF.

e. **Chord Line**. A straight line joining the centres of curvature of the leading and trailing edges of an aerofoil.

f. **Chord (c).** The distance between the leading and trailing edge measured along the chord line. The mean chord is often used as a datum linear dimension in the same way that the wing area (S) is used as a datum area.

g. **Wing Area (S)**. Area of the wing projected on a plane perpendicular to the normal axis.

h. **Mean line or Camber Line**. A line joining the leading and trailing edges of an aerofoil equidistant from the upper and lower surfaces. Maximum camber is usually expressed as a ratio of the maximum distance between the camber line and the chord line to chord length. Where the camber line lies above the chord line, the aerofoil is said to have positive camber.

j. **Angle of Attack (α).** The angle between the chord line and the flight path or RAF. In many textbooks this is referred to as Incidence.

k. **(Rigger's) Angle of Incidence.** The angle at which an aerofoil is attached to the fuselage. The angle between the mean chord line and the longitudinal fuselage datum. The term is often used erroneously instead of Angle of Attack.

l. **Thickness/Chord Ratio (t/c)**. The maximum thickness or depth of an aerofoil section expressed as a percentage of chord length.

m. **Centre of Pressure (CP)**. The point, usually on the chord line, through which the TR may be considered to act.

n. **Streamline**. The path traced by a particle in a steady fluid flow.

p. **Aspect Ratio** $= \frac{\text{span}}{\text{chord}} = \frac{\text{b}}{\text{c}}$ or $\frac{\text{span}^2}{\text{wing area}} = \frac{\text{b}^2}{\text{S}}$

q. **Wing Loading**. The weight per unit area of the wing $= \frac{\text{weight}}{\text{wing area}} = \frac{\text{W}}{\text{S}}$

r. **Load Factor (g or n)** $\text{n} = \frac{\text{Total Lift}}{\text{Weight}}$

AERODYNAMIC PRINCIPLES

General

4. Several methods or theories have been developed to predict the performance of a given wing/aerofoil shape. These can be used to explain the subtle changes in shape necessary to produce the required performance appropriate to the role of the aircraft. In practice, the appropriate wing shape is calculated from the performance criteria.

5. The theory in this volume is confined to the Equation of Continuity and Bernoulli's Theorem, thereby explaining lift by pressure distribution. In the Annex to this chapter will be found other theories, namely the Momentum Theory, Circulation Theory and Dimensional Analysis.

Pressure Distribution

6. The most useful, non-mathematical method, is an examination of the flow pattern and pressure distribution on the surface of a wing in flight. This approach will reveal the most important factors affecting the amount of lift produced, based on experimental (wind-tunnel) data. As a qualitative method however, it has limitations and the student will sometimes be presented with facts capable only of experimental proof or mathematical proof.

7. The pattern of the airflow round a aircraft at low speeds depends mainly on the shape of the aircraft and its attitude relative to the free stream flow. Other factors are the size of the aircraft, the density and viscosity of the air and the speed of the airflow. These factors are usually combined to form a parameter known as Reynolds Number (RN) and the airflow pattern is then dependent only on shape, attitude and Reynolds Number (See also para 40 et seq).

8. The Reynolds Number (ie size, density, viscosity and speed) and condition of the surface determine the characteristics of the boundary layer. This, in turn, modifies the pattern of the airflow and distribution of pressure around the aircraft. The effect of the boundary layer on the lift produced by the wings may be considered insignificant throughout the normal operating range of angles of attack. In later chapters it will be shown that the behaviour of the boundary layer has a profound effect of the lift produced at high angles of attack.

9. When considering the velocity of the airflow it does not make any difference to the pattern whether the aircraft is moving through the air or the air is flowing past the aircraft: it is the relative velocity which is the important factor.

Types of Flow

10. **Steady Streamline Flow.** In a steady streamline flow the flow parameters (eg speed, direction, pressure etc.) may vary from point to point in the flow but, at any point, are constant with respect to time. This flow can be represented by streamlines and is the type of flow which it is hoped will be found over the various components of an aircraft. Steady streamline flow may be divided into two types:

a. **Classical Linear Flow.** Fig 1 illustrates the flow found over a conventional aerofoil at low angle of attack in which the streamlines all more or less follow the contour of the body and there is no separation of the flow from the surface.

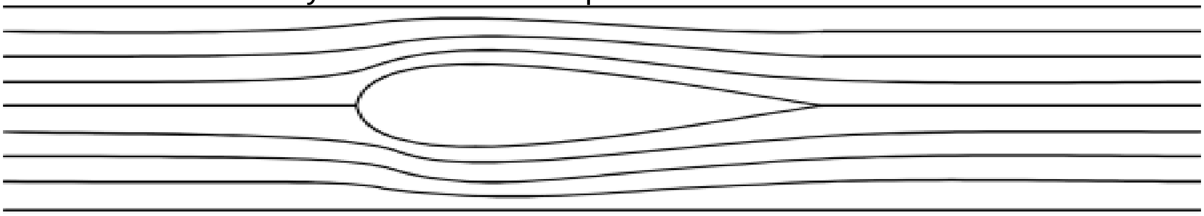


Fig 1 : Classical Linear Flow

b. **Controlled Separated Flow or Leading Edge Vortex Flow**. This is a halfway stage between steady streamline flow and unsteady flow described later. Due to boundary layer effects, generally at a sharp leading edge, the flow separates from the surface, not breaking down into a turbulent chaotic condition but, instead, forming a strong vortex which, because of its stability and predictability, can be controlled and made to give a useful lift force. Such flows illustrated in Fig 2 are found in swept and delta planforms, particularly at the higher angles of attack, and are dealt with in more detail in later chapters.

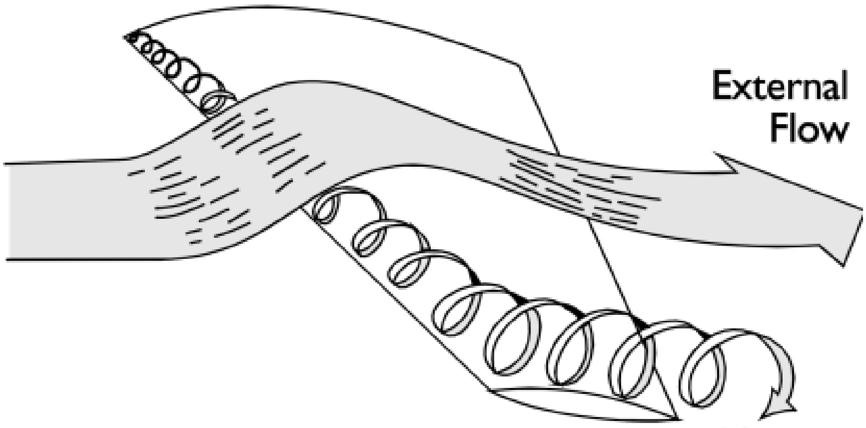


Fig 2 Leading Edge Vortex Flow

11. **Unsteady Flow**. In this type of flow the flow parameters vary with time and the flow cannot be represented by streamlines.

12. **Two-dimensional Flow**. If a wing is of infinite span, or, if it completely spans a wind tunnel from wall to wall, then each section of the wing will have exactly the same flow pattern round it except near the tunnel walls. This type of flow is called two-dimensional flow since the motion is confined to a plane parallel to the free stream direction.

13. **Velocity Indication.** As the air flows round the aircraft its speed changes. In subsonic flow a reduction in the velocity of the streamline flow is indicated by an increased spacing of the streamlines whilst increasing velocity is indicated by decreased spacing of the streamlines. Associated with the velocity changes there will be corresponding pressure changes.

14. **Pressure Differential**. As the air flows towards an aerofoil it will be turned towards the low pressure (partial vacuum) at the upper surface; this is termed 'upwash'. After passing over the aerofoil the airflow returns to its original position and state; this is termed 'downwash' and is shown in Fig 3. The reason for the pressure and velocity changes around an aerofoil is explained in later paragraphs. The differences in pressure between the upper and lower surfaces of an aerofoil are usually expressed as relative pressures by '–' and '+'. However, the pressure above is usually a lot lower than ambient pressure and the pressure below is usually slightly lower than ambient pressure (except at high angles of attack), ie both negative.

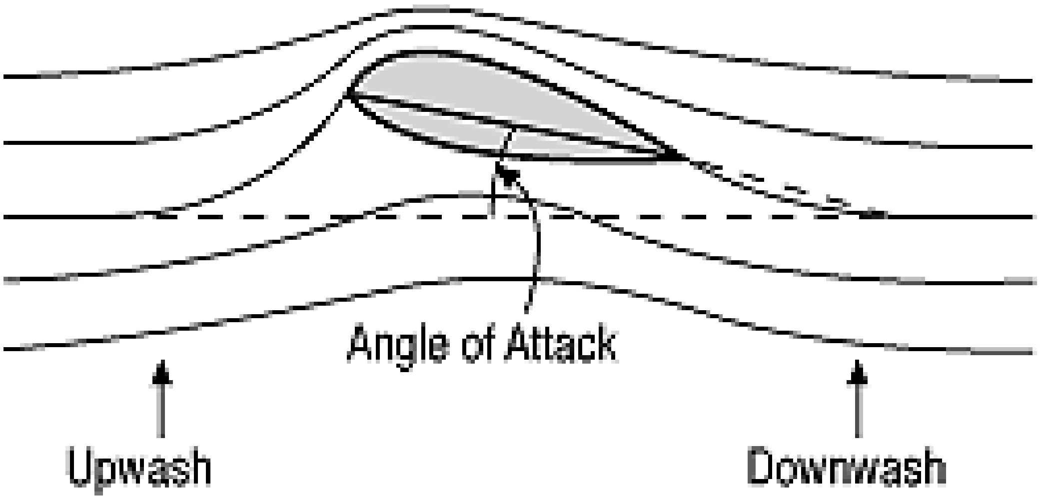


Fig 3 Two-dimensional Flow Around an Aerofoil

15. **Three-dimensional Flow**. The wing on an aircraft has a finite length and, therefore, whenever it is producing lift the pressure differential tries to equalize around the wing tip. This induces a span-wise drift of the air flowing over the wing, inwards on the upper surface and outwards on the lower surface, producing a three-dimensional flow.

16. **Vortices**. Because the effect of the spilling at the wing tip is progressively less pronounced from tip to root, then the amount of transverse flow reduces towards the fuselage. As the upper and lower airflows meet at the trailing edge they form vortices, small at the wing root and larger towards the tip (see Fig 4). These form one large vortex in the vicinity of the wing tip, rotating clockwise on the port wing and anti-clockwise on the starboard wing; viewed from the rear. Tip spillage means that an aircraft wing can never produce the same amount of lift as an infinite span wing. If the wing has a constant section and riggers angle of incidence from root to tip then the lift per unit span of the wing may be considered to be virtually constant until about 1.2 chord distance of the wing tip.

Fig 4 Three dimensional Flow

The end ‘a’ of the aerofoil section abuts the wind tunnel wall and may be regarded as a wing root. The wool streamer indicates virtually no vorticity. End ‘b’ is a free wing tip and marked vorticity can be noted.

17. **<u>Vortex Influences</u>.** The overall size of the vortex at the trailing edge will depend on the amount of the transverse flow. Therefore, the greater the force (pressure difference), the larger it will be. The familiar pictures of wing-tip vortices showing them as thin white streaks, only show the low pressure central core and it should be appreciated that the influence on the airflow behind the trailing edge is considerable. The number of accidents following loss of control by flying into wake vortex turbulence testifies to this. The vortex upsets the balance between the upwash and downwash of two-dimensional flow, reinforcing the downwash and reducing the effective angle of attack also inclining the lift vector slightly backwards as the effective relative airflow is now inclined downwards. The component of the lift, parallel to the line of flight is increased; this increase is termed the induced drag. The resolved lift vector perpendicular to the flight direction is reduced.

BASIC AERODYNAMIC THEORY

General

18. The shape of the aircraft (and boundary layer) will determine the velocity changes and consequently the airflow pattern and pressure distribution. For a simplified explanation of why these changes occur it is necessary to consider:

a. The Equation of Continuity.

b. Bernoulli’s Theorem.

A more detailed explanation of other aerodynamic theories is given in the Annex to this Chapter.

The Equation of Continuity

19. The Equation of Continuity states basically that mass can neither be created nor destroyed or, simply stated, **air mass flow is a constant**.

20. Consider the streamline flow of air through a venturi tube. The air mass flow, or mass per unit time, will be the product of the cross-sectional area (A), the flow velocity (V) and the density (ρ). This product will remain a constant value at all points along the tube.

i.e. $A.V.\rho$ = constant

This is the general equation of continuity which applies to both compressible and incompressible fluids.

21. In compressible flow theory it is convenient to assume that changes in fluid density will be insignificant at speeds below about 0.4 M. This is because the pressure changes are small and have little effect on the density. The equation of continuity may now be simplified to:

$$\mathrm{A} \times \mathrm{V} = \text{constant, or } \mathrm{V} = \frac{\text{constant}}{\mathrm{A}}$$

from which it may be seen that a reduction in the tube's cross-sectional area will result in an increase in velocity and vice versa. This equation enables the velocity changes round a given shape to be predicted mathematically.

Bernoulli's Theorem

22. Consider a gas in steady motion. It possesses the following types of energy:

a. Potential energy due to height.

b. Heat (Kinetic) energy.

c. Pressure (Potential) energy.

d. Kinetic energy due to motion.

In addition work and heat may pass in or out of the system.

23. Daniel Bernoulli demonstrated that in the **steady streamline flow of an ideal fluid**, the sum of the energies present remained constant. It is emphasised that the words in bold represent the limitations of Bernoulli's experiments. In low subsonic flow (<0.4 M), it is convenient to regard air as being incompressible and inviscid (ie ideal) and predictions of the pressure changes round a given aerofoil section agree closely with measured values. Above 0.4M, however, these simplifications would cause large errors in predicted values and are no longer permissible.

24. In low subsonic flow, Bernoulli's Theorem may be simplified still further by assuming changes in potential energy and heat energy to be insignificant and that there is no transfer of heat or work. For practical purposes therefore, in the streamline flow of air round a wing at low speed:

Pressure Energy + Kinetic Energy = Constant

It can be shown that this simplified law can be expressed in terms of pressure, thus:

$P + \frac{1}{2}\rho V^2$ = constant, where p = static pressure, ρ = density and V = flow velocity.

The significance of this law will be recognized if it is translated into words: static pressure + dynamic pressure is a constant. This constant is referred to as Total Head Pressure, stagnation pressure or pitot pressure.

25. It has already been stated that the flow velocity is governed by the shape of the aircraft. From Bernoulli's Theorem (simplified) it is evident that an increase in velocity causes a decrease in static pressure and vice versa.

<u>The Flat Plate Effect</u>

26. At the stall, there is a partial collapse of the low pressure on the top surface of the wing, considerably reducing the total lift. The contribution of the lower surface is relatively unchanged. The circulation theory of lift becomes invalid at any angle of attack beyond the stall; the aerofoil may then be regarded as a flat inclined plate as in Fig 5, producing lift from the combined effect of stagnation pressure and flow deflection from the underside (change of momentum).

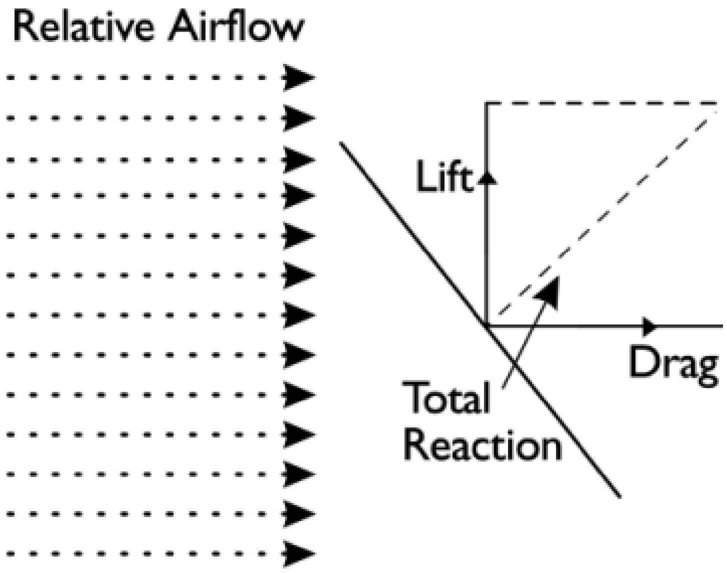


Fig 5 Inclined Flat Plate - Lift Acting at Centre of Area Pressure Distribution around an Aerofoil

27. Although the whole aircraft contributes towards both lift and drag it may be assumed that the wing is specifically designed to produce the necessary lift for the whole of the aircraft. Examination of the distribution of pressure round the wing is the most convenient non-mathematical way to see how the lift is produced. Fig 6 shows the pressure distribution round a modern general purpose aerofoil section in two-dimensional flow and the changes in pressure distribution due to attitude.

28. Pressure distribution round an aerofoil is usually measured with a manometer: this consists of a series of glass tubes filled with a coloured liquid and connected to small holes in the aerofoil surface. As air flows over the aerofoil the variations in pressure are indicated by the differing levels of fluid in the tubes. These measurements are in absolute pressure and it is useful to compare them to ambient pressure in order more easily to see the lifting effort produced by the aerofoil.

29. The pressure at a point on the aerofoil surface may be represented by a vector perpendicular to the surface whose length is proportional to the difference between absolute pressure at that point and free stream static pressure, ie proportional to (P - P_o). It is usual to convert this to a non-dimensional quantity called the pressure coefficient (Cp) by comparing it to free stream dynamic pressure (q), thus:

$$C_p = \frac{(p - p_o)}{q}$$

30. The convention for plotting these pressure coefficients is as follows:

a. Measured pressure higher than ambient pressure - at these points, (p - po) will be positive, giving a positive Cp and the vector is plotted towards the surface.

b. Measured pressure lower than ambient pressure - here, (p - po) will be negative, resulting in a negative Cp which is plotted away from the surface.

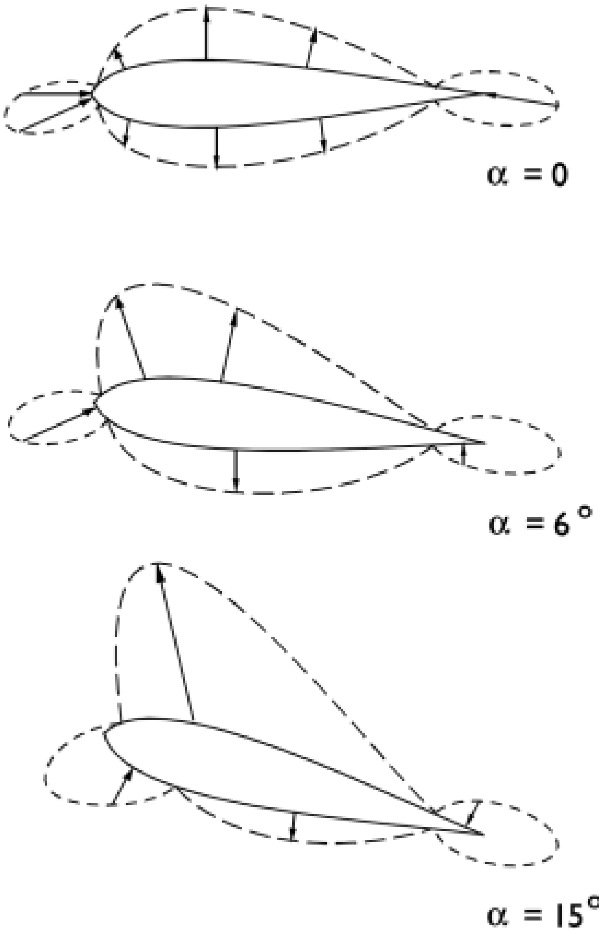


Fig 6 Pressure Distribution Around an Aerofoil

31. It is useful to consider the value of the Cp at the leading edge stagnation point where the air is brought to rest. The absolute pressure will be total head pressure = free stream static pressure + free stream dynamic pressure. The pressure coefficient will therefore be:

$$\frac{(p_o + q) - p_o}{q} \text{and therefore } C_p = +1$$

32. Each of the pressure coefficient vectors will have a component perpendicular to the free stream flow which is, by definition, a lift component. Because the pressure is plotted in coefficient form, the lift component will also be a coefficient, and is the local lift coefficient at

that point. It is possible therefore to obtain the total lift coefficient from the pressure distribution, by subtracting all the lift components pointing down (relative to the free stream) from all those pointing up.

33. Inspection of the pressure distribution diagrams gives an indication of the direction and magnitude of the total reaction (TR) and the position of the centre of pressure (CP). In particular, two facts are immediately apparent which will be of considerable use in later chapters:

a. The lift coefficient increases with an increase in angle of attack.

b. The CP moves forward with an increase in angle of attack.

34. A common way to illustrate the pressure distribution round an aerofoil section is to plot it in the form of a graph (see Fig 7). Notice that, whereas in the previous diagrams the Cp values are plotted perpendicular to the aerofoil surface, in the graph the Cp values are perpendicular to the chord line. Note also the convention of plotting negative values upwards to relate it to lift in the natural sense.

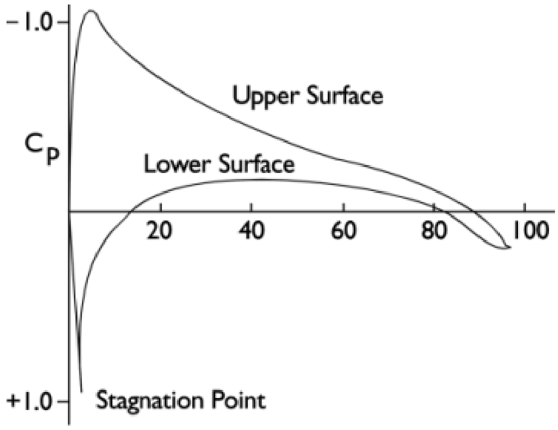


Fig 7 Graphical Representation of Aerofoil Pressure Distribution (Angle of Attack approx 10 degrees)

Summary

35. Airflow pattern, and therefore lift, depends upon:

a. Angle of attack.

b. Shape (thickness/chord ratio, camber).

c. Density of the air - Reynolds Number

d. Viscosity - Reynolds Number

e. Size - Reynolds Number

f. Speed - Reynolds Number

36. The equation of continuity states that:

a. Air mass flow is a constant.

b. Cross-sectional area x velocity x density = constant, i.e. $A.V.\rho = k$. It also assumes that pressure changes, being small, have little effect on ρ and therefore:

$A \times V = k$

$V = k/A$

and therefore a reduced A gives greater velocity (venturi).

37. Bernoulli's Theorem states that:

a. Pressure energy + kinetic energy = k and therefore $P + \frac{1}{2}\rho V^2 = k$ Therefore static pressure + dynamic pressure = k.

b. $P + \frac{1}{2}\rho V^2$ = total head, stagnation or pilot pressure.

REYNOLDS NUMBER

Introduction

38. In the early days of flying, when aircraft speeds were of the order of 30-40 mph, testing of aerofoils was a comparatively simple operation. But as speeds increased and the design of aircraft became more sophisticated, wind-tunnels were developed for the purpose of testing scale models. This led to problems in dynamic similarity which was easier to understand than to solve.

Scale

39. If we consider a 1/10th scale model, all the linear dimensions are 1/10th of the real aircraft but the areas are 1/100th; and if the model is constructed of the same materials, the mass is 1/1,000th of the real aircraft. So the model is to scale in some respects, but not in others. This is one of the difficulties in trying to learn from flying models of aircraft, and unless the adjustments of weights are very carefully handled, the results of tests in manoeuvre and spinning may be completely false.

Fluid Flow

40. During the 19th Century a physicist named Reynolds was involved in experiments with the flow of fluids in pipes and he made the important discovery that the flow changed from streamlined to turbulent when the velocity reached a value which was inversely proportional to the diameter of the pipe. The larger the pipe, the lower the velocity at which the flow became turbulent, eg if the critical velocity in a pipe of 2.5 cm diameter was 6 m/s then 3 m/s would be the critical velocity in a pipe of 5 cm diameter. He also discovered that the rule applied to the flow past any body placed within the stream. For example, if two spheres of different sizes were placed within a flow, then the transition to turbulence would occur when the velocity reached a value which was inversely proportional to the diameter of each sphere. Turbulence would therefore occur at a lower speed of flow over the larger sphere than over the smaller and, furthermore, the transition point would be at the point of maximum thickness of the body, relative to the flow.

Scale Correction

41. Reynolds principle says that the value of velocity x size must be the same for both a model experiment and for the full size aircraft it represents. If it is necessary to carry out a test on a 1/10th scale model to determine what would happen on the full size aircraft at 200 kt, the wind-tunnel speed would have to be 2,000 kt. Furthermore, the wind-tunnel would have to be very large, to prevent interference between the tunnel walls and the flow over the model, especially at such high Mach numbers. In addition, the area of the model would be 1/100th that of the aircraft and the wing of the model would have to support forces equal to those on a full size aircraft.

42. Fortunately, Reynolds also discovered that if different fluids were used, the type of flow was affected by the density and viscosity of the fluid. In fact, he established that similarity of flow pattern would be achieved if the value of

$$\frac{\text{density} \times \text{velocity} \times \text{size}}{\text{viscosity}} \text{ was constant}$$

Clearly, it is not very practical to fill a wind-tunnel with oil or water, and accelerate it to 150 or 200 kt to simulate higher flight speeds, but it is quite possible to increase the density of the air by using a high pressure tunnel. Increasing the pressure has little or no effect upon the viscosity, so that with increased density it is possible to reduce the velocity and/or size and still maintain aerodynamic similarity. For example, if the air is compressed to 25 atmospheres - and this is possible - then the density factor is 25, with no corresponding increase in viscosity (μ). It is then possible to test the model referred to in para 41, at

$$\frac{2{,}000\text{kt}}{25} \text{i.e. at 80 kt.}$$

Viscosity

43. Although a change in density does not affect the viscosity of the air, the temperature does, and so it is necessary to cool the compressed air to keep the viscosity constant. Unlike liquids, which become less viscous with rise in temperature, air becomes more viscous, and any increase in viscosity would offset the benefits of increased density.

Reynolds Number

44. For every wind-tunnel test there is one Reynolds Number (RN), and it is always published with the results of the test.

$$\text{RN} = \rho\frac{\text{VL}}{\mu} \text{ where}$$

ρ is density in kg per M^3 (1.2250 for air at sea level), V is the velocity of the test in metres per second, L is a dimension of the body (for aerofoils the chord length is used),
μ is the viscosity of the fluid.

Considering the units involved it is not surprising to see test results quoted at RN = 4×10^6, or even 12×10^6 (12,000,000).

Aerodynamic Forces

45. Since one of the major problems in using models was the effect of the large aerodynamic force felt on a small model, it is useful to look at the effect of using high pressure tunnels. For example, taking again a 1/10th model, a speed of 80 kt and 25 atmospheres, to test for a full-scale flight at 200 kt, the forces will be:

$$\frac{1}{100}\text{th (scale)} \times \frac{80^2}{200^2}\text{(speed)} \times 25 \text{ density factor}$$

$$= \frac{1}{100} \times \frac{6400}{40{,}000} \times \frac{25}{1} = \frac{1}{25}$$

Thus dynamic similarity is achieved, with forces that are 1/25th of the full scale forces; even that is quite high.

Inertial and Viscous Forces

46. Any particular flow experiment on geometrically-similar bodies is completely determined once we settle the speed (V), the length of the body (L), the density of the fluid (ρ) and the viscosity (μ); that is, the Reynolds Number. Furthermore, RN is a measure of the ratio between the viscous forces and the inertial forces of the fluid.

47. The inertial force acting on a typical fluid particle is measured by the product of its mass and its acceleration. Now the mass per unit volume of the fluid is, by definition, the density (ρ), while the volume is proportional to the cube of the characteristic length (L^3), hence the mass is proportional to ρL^3. The acceleration is the rate of change of velocity; that is, the change in velocity divided by the time during which the change occurs. The change in the velocity, as the fluid accelerates and decelerates over the body, is proportional to (V). The time is proportional to the time taken by a fluid particle to travel the length of the body at the speed (V); so the time is

$$\frac{L}{V}$$

The acceleration is therefore proportional to

$$V \div \frac{L}{V} \text{ ie } \frac{V^2}{L}$$

The inertial force, which is mass x acceleration can now be expressed:

$$\text{inertial force} \propto \frac{\rho L^3}{I} \times \frac{V^2}{L}$$

$$\propto \rho\ L^2 V^2$$

48. The viscous forces are determined by the product of the viscous sheer stress and the surface area over which it acts. The area is proportional to the square of the characteristic length, that is, to L^2. The viscous sheer stress is proportional to viscosity m and to the rate of change of speed with distance, that is

$$\frac{V}{L}$$

Therefore the viscous force is proportional to:

$$L^2 \times\ \mu\ \times \frac{V}{L} = L\mu V$$

49. Comparing inertial forces with viscous forces we have:

$$\frac{\text{inertial forces}}{\text{viscous forces}} \propto \frac{L^2 \rho V^2}{L\mu V} = \frac{\rho VL}{\mu}$$

which is the formula for Reynolds Number. is $\frac{\mu}{\rho}$ the kinematic viscosity of the fluid and when this is constant the only variables are V and L.

50. It is now possible to determine RN for a series of tests in which different aerofoils are compared; or, conversely, to test one aerofoil over a range of Reynolds Numbers which correspond to various speeds in flight. In practice the actual values of density and viscosity are of little consequence, what really matters is the ratio of inertial forces to viscous forces, and that is precisely what RN indicates. Obviously, at high values of RN the viscous forces

are low in comparison, because RN may indicate that the inertial forces are substantially greater.

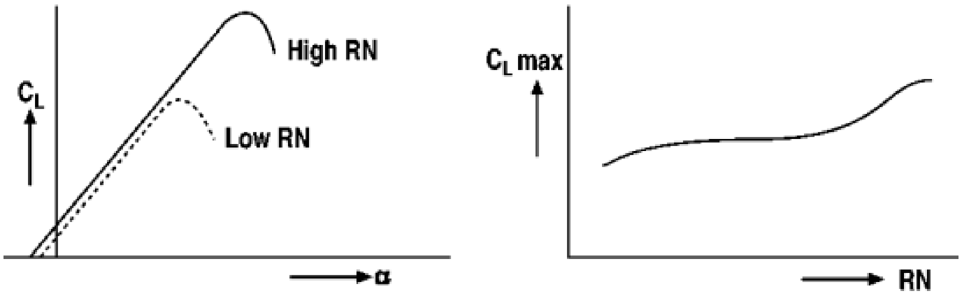


Fig 8 Scale Effect on CL and CL max Curves

51. In Fig 8 a graph of the effect of RN on the C_L curve shows that at a high value of RN the stall is delayed to a higher angle of attack and that the C_L max is increased. This merely means that if the pilot flies his aircraft to the high speed stall the wings will produce more lift (and, incidentally, less drag) because, if the aircraft is flown at a given height the density and temperature (which affects viscosity) are constant, and the only variable is speed. The simple reason is that the turbulent boundary layer has greater inertial force - or greater kinetic energy - the effect of which is to delay boundary layer separation. This results in a higher stalling angle, higher C_{Lmax}, and to complete the picture, a lower value of drag.

Lift

Introduction

1. This chapter will deal in a little more detail with pressure distribution and Centre of Pressure (CP) movement, define and discuss aerodynamic centre and then move on to the factors affecting lift and the lift/drag ratio. Finally the various types of aerofoils will be discussed.

Distribution of Pressure About the Wing

2. Fig 1 illustrates an actual pressure plot around an aerofoil at 6° angle of attack. The straight lines indicate the positions from which the tappings were taken and the positive and negative pressures are those above and below free stream static pressure. Conditions at the trailing edge (TE) are difficult to plot because of the small values of pressure there and the difficulty of providing adequate tappings.

3. Although most low speed aerofoils are similar in shape, each section is intended to give certain specific aerodynamic characteristics. Therefore, there can be no such thing as a typical aerofoil section or a typical aerofoil pressure distribution and it is only possible to discuss pressure distributions around aerofoils in the broadest of general terms. So, in general, at conventional angles of attack, compared with the free stream static pressure there is a pressure decrease over much of the upper surface, a lesser decrease over much of the lower surface so that the greatest contribution to overall lift comes from the upper surface.

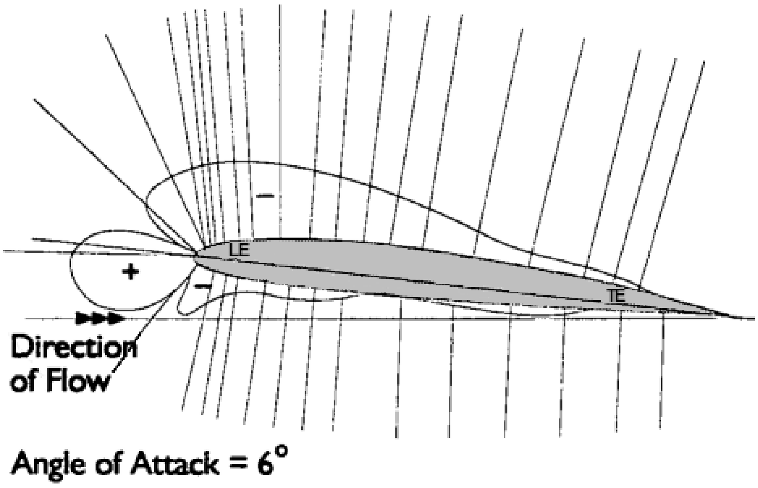


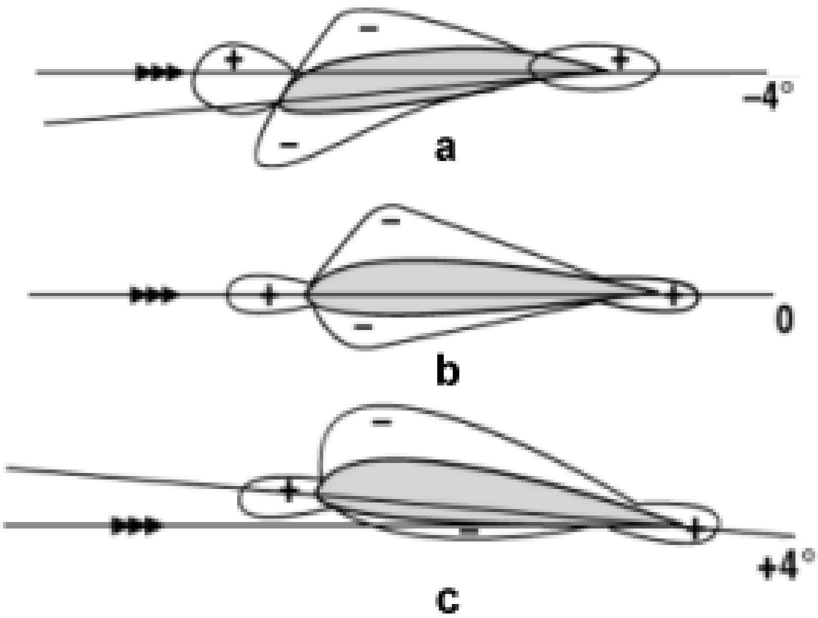
Fig 1 Pressure Plotting

4. The aerofoil profile presented to the airflow determines the distribution of velocity and hence the distribution of pressure over the surface. This profile is determined by the aerofoil geometry, ie thickness distribution and camber, and by the angle of attack. The greatest positive pressures occur at stagnation points where the flow is brought to rest, at the trailing edge, and somewhere near the leading edge (LE), depending on the angle of attack. At the front stagnation point the flow divides to pass over and under the section. At this point there must be some initial acceleration of the flow at the surface otherwise there could be no real velocity anywhere at the aerofoil surface, therefore there must be some initial reduction of pressure below the stagnation value. If the profile is such as to produce a continuous acceleration there will be a continuous pressure reduction and vice versa. Some parts of

the contour will produce the first effect, other parts the latter, bearing in mind always that a smooth contour will produce a smoothly changing pressure distribution which must finish with the stagnation value at the trailing edge.

5. Fig 2 shows the pressure distribution around a particular aerofoil section at varying angles of attack. The flow over the section accelerates rapidly around the nose and over the leading portion of the surface, the rate of acceleration increasing with increase in angle of attack. The pressure reduces continuously from the stagnation value through the free stream value to a position when a peak negative value is reached. From there onwards the flow is continuously retarded, increasing the pressure through the free stream value to a small positive value towards the trailing edge. The flow under the section is accelerated much less rapidly than that over the section, reducing the pressure much more slowly through the free stream value to some small negative value, with subsequent deceleration and increase in pressure through free stream value to a small positive value toward the trailing edge. If the slight concavity on the lower surface towards the trailing edge was carried a little further forward, it might be possible to sustain a positive pressure over the whole of the lower surface at the higher angles of attack. However, although this would increase the lifting properties of the section, it might also produce undesirable changes in the drag and pitching characteristics. Therefore, it can be seen that any pressure distribution around an aerofoil must clearly take account of the particular aerofoil contour.

6. From examinations of Fig 2 it can be seen that at small angles of attack the lift arises from the difference between the pressure reductions on the upper and lower surfaces, whilst at the higher angles of attack the lift is due partly to the decreased pressure above the section and partly to the increased pressure on the lower surface. At a small negative angle of attack (about -4° for this aerofoil) the decrease in pressure above and below the section would be equal and the section would give no lift. At the stalling angle the low pressure area on the top of the section suddenly reduces and such lift as remains is due principally to the pressure increase on the lower surface.



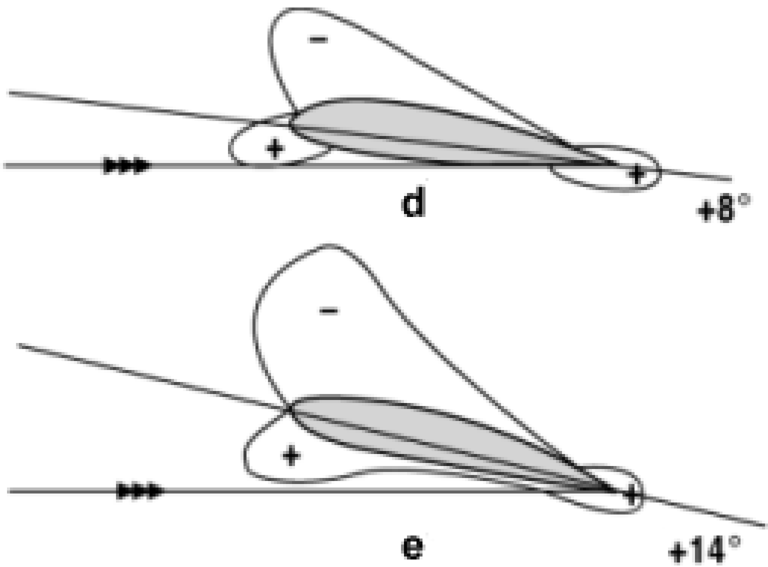


Fig 2 Pressure Distribution About an Aerofoil

Centre of Pressure (CP)

7. The overall effect of these pressure changes on the surface of the aerofoil can be represented in various simplified ways, one of which is to represent the effects by a single aerodynamic force acting at a particular point on the chord line, called the centre of pressure (CP). The location of the CP is a function of camber and section lift coefficient, both the resultant force and its position varying with angle of attack (see Fig 3). As the angle of attack is increased the magnitude of the force increases and the CP moves forward; when the stall is reached the force decreases abruptly and the CP generally moves back along the chord. With a cambered aerofoil the CP movement over the normal working range of angles of attack is between 20 - 30% of the chord aft of the leading edge. With a symmetrical aerofoil there is virtually no CP movement over the working range of angles of attack at subsonic speeds.

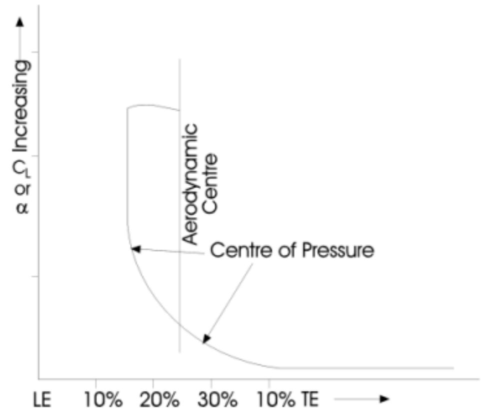


Fig 3 Movement of the Centre of Pressure

Aerodynamic Centre

8. An aircraft pitches about the lateral axis which passes through the centre of gravity. The wing pitching moment is the product of lift and the distance between the CG and the CP of the wing. Unfortunately, the CP moves when the angle of attack is altered so calculation of the pitching moment becomes complicated.

9. The pitching moment of a wing can be measured experimentally by direct measurement on a balance or by pressure plotting. The pitching moment coefficient (C_m) is calculated as follows:

$$C_m = \frac{\text{Pitching moment}}{qSc}$$

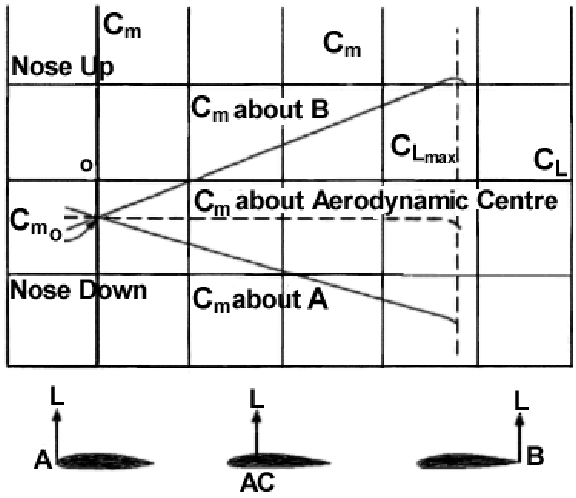
where c is the mean aerodynamic chord, q is dynamic pressure, and S is the wing area. The value of pitching moment and therefore C_m will depend upon the point about which the moment is calculated and will vary because the lift force and the position of the CP change with angle of attack.

10. If pitching moments are measured at various points along the chord for several values of C_L one particular point is found where the C_m This point occurs where the change in C_L with angle of attack is offset by the change in distance between CP and CG. This is the aerodynamic centre (AC). For a flat or curved plate in inviscid, incompressible flow the aerodynamic centre is at approximately 25% of the chord from the leading edge. Thickness of the section and viscosity tend to move it forward and compressibility moves it rearwards. Some modern low drag aerofoils have the AC a little further forward at approximately 23% chord.

11. There are two ways of considering the effects of changing angle of attack on the pitching moment of an aerofoil. One way is to consider change in lift acting through a CP which is moving with angle of attack; the other simpler way is to consider changes in lift always acting through the AC which is fixed.

12. The rate of change of C_m with respect to C_L or angle of attack is constant through most of the angle of attack range and the value of $\frac{C_m}{C_L}$ depends on the point on the aerofoil at which C_m is measured. Curves of C_m versus C_L are shown in Fig 4. It can be seen that a residual pitching moment is present at zero lift. This is because an aerofoil with positive camber has a distribution of pressure as illustrated in Fig 5. It should be noted that the pressure on the upper surface towards the leading edge is higher than ambient and towards the trailing edge the pressure is lower than ambient. This results in a nose down (negative) pitching moment even though there is no net lift at this angle of attack. The C_m at zero lift angle of attack is called C_m and, since the pitching moment about the AC is constant with C_L by definition, its value is equal to C_m. The value of C_m is determined by camber and is usually negative but is zero for a symmetrical aerofoil and can be positive

when there is reflex curvature at the trailing edge. When C_m is measured at point A (Fig 4) an increase in C_L will cause an increase in lift and a larger negative (nose down) moment. When measured at point B an increase in C_L will cause the moment to become less negative and eventually positive (nose up).



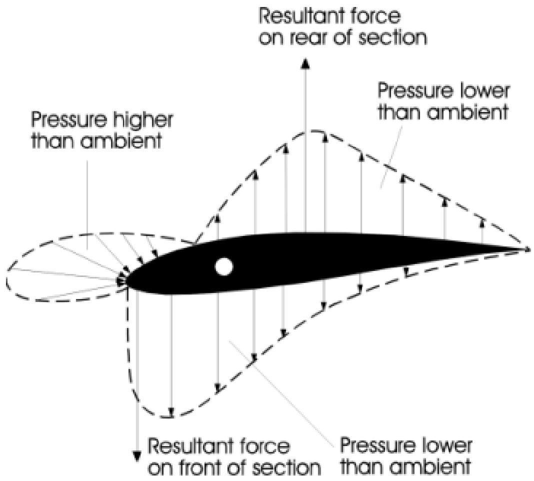


Fig 4 C_m Against C_L

Fig 5 Pressure Pattern at Zero Lift Angle of Attack

13. Approaching C_{Lmax} the C_m/C_L graph departs from the straight line, Fig 6. The C_L decreases and the CP moves aft. If at this stage the C_m becomes negative it tends to unstall the wing and is stable. If the Cm becomes positive the pitch up aggravates the stall and is unstable. This is known as pitch-up and is associated with highly swept wings.

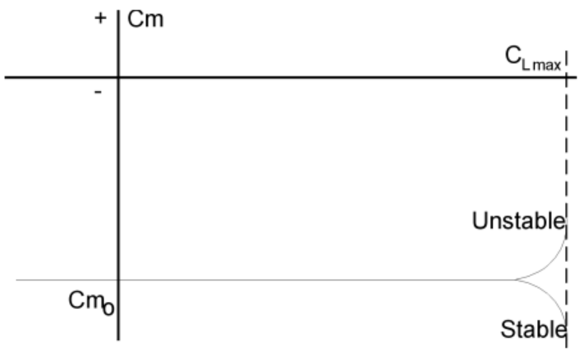


Fig 6 C_m In The Region of C_{Lmax}

Lift

14. By definition lift is that component of the total aerodynamic reaction which is perpendicular to the flight path of the aircraft.

15. It can be demonstrated experimentally that the total aerodynamic reaction, and therefore the lift acting on a wing moving through air, is dependent upon at least the following variables:

a. Free stream velocity (V^2)

b. Air density (ρ).

c. Wing area (S).

d. Wing shape in section and in planform.

e. Angle of attack (α).

f. Condition of the surface.

g. Viscosity of the air (μ).

h. The speed of sound, ie the speed of propagation of small pressure waves (a).

16. In Chap 2, and earlier in this chapter, it was seen that lift increased when the angle of attack of a given aerofoil section was increased; and that the increase in lift was achieved mechanically by greater acceleration of the airflow over the section, with an appropriate decrease in pressure. The general and simplified equation for aerodynamic force is '$\frac{1}{2}\rho V^2 S$ X a' coefficient, and the coefficient indicates the change in the force which occurs when the angle of attack is altered.

17. The equation for lift is $C_L \frac{1}{2}\rho V^2 S$, and C_L for a given aerofoil section and planform allows for angle of attack and all the unknown quantities which are not represented in the force formula. Three proofs for the lift equation are given in the Annex to Chap 2.

Coefficient of Lift (C_L)

18. The coefficient of lift is obtained experimentally at a quoted Reynolds Number from the equation:

$$\mathrm{Lift} = \mathrm{C}_L \frac{1}{2} \rho \mathrm{V}^2 \mathrm{S}$$

$$\mathrm{C}_L = \frac{\mathrm{Lift}}{\frac{1}{2}\rho \mathrm{V}^2 \mathrm{S}} = \frac{\mathrm{lift}}{\mathrm{qS}}$$

and the values are plotted against angle of attack. It is then possible to consider the factors affecting lift in terms of C_L and to show the effects on the C_L curve.
Factors Affecting C_L

19. The coefficient of lift is dependent upon the following factors:

a. Angle of attack.

b. Shape of the wing section and planform.

c. Condition of the wing surface.

d. Reynolds Number

$$\left(\frac{\rho \mathrm{VL}}{\mu}\right)$$

e. Speed of sound (Mach number).

20. **Angle of Attack**. A typical lift curve is shown in Fig 7, for a wing of 13% thickness/chord (t/c) ratio and 2% camber. The greater part of the curve is linear and the airflow follows the design contour of the aerofoil almost to the trailing edge before separation. At higher angles of attack the curve begins to lean over slightly, indicating a loss of lifting effectiveness. From the point of maximum thickness to the trailing edge of the aerofoil, the flow outside the boundary layer is decelerating, accompanied by a pressure rise (Bernoulli's theorem). This adverse pressure gradient thickens the existing boundary layer. In the boundary layer, the airflow's kinetic energy has been reduced by friction, the energy loss appearing as heat. The weakened flow, encountering the thickened layer, slows still further. With increasing angle of attack, the boundary layer separation point (Chap 4, para 19) moves rapidly forward, the detached flow causing a substantial reduction of C_L. The aerofoil may be considered to have changed from a streamlined body to a bluff one, with the separation point moving rapidly forwards from the region of the trailing edge. The desirable progressive stall of an actual wing is achieved by wash-out at the tips or change of aerofoil section along the span, or a combination of both.

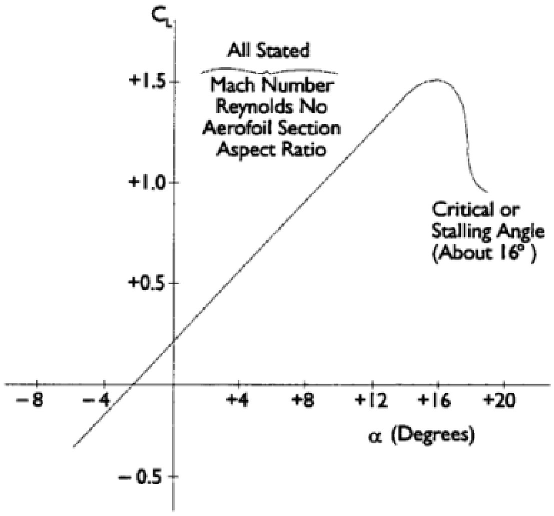


Fig 7 Typical Lift Curve for a Moderate Thickness Cambered Section

21. **Effect of Shape.** Changes in the shape of a wing may be considered under the following headings:

a. **Leading Edge Radius.** The shape of the leading edge, and the condition of its surface, largely determines the stalling characteristics of a wing. In general, a blunt leading edge with a large radius will result in a well-rounded peak to the C_L curve. A small radius, on the other hand, invariably produces an abrupt stall but this may be modified considerably by surface roughness which is discussed later.

b. **Camber**. The effect of camber is illustrated in Fig 8. Line (a) represents the curve for a symmetrical section. Lines (b) and (c) are for sections of increasing camber. A symmetrical wing at zero angle of attack will have the same pressure distribution on its upper and lower surfaces, therefore it will not produce lift.

As the angle of attack is increased, the stagnation point moves from the chord line to a point below, moving slightly further backwards with increase in angle of attack. This effectively lengthens the path of the flow over the top surface and reduces it on the lower, thus changing the symmetrical section (Fig 9a) to an apparent cambered one as in Fig 9b.

A positively cambered wing will produce lift at zero angle of attack because the airflow attains a higher velocity over the upper surface creating a pressure differential and lift. This gives it a lead over the symmetrical section at all normal angles of attack but pays the penalty of an earlier stalling angle as shown by the C_L versus aα curve which shifts up and left in Fig 8 as the camber is increased. The angle of attack at which the C_L is zero is known as the zero-lift angle of attack (α_{L0}) and a typical value is -3° for a cambered section.

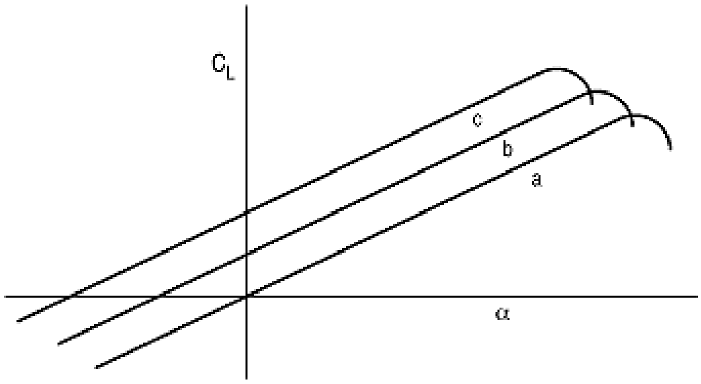


Fig 8 Effect of Camber

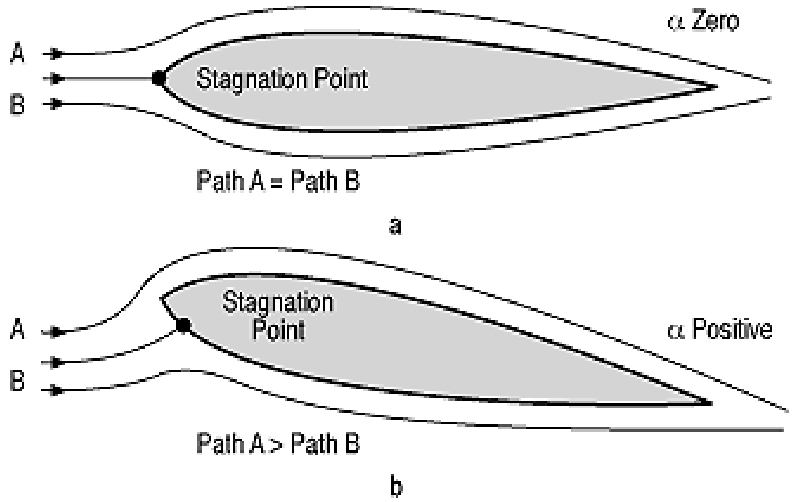


Fig 9 Symmetrical Aerofoil

c. **Aspect Ratio.** Fig 10 shows the downward component of airflow at the rear of the wing, caused by trailing edge vortices and known as induced downwash (ω). The induced downwash causes the flow over the wing to be inclined slightly downwards from the direction of the undisturbed stream (V) by the angle α_1. This reduces the effective angle of attack, which determines the airflow and the lift and drag forces acting on the wing. The effect on the C_L by change of aspect ratio (AR) will depend on how the effective angle of attack is influenced by change in AR. It has been shown in the previous chapter, that a wing of infinite span has no induced downwash. It can be demonstrated that the nearer one gets to that ideal, ie high AR, the less effect the vortices will have on the relative airflow along the semispan and therefore the least deviation from the shape of the C_L curve of the wing with infinite AR. It can be seen from Fig 11 that at any angle α, apart from the zero lift angle, the increase in C_L of the finite wing lags the infinite wing, the lag increasing with reducing

AR due to increasing α_1. Theoretically the C_L peak values should not be affected, but experimental results show a slight reduction of C_{Lmax} as the aspect ratio is lowered.

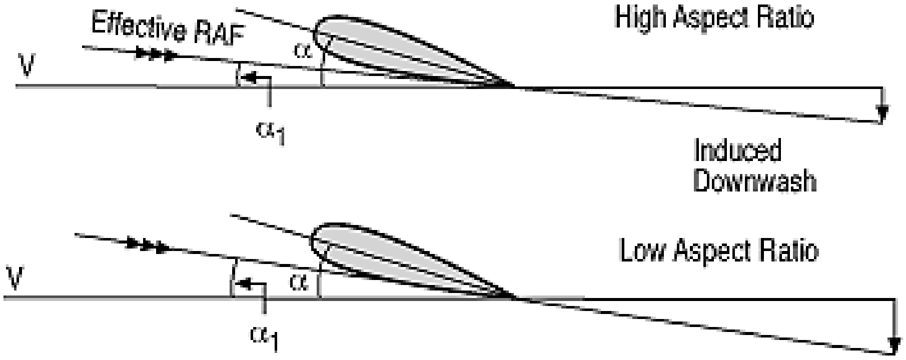


Fig 10 Effect of Aspect Ratio on the Induced Downwash

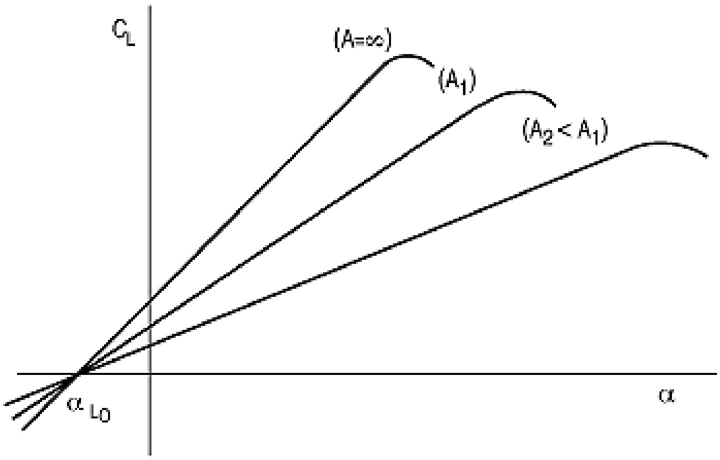


Fig 11 Influence of Aspect Ratio A on the Lift Curve

d. **<u>Sweepback</u>.** If an aircraft's wings are swept and the wing area remains the same, then by definition (span^2/area) the aspect ratio must be less than the AR of the equivalent straight wing. The shape of the C_L vs angle of attack curve for a swept wing, compared to a straight wing, is similar to the comparison between a low and a high aspect ratio wing. However, this does not explain the marked reduction in C_{Lmax} at sweep angles in excess of 40-45°, which is mainly due to earlier flow separation from the upper surface. An alternative explanation is to resolve the airflow over a swept wing into two components. The component parallel to the leading edge produces no lift. Only the component normal to the leading edge is considered to be producing lift. As this component is always less than the free stream flow at all angles of sweep, a swept wing will always produce less lift than a straight wing. See Fig 12.

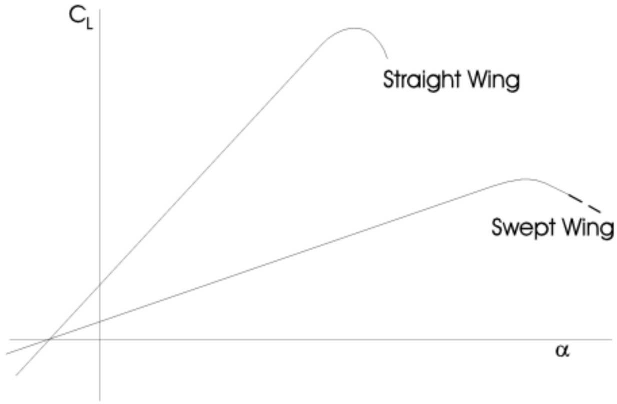


Fig 12 Effect of Sweepback on Lift Coefficient

22. **Effect of Surface Condition**. It has long been known that surface roughness, especially near the leading edge, has a considerable effect on the characteristics of wing sections. The maximum lift coefficient, in particular, is sensitive to the leading edge roughness. Fig 13 illustrates the effect of a roughened leading edge compared to a smooth surface. In general, the maximum lift coefficient decreases progressively with increasing roughness of the leading edge. Roughness of the surface further downstream than about 20% chord from the leading edge has little effect on C_{Lmax} or the lift-curve slope. The standard roughness illustrated is more severe than that caused by usual manufacturing irregularities or deterioration in service, but is considerably less severe than that likely to be encountered in service as a result of the accumulation of ice, mud or combat damage. Under test, the leading edge of a model wing is artificially roughened by applying carborundum grains to the surface over a length of 8% from the leading edge of both surfaces.

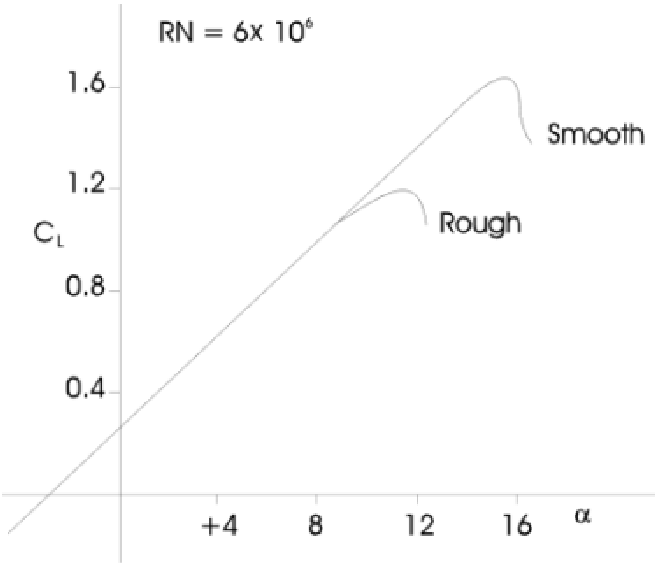


Fig 13 Effect of Landing Edge Roughness

23. **Effect of Reynolds Number**. The formula for Reynolds Number is $\frac{\rho VL`}{\mu}$, that is density x velocity x a mean chord length, divided by viscosity. A fuller explanation of Reynolds Number is given in Chap 2. If we consider an aircraft operating at a given altitude, L is constant, ρ is constant, and at a given temperature the viscosity is constant: the only variable is V. For all practical purposes the graph in Fig 14 shows the effect on C_L of increasing velocity on a general purpose aerofoil section. It should be remembered than an increase in Reynolds Number, for any reason, will produce the same effect. Fig 14 shows that with increasing velocity both the maximum value of C_L and the stalling angle of attack is increased. An increase in the velocity of the airflow over a wing will produce earlier transition and an increase in the kinetic energy of the turbulent boundary layer due to mixing; the result is delayed separation. An increase in density, or a reduction in viscosity

will have the same effect on the stall. The effect shown in Fig 14 is generally least for thin sections (t/c <12%) and greatest for thick, well-cambered sections.

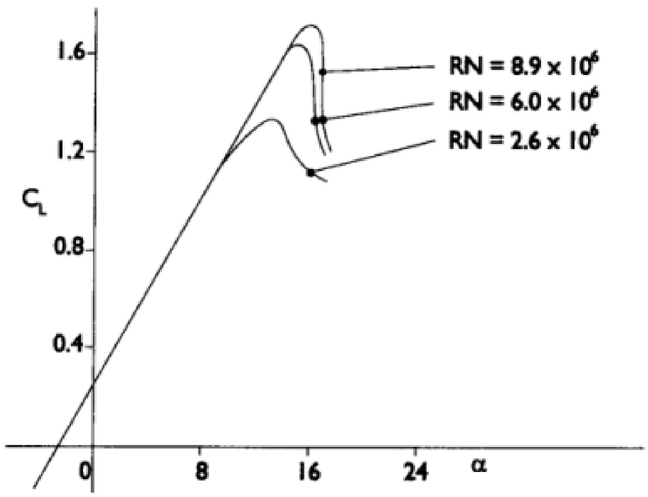


Fig 14 Effect of Reynolds Number on C_{Lmax}

24. **Effect of Mach Number**. The effect of Mach number is discussed in the chapter on Transonic and Supersonic Aerodynamics.

Aerofoils

25. The performance of an aerofoil is governed by its contour. Generally, aerofoils can be divided into three classes:

a. High lift.

b. General purpose

c. High speed

26. **High Lift Aerofoils**. A typical high lift section is shown in Fig 15a.

a. High lift sections employ a high t/c ratio, a pronounced camber, and a well-rounded leading edge: their maxmum thickness is at about 25%-30% of the chord aft of the leading edge.

b. The greater the camber, ie the amount of curvature of the mean camber line, the greater the shift of centre of pressure for a given change in the angle of attack. The range of movement of the CP is therefore large on a high lift section. This movement can be greatly decreased by reflexing upwards the trailing edge of the wing, but some lift is lost as a result.

Fig 15a Aerofoil Sections

c. Sections of this type are used mainly on sailplanes and other aircraft where a high C_L is all important and speed a secondary consideration.

27. **General Purpose Aerofoils**. A typical general purpose section is shown in Fig 15b.

a. General purpose sections employ a lower t/c ratio, less camber and a sharper leading edge than those of the high lift type, but their maximum thickness is still at about 25% - 30% of the chord aft of the leading edge. The lower t/c ratio results in less drag and a lower C_L than those of a high lift aerofoil.

b. Sections of this type are used on aircraft whose duties require speeds which, although higher than those mentioned in para 26, are not high enough to subject the aerofoil to the effects of compressibility.

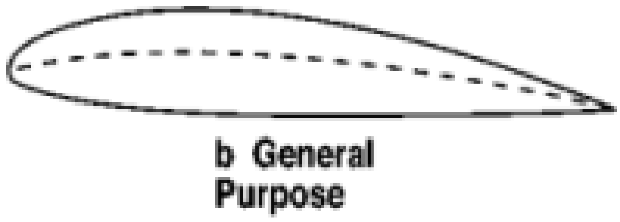


Fig 15b Aerofoil Sections

28. **High Speed Aerofoils**. Typical high speed sections are shown in Fig 15c.

a. Most high speed sections employ a very low t/c ratio, no camber and a sharp leading edge. Their maximum thickness is at about the 50% chord point.

b. Most of these sections lie in the 5% - 10% t/c ratio band, but even thinner sections have been used on research aircraft. The reason for this is the overriding requirement for low drag; naturally the thinner sections have low maximum lift coefficients.

c. High speed aerofoils are usually symmetrical about the chord line; some sections are wedge-shaped whilst others consist of arcs of a circle placed symmetrically about the chord line. The behaviour and aerodynamics of these sections at supersonic speeds are dealith in detail in Sect 3, Chap 1.

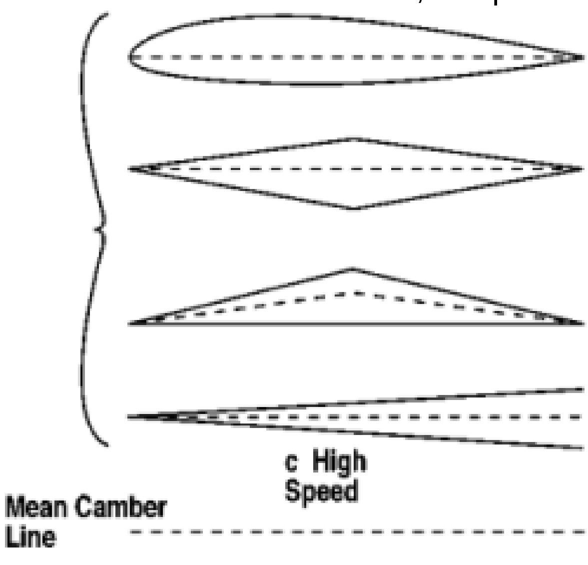


Fig 15c Aerofoil Sections

Performance

29. The performance of all aerofoils is sensitive to small changes in contour. Increasing or decreasing the thickness by as little as 1% of the chord, or moving the point of maximum camber an inch or so in either direction, will alter the characteristics. In particular, changes in the shape of the leading edge have a marked effect on the maximum lift and drag obtained and the behaviour at the stall - a sharp leading edge stalling more readily than one that is well rounded. Also it is important that the finish of the wing surfaces be carefully preserved if the aircraft is expected to attain its maximum performance. Any dents or scratches in the surface bring about a deterioration in the general performance. These points are of particular importance on high performance aircraft when a poor finish can result in a drastic reduction not only in performance, but also in control at high Mach numbers.

Summary

30. The pressure distribution around an aerofoil varies considerably with shape and angle of attack, however, at conventional angles of attack, the greatest contribution to overall lift comes from the upper surface.

31. There are two points through which the lift force may be considered to act. The first is a moving point called the centre of pressure, and the second is a fixed point called the aerodynamic centre. The aerodynamic centre is used in most work on stability.

32. Lift is dependent upon the following variables:

a. Free stream velocity.

b. Air density.

c. Wing area.

d. Wing shape in section and platform.

e. Angle of attack.

f. Condition of the surface.

g. Viscosity of the air.

h. The speed of sound.

33. The coefficient of lift is dependent upon the following factors:

a. Angle of attack.

b. Shape of the wing section and planform.

c. Condition of the wing surface.

d. Speed of sound.

e. Reynolds Number $\left(\frac{\rho \mathrm{VL}}{\mu}\right)$

34. Aerofoils are generally divided into three classes:

a. High lift.

b. General purpose.

c. High speed.

Drag

Introduction

1. Each part of an aircraft in flight produces an aerodynamic force. Total drag is the sum of all the component of the aerodynamic forces which act parallel and opposite to the direction of flight. Each part of total drag represents a value of resistance of the aircraft's movement, that is, lost energy.

Components of Total Drag

2. Some text books still break down Total Drag into the old terms Profile Drag and Induced Drag. These latter terms are now more widely known as Zero Lift Drag and Lift Dependent Drag respectively and are described later. There are three points to be borne in mind when considering total drag:

a. The causes of subsonic drag have changed very little over the years but the balance of values has changed eg parasite drag is such a small part of the whole that it is no longer considered separately, except when describing helicopter power requirements.

b. An aircraft in flight will have drag even when it is not producing lift.

c. In producing lift the whole aircraft produce additional drag and some of this will be increments in those components which make up zero lift drag.

3. **Zero Lift Drag.** When an aircraft is flying at zero lift angle of attack the resultant of all the aerodynamic forces acts parallel and opposite to the direction of flight. This is known as Zero Lift Drag (but Profile Drag or Boundary Layer Drag in some textbooks) and is composed of:

a. Surface friction drag.

b. Form drag (boundary layer normal pressure drag).

c. Interference drag.

4. **Lift Dependent Drag.** In producing lift the whole aircraft will produce additional drag composed of:

a. Induced drag (vortex drag).

b. Increments of:

(1) Form drag.

(2) Surface friction drag.

(3) Interference drag.

ZERO LIFT DRAG

The Boundary Layer

5. Although it is convenient to ignore the effects of viscosity whenever possible, certain aspects of aerodynamics cannot be explained if viscosity is disregarded.

6. Because air is viscous, any object moving through it collects a group of air particles which it pulls along. A particle directly adjacent to the object's surface will, because of viscous adhesion, be pulled along at approximately the speed of the object. A particle slightly further away from the surface will also be pulled along; however its velocity will be slightly less than the object's velocity. As we move further and further away from the surface the particles of air are affected less and less, until a point is reached where the movement of the body does not cause any parallel motion of air particles whatsoever.

7. The layer of air extending from the surface to the point where no dragging effect is discernable is known as the boundary layer. In flight, the nature of the boundary layer determines the maximum lift coefficient, the stalling characteristics of a wing, the value of form drag, and to some extent the high speed characteristics of an aircraft.

8. The viscous drag force within the boundary layer is not sensitive to pressure and density variations and is therefore unaffected by the variations in pressures at right angles (normal) to the surface of the body. The coefficient of viscosity of air changes in a similar manner to temperature and therefore decreases with altitude.

Surface Friction Drag

9. The surface friction drag is determined by:

   a. The total surface area of the aircraft.

   b. The coefficient of viscosity of the air.

   c. The rate of change of velocity across the flow.

10. **Surface Area.** The whole surface area of the aircraft has a boundary layer and therefore has surface friction drag.

11. **Coefficient of Viscosity**. The absolute coefficient of viscosity (μ) is a direct measure of the viscosity of a fluid, ie it is the means by which a value can be allotted to this property of a fluid. The greater the viscosity of the air the greater the dragging effect on the aircraft's surface.

12. **Rate of Change of Velocity**. Consider the flow of air moving across a thin flat plate, as in Fig 1. The boundary layer is normally defined as that region of flow in which the speed is less than 99% of the free stream flow, and usually exists in two forms, laminar and turbulent. In general, the flow at the front of a body is laminar and becomes turbulent at a point some distance along the surface, known as the transition point From Fig 1 it can be seen that the rate of change of velocity is greater at the surface in the turbulent flow than in the laminar. This higher rate of change of velocity results in greater surface friction drag. The velocity profile for the turbulent layer shows the effect of mixing with the faster moving

air above the boundary layer. This is an important characteristic of the turbulent flow since it indicates a higher level of kinetic energy. Even when the boundary layer is turbulent however, a very thin layer exists immediately adjacent to the surface in which random velocities are smoothed out. This very thin layer (perhaps 1% of the total thickness of the turbulent layer) remains in the laminar state and is called the laminar sub-layer. Though extremely thin, the presence of this layer is important when considering the surface friction drag of a body and the reduction that can be obtained in the drag of a body as a result of smoothing the surface.

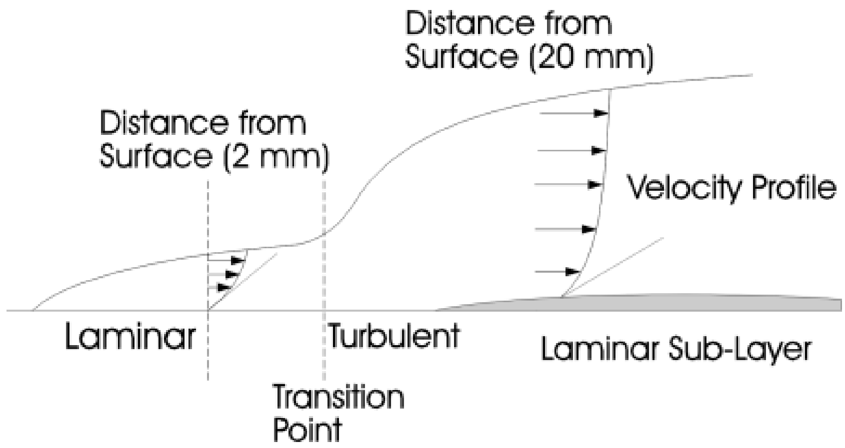


Fig 1 Boundary Layer

Transition to Turbulence

13. It follows from para 12 that forward movement of the transition point increases the surface friction drag. The position of the transition point depends upon:

a. Surface condition.

b. Speed of the flow.

c. Size of the object.

d. Adverse pressure gradient.

14. **Surface Condition**. Both the laminar and turbulent boundary layers thicken downstream, the average thickness varying from approximately 2 mm at a point 1 m downstream of the leading edge, to 20 mm at a point 1 m downstream of the transition point. Generally, the turbulent layer is about ten times thicker than the laminar layer but exact values vary from surface to surface. The thin laminar layer is extremely sensitive to surface irregularities. Any roughness which can be felt by the hand, on the skin of the aircraft, will cause transition to turbulence at that point, and the thickening boundary layer will spread out fanwise down-stream causing a marked increase in surface friction drag.

15. **Speed and Size**. The nineteenth century physicist, Reynolds, discovered that in a fluid flow of given density and viscosity the flow changed from streamline to turbulent when the velocity reached a value that was inversely proportional to the thickness of a body in the flow. That is, the thicker the body, the lower the speed at which transition occurred. Applied to an aerofoil of given thickness it follows that an increase of flow velocity will cause the transition point to move forward towards the leading edge. (A fuller explanation of Reynolds Number (RN) is given in Chap 2.) Earlier transition means that a greater part of the surface is covered by a turbulent boundary layer, creating greater surface friction drag. However, it should be remembered that the turbulent layer has greater kinetic energy than the laminar, the effect of which is to delay separation, thereby increasing the maximum value of C_L (see Chap 3 - Lift).

16. **Adverse Pressure Gradient**. It has been found that a laminar boundary layer cannot be maintained, without mechanical assistance, when the pressure is rising in the direction of flow, ie in an adverse pressure gradient. Thus on the curved surfaces of an aircraft the transition point is usually beneath, or near to, the point of minimum pressure and this is normally found to be at the point of maximum thickness. Fig 2 illustrates the comparison between a flat plate and a curved surface.

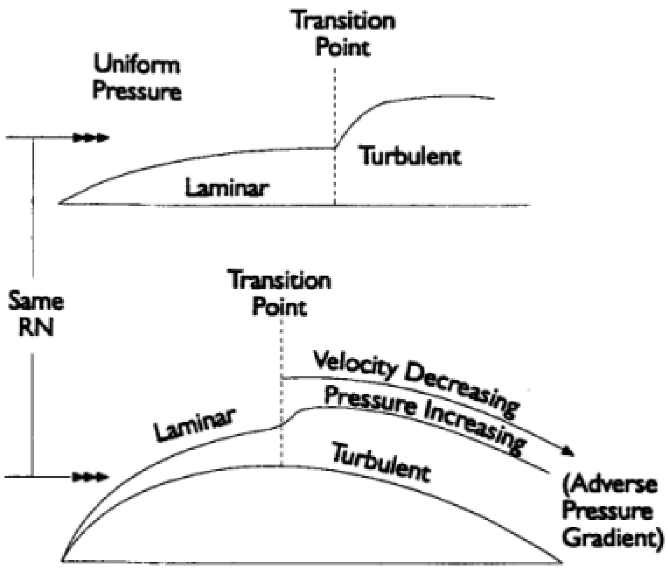


Fig 2 Effect of Adverse Pressure Gradient

Form Drag (Boundary Layer Normal Pressure Drag)

17. The difference between surface friction and form drag can be easily appreciated if a flat plate is considered in two attitudes, first at zero angle of attack when all the drag is friction drag, and second at 90° angle of attack when all the drag is form drag due to the separation.

18. **Separation Point.** The effect of surface friction is to reduce the velocity, and therefore the kinetic energy, of the air within the boundary layer. On a curved surface the effect of the adverse pressure gradient is to reduce further the kinetic energy of the boundary layer. Eventually, at a point close to the trailing edge of the surface, a finite amount of the boundary layer stops moving, resulting in eddies within the turbulent wake.

Fig 3 shows the separation point and the flow reversal which occurs behind that point. Aft of the transition point, the faster moving air above mixes with the turbulent boundary layer and

therefore has greater kinetic energy than the laminar layer. The turbulent layer will now separate as readily under the influence of the adverse pressure as would the laminar layer.

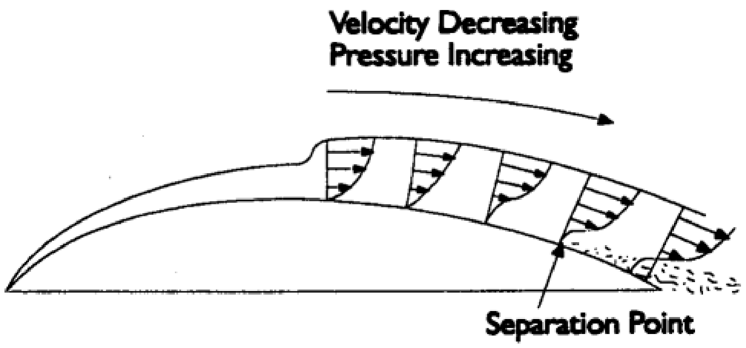


Fig 3 Boundary Layer Separation

Streamlining

19. When a boundary layer separates some distance forward of the trailing edge, the pressure existing at the separation point will be something less than at the forward stagnation point. Each part of the aircraft will therefore be subject to a drag force due to the differences in pressure between its fore and aft surface areas. This pressure drag (boundary layer normal pressure drag) can be a large part of the total drag and it is therefore necessary to delay separation for as long as possible. The streamlining of any object is a means of increasing the fineness ratio to reduce the curvature of the surfaces and thus the adverse pressure gradient (fineness ratio of an aerofoil is $\frac{\text{chord}}{\text{thickness}}$).

Interference Drag

20. On a complete aircraft the total drag is greater than the sum of the values of drag for the separate parts of the aircraft. The additional drag is the result of flow interference at wing/fuselage, wing/nacelle and other such junctions leading to modification of the boundary layers. Further turbulence in the wake causes a greater pressure difference between fore and aft surface areas and therefore additional resistance to movement. For subsonic flight this component of total drag can be reduced by the addition of fairings at the junctions, eg at the trailing edge wing roots.

Summary

21. The drag created when an aircraft is not producing lift, eg in a truly vertical flight path, is called zero lift drag; it comprises:

a. Surface friction drag.

b. Form drag (boundary layer normal pressure drag).

c. Interference drag.

22. Surface friction drag is dependent upon:

    a. Total wetted area.

    b. Viscosity of the air.

    c. Rate of change of velocity across the flow:

        (1) Transition point.

        (2) Surface condition.

        (3) Speed and size.

        (4) Adverse pressure gradient.

23. Form drag is dependent upon:

    a. Separation point:

        (1) Transition point.

        (2) Adverse pressure gradient.

    b. Streamlining.

24. Interference drag is caused by the mixing of airflows at airframe junctions.

25. Zero lift drag varies as the square of the equivalent air speed (EAS).

LIFT DEPENDENT DRAG

General

26. All of the drag which arises because the aircraft is producing lift is called lift dependent drag. It comprises in the main induced drag, but also contains increments of the types of drag which make up zero lift drag. The latter are more apparent at high angles of attack.

Induced Drag (Vortex Drag)

27. If a finite rectangular wing at a positive angle of attack is considered, the spanwise pressure distribution will be as shown in Fig 4. On the underside of the wing, the pressure is higher than that of the surrounding atmosphere so the air spills around the wing tips, causing on outward airflow towards them. On the upper surface, the pressure is low, and the air flows inwards. This pattern of airflow results in a twisting motion in the air as it leaves the trailing edge. Viewed from just downstream of the wing, the air rotates and forms a series of vortices along the trailing edge, and near the wing tips the air forms into a concentrated vortex. Further downstream all of the vorticity collects into trailing vortices as

seen in Fig 5. The wing tip vortices intensify under high lift conditions, eg during manoeuvre, and the drop in pressure at the core may be sufficient to cause vapour trails to form.

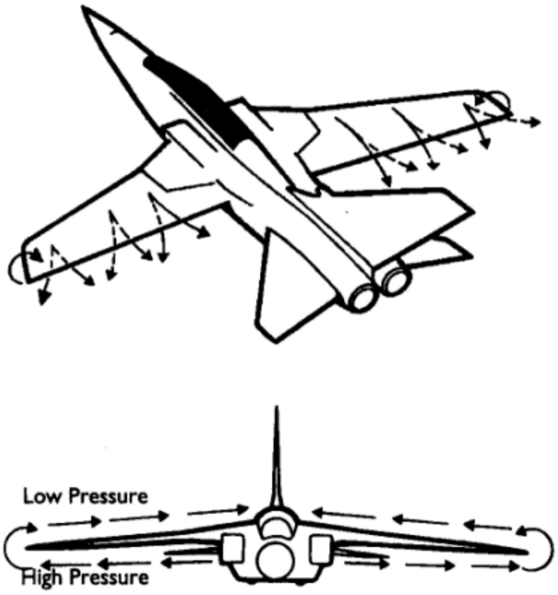


Fig 4 Spanwise Flow

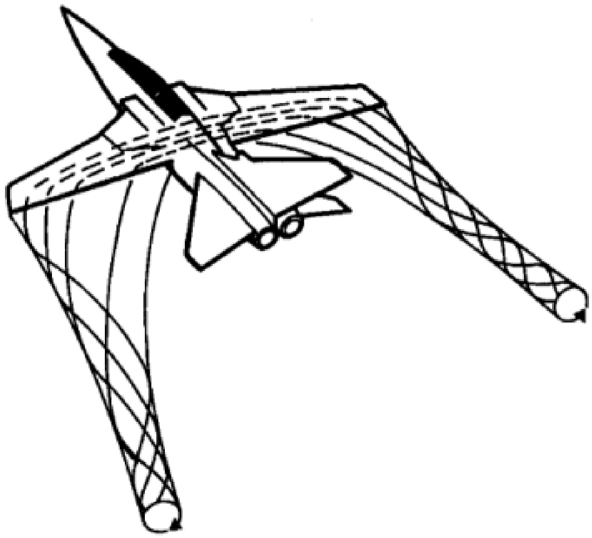


Fig 5 Trailing Vortices

28. **Induced Downwash.** The trailing vortices modify the whole flow pattern. In particular, they alter the flow direction and speed in the vicinity of the wing and tail surfaces. The trailing vortices therefore have a strong influence on the lift, drag and handling qualities of an aircraft. Fig 6 shows how the airflow behind the wing is being drawn downwards. This effect is known as downwash which also influences the flow over the wing itself, with important consequences. Firstly the angle of attack relative to the modified total airstream direction is reduced. This in effect is a reduction in angle of attack, and means that less lift will be generated unless the angle of attack is increased. The second and more important consequence is that what was previously the lift force vector is now tilted backward relative to the free stream flow. There is therefore a rearward component of the force which is

induced drag or vortex drag. A further serious consequence of downwash is that the airflow approaching the tailplane is deflected downwards so that the effective angle of attack of the tailplane is reduced.

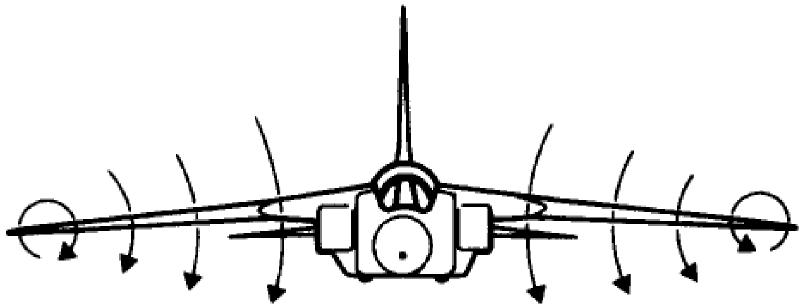


Fig 6 Downwash

Diagrammatic Explanation

29. Consider a section of a wing of infinite span which is producing lift but has no trailing edge vortices. Fig 7a shows a total aerodynamic reaction (TR) which is divided into lift (L) and drag (D). The lift component, being equal and opposite to weight, is at right angles to the direction of flight, and the drag component is parallel and opposite to the direction of flight. The angle at which the total reaction lies to the relative airflow is determined only by the angle of attack of the aerofoil.

30. Fig 7b shows the same section, but of a wing of finite span and therefore having trailing edge vortices. The effect of the induced downwash - due to the vortices - is to tilt downwards the effective relative airflow, thereby reducing the effective angle of attack. To regain the consequent loss of lift the aerofoil must be raised until the original lift value is restored (see Fig 7c). The total reaction now lies at the original angle, but relative to the effective airflow, the component parallel to the direction of flight is longer. This additional value of the drag - resulting from the presence of wing vortices is known as induced drag or vortex drag.

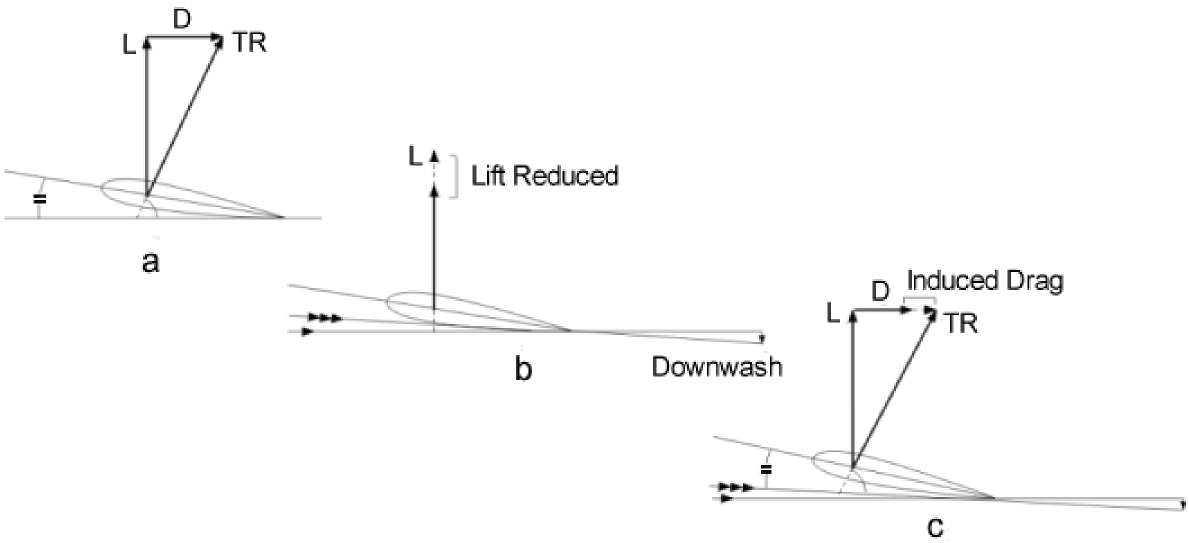


Fig 7 Effect of Downwash on Lift and Drag

Factors Affecting Induced Drag

31. The main factors affecting vortex formation and therefore induced drag are:

a. Planform.

b. Aspect ratio.

c. Lift and weight.

d. Speed.

For an elliptical planform, which gives the minimum induced drag at any aspect ratio:

$$C_{Di} = \frac{C_L^2}{\pi A}$$

where C_{Di} = coefficient of induced drag

A = aspect ratio

A correction factor k is required for other planforms.

32. **Planform**. Induced drag is greatest where the vortices are greatest, that is, at the wing tips; and so, to reduce the induced drag the aim must be to achieve an even spanwise pressure distribution. An elliptical planform has unique properties due to elliptic spanwise lift distribution, viz:

a. The downwash is constant along the span.

b. For a given lift, span and velocity, this planform creates the minimum induced drag.

An elliptical wing poses manufacturing difficulties, fortunately a careful combination of taper and washout, or section change, at the tips, can approximate to the elliptic ideal.

33. **Aspect Ratio (AR).** It has been previously stated that, if the AR is infinite, then the induced drag is zero. The nearer we can get to this impossible configuration, then the less induced drag is produced. The wing tip vortices are aggravated by the increased tip spillage, caused by the transverse flow over the longer chord of a low AR wing and the enhanced induced downwash affects a greater proportion of the shorter span. Induced drag is inversely proportional to the AR, eg if the AR is doubled, then the induced drag is halved.

34. **Effect of Lift and Weight**. The induced downwash angle (α_1) (see Chap 3 Fig 10) - and therefore the induced drag - depends upon the difference in pressure between the upper and lower surfaces of the wing, and this pressure difference is the lift produced by the wing. It follows then that an increase in C_L (eg during manoeuvres or with increased weight) will increase the induced drag at that speed. In fact, the induced drag varies as C_L^2 and, therefore, as weight^2, at a given speed.

35. **Effect of Speed**. If, while maintaining level flight, the speed is reduced to, say, half the original, then the dynamic pressure producing the lift ($\frac{1}{2}\rho V^2$) is reduced four times. To restore the lift to its original value, the value of C_L must be increased four-fold. The increased angle of attack necessary to do this inclines the lift vector to the rear, increasing the contribution to the induced drag. In addition, the vortices are affected, since the top and bottom aerofoil pressures are altered with the angle of attack

36. **High Angles of Attack.** Induced drag at high angles of attack, such as occur at take-off, can account for nearly three-quarters of the total drag, falling to an almost insignificant figure at high speed.

Increments of Zero Lift Drag Resulting from Lift Production

37. **Effect of Lift**. Remembering that two of the factors affecting zero lift drag are transition point and adverse pressure gradient, consider the effect of increasing lift from zero to the maximum for manoeuvre. Forward movement of the peak of the low pressure envelope will cause earlier transition of the boundary layer to turbulent flow, and the increasing adverse pressure gradient will cause earlier separation. Earlier transition increases the surface friction drag and earlier separation increases the form drag.

38. **Frontal Area.** As an aircraft changes its angle of attack, either because of a speed change or to manoeuvre, the frontal area presented to the airflow is changed and consequently the amount of form drag is changed.

39. Interference Drag. Interference drag arises from the mixing of the boundary layers at junctions on the airframe. When the aircraft is producing lift, the boundary layers are thicker and more turbulent and therefore create greater energy losses where they mix. The increments of surface friction, form and interference drag arise because the aircraft is producing lift, and these values of additional drag may be included in lift dependent drag. It follows that the greater the lift, the greater the drag increments, and, in fact, this additional drag is only really noticeable at high angles of attack.

Variation of Drag with Angle of Attack

40. Fig 8 shows that total drag varies steadily with change of angle of attack, being least at small negative angles and increasing on either side. The rate of increase becomes marked at angles of attack above about 8 and after the stall it increases at a greater rate. The sudden rise at the stall is caused by the turbulence resulting from the breakdown of steady flow.

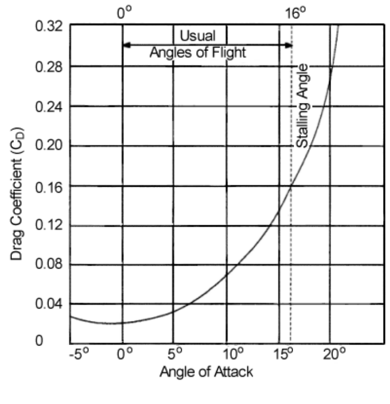


Fig 8 Typical Drag Curve for a Cambered Section

Variation of Lift/Drag Ratio with Angle of Attack

41. It is apparent that for a given amount of lift it is desirable to have the least possible drag from the aerofoil. Typically, the greatest lifting effort is obtained at an angle of attack of about 16° and least drag occurs at an angle of attack of about –2°. Neither of these angles is satisfactory, as the ratio of lift to drag at these extreme figures is low. What is required is the maximum lifting effort compared with the drag at the same angle, ie the highest lift/drag ratio (L/D ratio).

42. The L/D ratio for an aerofoil at any selected angle of attack can be calculated by dividing the C_L at that angle of attack by the corresponding C_D. In practice the same result is obtained irrespective of whether the lift and drag or their coefficients are used for the calculation:

$$\frac{L}{D} = \frac{C_L \frac{1}{2}\rho V^2 S}{C_D \frac{1}{2}\rho V^2 S} = \frac{C_L}{C_D}$$

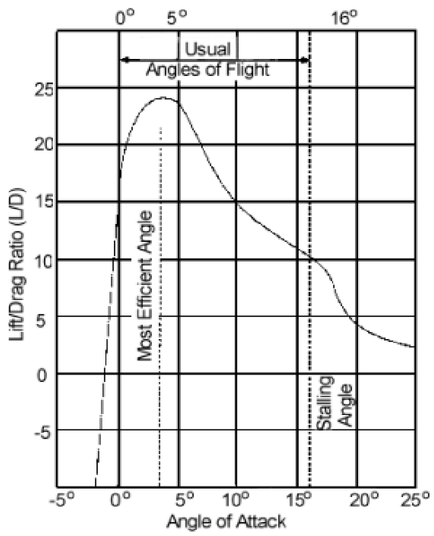


Fig 9 Variation of L/D Ratio with Angle of Attack

43. Fig 9 shows that the lift/drag ratio increases rapidly up to an angle of attack of about 4° at which point the lift may be between 12 to 25 times the drag, the exact figure depending on the aerofoil used. At larger angles the L/D ratio decreases steadily, because even though the lift itself is still increasing the proportion of drag is rising at a faster rate. One important feature of this graph is the indication of the angle of attack for the highest L/D ratio; this angle is one at which the aerofoil gives its best all-round performance. At a higher angle the required lift is obtained at a lower, and hence, uneconomical speed; at a lower angle it is obtained at a higher, and also uneconomical, speed.

Summary

44. Lift dependent drag comprises:

a. Induced drag (vortex drag).

b. Increments of:

(1) Surface friction drag.

(2) Form drag.

(3) Interference drag.

45. Induced drag varies as:

a. C_L

b. $\frac{1}{V^2}$

c. Weight^2.

d. $\frac{1}{\text{aspect ratio}}$

TOTAL DRAG

General

46. A typical total drag curve is shown in Fig 10. This curve is valid for one particular aircraft for one weight only in level flight. Speeds of particular interest are indicated on the graph:

a. The shaded area is the minimum product of drag and velocity and is therefore gives the minimum power speed (V_{MP}).

b. V_{IMD} is the lowest drag speed and it coincides with the best lift/drag ratio speed.

c. Maximum EAS/drag ratio speed is the main aerodynamic consideration for best range. It has the value of 1.32 (V_{IMD}).

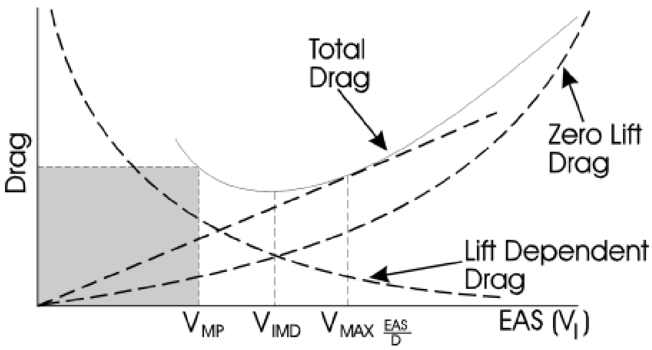


Fig 10 Total Drag Curve

STALLING

Introduction

1. It was stated that the nature of the boundary layer determined the stalling characteristics of a wing. In particular the phenomenon of boundary layer separation is extremely important. This chapter will first discuss what happens when a wing stalls, it will then look at the aerodynamic symptoms and the variations in the basic stalling speed and finally consider autorotation.

Boundary Layer Separation

2. Boundary layer separation is produced as a result of the adverse pressure gradient developed round the body. The low energy air close to the surface is unable to move in the opposite direction to the pressure gradient and the flow close to the surface flows in the reverse direction to the free stream. The development of separation is shown in Fig 1. A normal typical velocity profile is shown corresponding to point A, while a little further down the surface, at point B, the adverse pressure gradient will have modified the velocity profile as shown. At point C the velocity profile has been modified to such an extent that, at the surface, flow has ceased. Further down the surface, at point D, the flow close to the surface has reversed and the flow is said to have separated. Point C is defined as the separation point. In the reversed flow region aft of this point the flow is eddying and turbulent, with a mean velocity of motion in the opposite direction to the free stream.

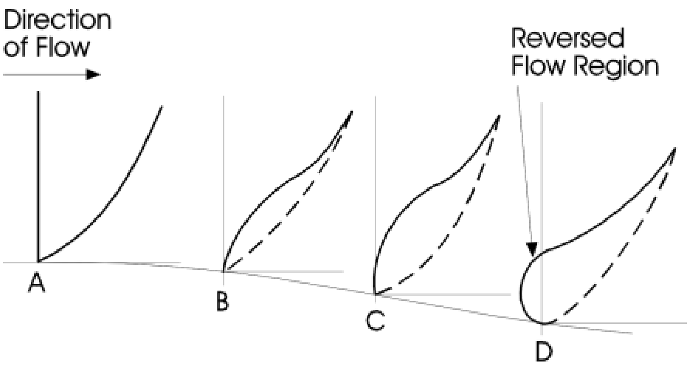


Fig 1 Velocity Profile

3. **Trailing Edge Separation**. On a normal subsonic section virtually no flow separation occurs before the trailing edge at low angles of attack, the flow being attached over the rear part of the surface in the form of a turbulent boundary layer. As the angles of attack increases, so the adverse pressure gradient is increased as explained in Chap 4, and the boundary layer will begin to separate from the surface near the trailing edge of the wing, see Fig 2. As the angle of attack is further increased the separation point will move forwards along the surface of the wing towards the leading edge. As the separation point moves forward the slope of the lift/angles of attack curve decreases and eventually an angles of attack is reached at which the wing is said to stall. The flow over the upper

surface of the wing is then completely broken down and the lift produced by the wing decreases.

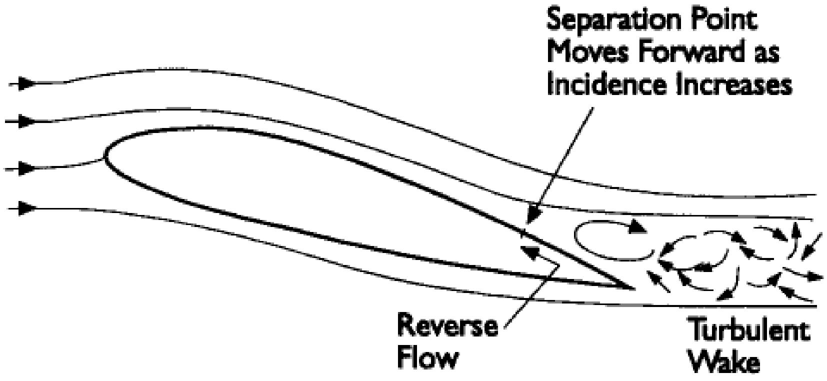


Fig 2 Trailing Edge Separation

4. **<u>Leading Edge Separation</u>.** Though this type of turbulent trailing edge separation is usually found on conventional low speed wing sections, another type of separation sometimes occurs on thin wings with sharp leading edges. This is laminar flow separation; the flow separating at the thin nose of the aerofoil before becoming turbulent. Transition may then occur in the separated boundary layer and the layer may then re-attach further down the body in the form of a turbulent boundary layer. Underneath the separated layer a stationary vortex is formed and this is often termed a bubble (Fig 3). The size of these bubbles depends on the aerofoil shape and has been found to vary from a very small fraction of the chord (short bubbles) to a length comparable to that of the chord itself (long bubbles). The long bubbles affect the pressure distribution even at small angles of attack, reducing the lift-curve slope. The eventual stall on this type of wing is more gradual. However, the short bubbles have little effect on the pressure distrubution, and hence on the lift curve slope, but when the bubble eventually bursts the corresponding stall is an abrupt one.

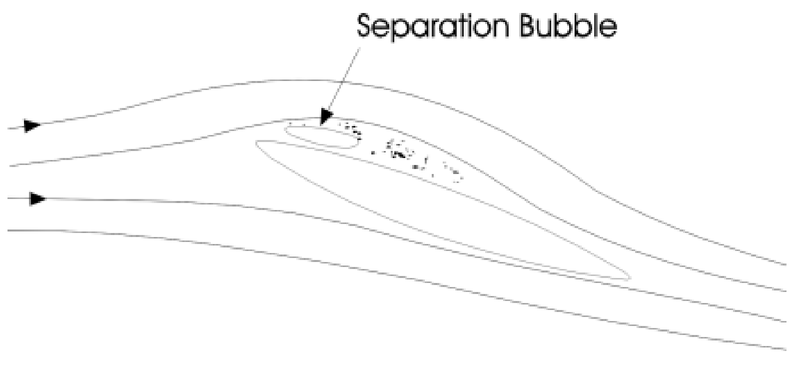


Fig 3 Leading Edge Separation

5. **<u>Critical Angle</u>**. The marked reduction in the lift coefficient which accompanies the breakdown of airflow over the wing occurs at the critical angle of attack for a particular wing. In subsonic flight an aircraft will always stall at the same critical angle of attack except at high Reynolds Numbers (Chap 2). A typical lift curve showing the critical angle is seen in Fig 4; it should be noted that not all lift is lost at the critical angle, in fact the aerofoil will give a certain amount of lift up to 90°.

Aerodynamic Symptoms

6. The most consistent symptom, or stall warning, arises from the separated flow behind the wing passing over the tail surfaces. The turbulent wake causes buffeting of the control surfaces which can usually be felt at the control column and rudder pedals. As the separation point starts to move forward, to within a few degrees of the critical angle of attack, the buffeting will usually give adequate warning of the stall. On some aircraft separation may also occur over the cockpit canopy to give additional audible warning. The amount of pre-stall buffet depends on the position of the tail surfaces with respect to the turbulent wake. When the trailing edge flap is lowered the increased downwash angle behind the (inboard) flaps may reduce the amount of buffet warning of the stall.

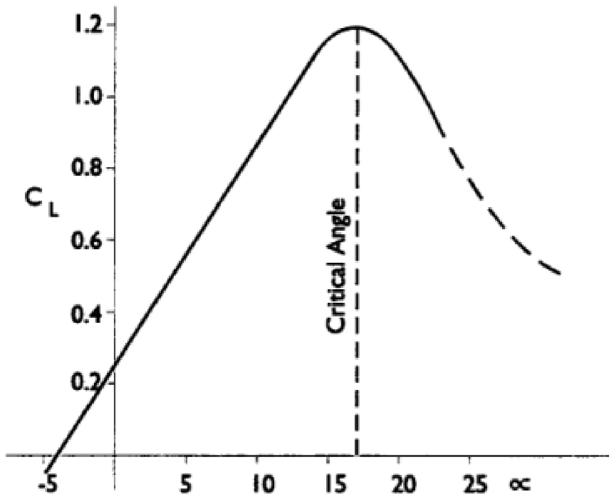


Fig 4 Lift Curve

Pitching Moments

7. As angle of attack is increased through the critical angle of attack the wing pitching moment changes. Changes in the downwash angle behind the wing also cause the tail pitching moment to change. The overall effect varies with aircraft type and may be masked by the rate at which the elevator is deflected to increase the angle of attack. Most aircraft, however, are designed to produce a nose-down pitching moment at the critical angle of attack.

Tip Stalling

8. The wing of an aircraft is designed to stall progressively from the root to the tip. The reasons for this are threefold:

a. To induce early buffet symptoms over the tail surface.

b. To retain aileron effectiveness up to the critical angle of attack.

c. To avoid a large rolling moment, which would arise if the tip of one wing stalled before the other (wing drop).

9. A rectangular straight wing will usually stall from the root because of the reduction in effective angle of attack at the tips caused by the wing tip vortex. If washout is incorporated to reduce vortex drag, it also assists in delaying tip stall. A tapered wing on the other hand will aggravate the tip stall due to the lower Reynolds Number (smaller chord) at the wing tip.

10. The most common features designed to prevent wing tip stalling are:

a. **Washout**. A reduction in incidence at the tips will result in the wing root reaching its critical angle of attack before the wing tip.

b. **Root Spoilers**. By making the leading edge of the root sharper, the airflow has more difficulty in following the contour of the leading edge and an early stall is induced.

c. **Change of Section**. An aerofoil section with more gradual stalling characteristics may be employed towards the wing tips (increased camber).

d. **Slats and Slots**. The use of slats and/or slots on the outer portion of the wing increases the stalling angle of that part of the wing. Slats and slots are dealt with more fully in Chap 8.

STALLING SPEED

General

11. In level flight the weight of the aircraft is balanced by the lift, and from the lift formula $\left(\mathrm{Lift} = C_L \frac{1}{2}\rho V^2 S\right)$ can be seen that lift is reduced whenever any of the other factors in the formula are reduced. For all practical purposes density (ρ) and wing area (S) can be considered constant (for a particular altitude and configuration). If the engine is throttled back the drag will reduce the speed, and, from the formula, lift will be reduced. To keep the lift constant and so maintain level flight, the only factor that is readily variable is the lift coefficient (C_L).

12. As has been shown, the C_L can be made larger by increasing the angle of attack, and by so doing the lift can be restored to its original value so that level flight is maintained at the reduced speed. Any further reduction in speed necessitates a further increase in the angle of attack, each succeeding lower IAS corresponding to each succeeding higher angle of attack. Eventually, at a certain IAS, the wing reaches its stalling angle, beyond which point any further increase in angle of attack, in an attempt to maintain the lift, will precipitate a stall.

13. The speed corresponding to a given angle of attack is obtained by transposing the lift formula, thus:

$$L = C_L \frac{1}{2}\rho_o V_1^2 S \quad \therefore \quad V_1^2 = \frac{L}{C_L \frac{1}{2}\rho_o S}$$

$$\therefore \quad V_1 = \sqrt{\frac{L}{C_L \frac{1}{2}\rho_o S}}$$

If it is required to know the speed corresponding to the critical angle of attack, the value of C_L in the above formula is C_{Lmax} and:

$$V_{I\ stall} = \sqrt{\frac{L}{C_{Lmax}\frac{1}{2}\rho_o S}}$$

Inspection of this formula shows that the only two variables (clean aircraft) are V, and L, ie:

$$V_{Istall} \propto \sqrt{\text{lift}}$$

14. This relationship is readily demonstrated by the following examples:

a. **Steep Dive**. When pulling out of a dive, if the angle of attack is increased to the critical angle, separation will occur and buffet will be felt at a high air speed.

b. **Vertical Climb**. In true vertical flight lift is zero and no buffet symptoms will be produced even at zero IAS.

Basic Stalling Speed

15. The most useful stalling speed to remember is the stalling speed corresponding to the critical angle of attack in straight and level flight. It may be defined as the speed below which a clean aircraft of stated weight, with the engines throttled back, can no longer maintain straight and level flight. This speed is listed in the Aircrew Manual for a number of different weights.

16. Applying these qualifications to the formulae in para 13, it can be seen that level flight requires a particular value of lift, ie L=W, and:

$$V_B \sqrt{\frac{W}{C_{Lmax}\frac{1}{2}\rho_o S}}$$

where V_B = basic stalling speed.

17. If the conditions in para 15 are not met, the stalling speed will differ from the basic stalling speed. The factors which change V_B are therefore:

a. Change in weight.

b. Manoeuvre (load factor).

c. Configuration (changes in C_{Lmax}).

d. Power and slip-stream.

Weight Change

18. The relationship between the basic stalling speeds at two different weights can be obtained from the formula in para 16, ie the ratio of V_{B2}: V_{B1}

$$= \left(\sqrt{\frac{W_1}{C_{Lmax}\frac{1}{2}\rho_o S}}\right) : \left(\sqrt{\frac{W_2}{C_{Lmax}\frac{1}{2}\rho_o S}}\right)$$

and, as the two denominators on the right-hand side are identical:

$$V_{B_1} : V_{B_2} = \sqrt{W_2} : \sqrt{W_1} \text{ or}$$

$$\frac{V_{B_2}}{V_{B_1}} = \sqrt{\frac{W_2}{W_1}}$$

from which

$$V_{B_2} = V_{B_1}\sqrt{\frac{W_2}{W_1}}$$

where V_{B1} and V_{B2} are the basic stalling speeds at weights W_1, and W_2 respectively.

19. This relationship is true for any given angle of attack provided that the appropriate value of C_L is not affected by speed. The reason is that, to maintain a given angle of attack in level flight, it is necessary to reduce the dynamic pressure (IAS) if the weight is reduced.

Manoeuvre

20. The relationship between the basic stalling speed and the stalling speed in any other manoeuvre (V_M) can be obtained in a similar way by comparing the general formula in para 13 to the level flight formula in para 16. Thus the ratio V_M : V_B =

$$\left(\sqrt{\frac{L}{C_{Lmax}\frac{1}{2}\rho_o S}}\right) : \left(\sqrt{\frac{W}{C_{Lmax}\frac{1}{2}\rho_o S}}\right)$$

Again, the denominators on the right-hand side are identical and so:

$$V_M : V_b = \sqrt{L} : \sqrt{W} \text{ or } \frac{V_M}{V_B} = \sqrt{\frac{L}{W}}$$

from which,

$$V_M = V_B\sqrt{\frac{L}{W}}.$$

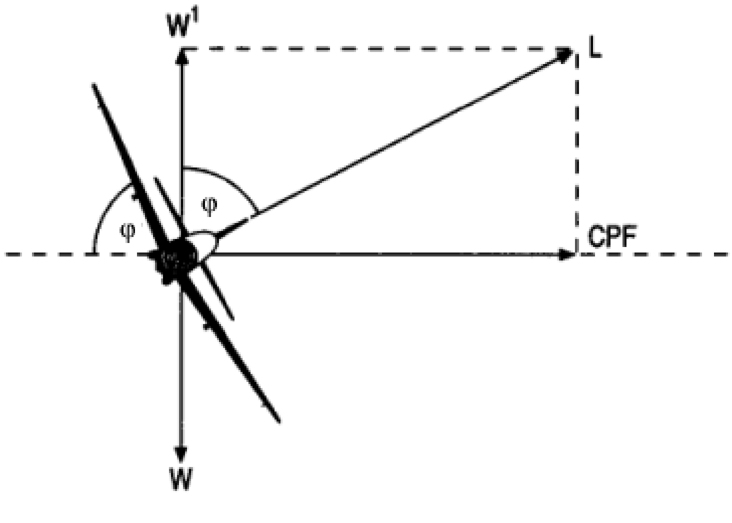
21. The relationship $\left(\frac{L}{W}\right)$ is the load factor, n, and is indicated on the accelerometer (if fitted). Thus $V_M = V_B \sqrt{n}$, and, in a 4g manoeuvre, the stalling speed is twice the basic stalling speed.

22. In the absence of an accelerometer the artificial horizon may be used as a guide to the increased stalling speed in a level turn.

From Fig 5, $\cos \varphi = \frac{W^1}{L} = \frac{W}{L}$ and therefore, $\frac{L}{W} = \frac{1}{\cos \varphi}$ and, substituting in the formula in para 20:

$$V_M = V_B \sqrt{\frac{1}{cos\varphi}}$$

and, in a 60° bank turn the stalling speed is $\sqrt{2}$ or 1.4 times the basic stalling speed.



φ = Angle of Bank
W¹ = Vertical Component of Lift = W
CPF = Horizontal Component of Lift = Centripetal Force

Fig 5 Forces on an Aircraft in a Level Turn

Configuration

23. From the formula in para 16 it can be seen that the stalling speed is inversely proportional to C_{Lmax} ie in level flight

$$V_B \propto \frac{1}{\sqrt{C_{Lmax}}}$$

24. Any change in C_{Lmax} due to the operation of high lift devices or due to compressibility effects will affect the stalling speed. In particular, lowering flaps or extending slats will result in a new basic stalling speed. These changes are usually listed in the Aircrew Manual.

Power

25. At the basic stalling speed the engines are throttled back and it is assumed that the weight of the aircraft is entirely supported by the wings. If power is applied at the stall the high nose attitude produces a vertical component of thrust which assists in supporting the weight and less force is required from the wings. This reduction in lift is achieved at the same angle of attack (C_{Lmax}) by reducing the dynamic pressure (IAS) and results in a lower stalling speed.

26. From Fig 6 it can be seen that L = W–T sin as which is less than the power-off case; and, as $V_M \alpha \sqrt{L}$, V_M with power on < VB.

27. It should be noted that, for simplicity, the load on the tailplane has been ignored and the engine thrust line assumed parallel to the wing chord line.

28. **Slipstream Effect**. For a propeller-powered aircraft an additional effect is caused by the velocity of the slipstream behind the propellers.

29. **Vector Change to RAF**. In Fig 7 the vector addition of the free stream and slipstream velocities results in a change in the RAF over that part of the wing affected by the propellers.

a. **Increase in Velocity**. The local increase in dynamic pressure will result in more lift behind the propellers relative to the power-off case. Thus, at a stalling angle of attack, a lower IAS is required to support the weight, ie the stalling speed is reduced.

b. **Decrease in Angle of Attack**. The reduction in angle of attack partially offsets the increase in dynamic pressure but does not materially alter the stalling speed unless C_{Lmax} is increased. The only effect will be to increase the attitude at which the stall occurs. Unless the propeller slipstream covers the entire wing, the probability of a wing drop will increase because the wings will stall progressively from the tips which are at a higher angle of attack than the wings behind the propellers.

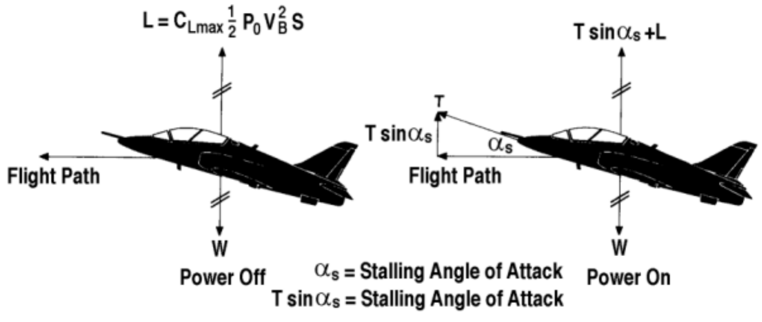
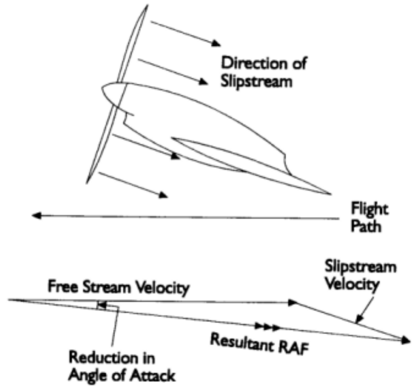


Fig 6 Comparison of Power Off and Power On Stalling



1-1-1-5 Fig 7 Slipstream Effect

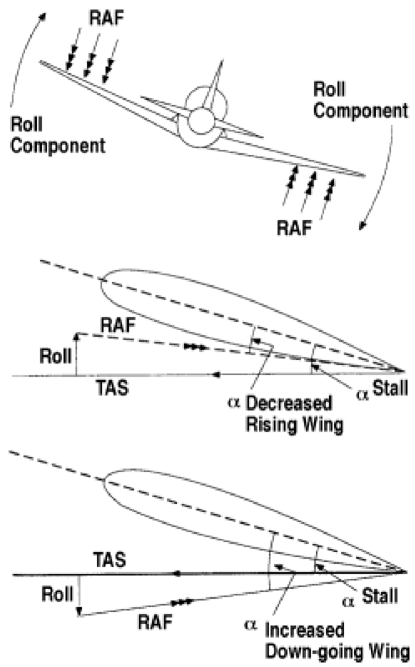


Fig 8 Vector Addition of Roll and Forward Velocities

AUTOROTATION

General

30. The autorotational properties of a wing are due to the negative slope of the C_L / α curve when α is greater than the stalling angle of attack.

31. With reference to the stalled aircraft illustrated at Fig 8, if the aircraft starts to roll there will be a component of flow induced tending to increase the angle of attack of the down-going wing and decrease the angle of attack of the up-going wing. The cause of the roll may be either accidental (wing-drop) deliberate (further effects of applied rudder) or use of aileron at the stall.

32. The effect of this change in angle of attack on the C_L and C_D (see Fig 9) is that the “damping in roll” effect normally produced at low a is now reversed. The increase in angle of attack of the down-going wing decreases the C_L and increases the C_D. Conversely, the

decrease in angle of attack of the up-going wing slightly decreases the C_L and decreases the C_D. The difference in lift produces a rolling moment towards the down-going wing tending to increase the angular velocity. This angular acceleration is further increased by the roll induced by the yawing motion due to the large difference in drag.

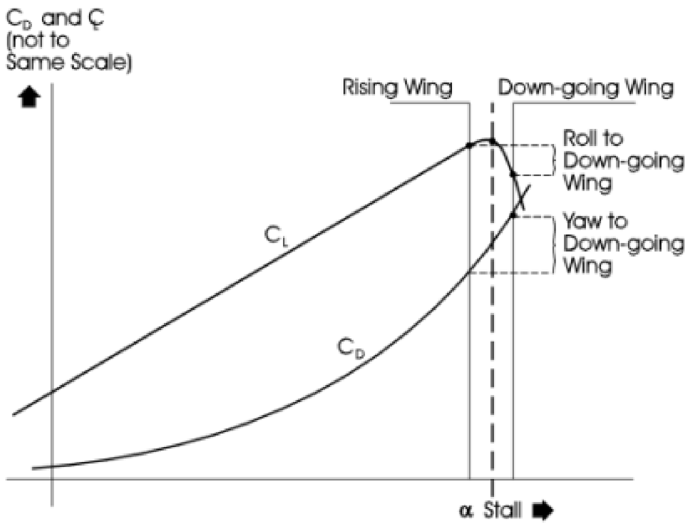


Fig 9 Autorotation

33. The cycle is automatic in the sense that the increasing rolling velocity sustains or even increases the difference in angle of attack. It should be noted, however, that at higher angles, the slope of the C_L curve may recover again to zero. This may impose a limit on the α at which autorotation is possible.

34. It is emphasized that autorotation, like the stall, is an aerodynamic event which is dependent on angle of attack. It is therefore possible to autorotate the aircraft in any attitude and at speeds higher than the basic stalling speed. This principle is the basis of many of the more advanced aerobatic manoeuvres.

Summary

35. Boundary layer separation is produced as a result of the adverse pressure gradient developed round the body.

36. In subsonic flight an aircraft will always stall at the same critical angle of attack.

37. The wing of an aircraft is designed to stall progressively from the root to the tip. The reasons for this are:

a. To induce early buffet symptoms over the tail surface.

b. To retain aileron effectiveness up to the critical angle of attack.

c. To avoid a large rolling moment which would arise if the tip of one wing stalled before the other.

38. The most common design features for preventing tip stalling are:

a. Washout.

b. Root spoilers.

c. Change of section.

d. Slats and slots.

39. Basic stalling speed is the speed below which a clean aircraft of stated weight, with engines throttled back, can no longer maintain straight and level flight.

40. The formula for the basic stalling speed is:

$$V_B = \sqrt{\frac{W}{C_{Lmax}\frac{1}{2}\rho_o S}}$$

Factors which affect V_B are:

a. Change in weight:

$$V_{B2} = V_{B_1}\sqrt{\frac{W_2}{W_1}}$$

b. Manoeuvre (load factor):

$$V_M = V_B\sqrt{n} \text{ or } V_M = V_B\sqrt{\frac{1}{\cos\varphi}}$$

c. Configuration (changes in): C_{Lmax}

$$V_B \propto \frac{1}{C_{Lmax}}$$

d. Power and Slip-stream:

$$V_M \text{power on} < V_B$$

SPINNING

Introduction

1. Spinning is a complicated subject to analyse in detail. It is also a subject about which it is difficult to make generalizations which are true for all aircraft. One type of aircraft may behave in a certain manner in a spin whereas another type will behave completely differently under the same conditions. This chapter is based on a deliberately-induced, erect spin to the right although inverted and oscillatory spins are discussed in later paragraphs.

2. The accepted sign conventions applicable to this chapter are given in Table 1, together with Fig 1.

Phases of the Spin

3. The spin man oeuvre can be divided into three phases:

a. The incipient spin.

b. The fully-developed spin.

c. The recovery.

4. **The Incipient Spin**. A necessary ingredient of a spin is the aerodynamic phenomenon known as autorotation. This leads to an unsteady man oeuvre which is a combination of:

a. The ballistic path of the aircraft, which is itself dependent on the entry attitude.

b. Increasing angular velocity generated by the authoritative rolling moment and drag-induced yawing moment.

5. **The Steady Spin**. The incipient stage may continue for some 2-6 turns after which the aircraft will settle into a steady stable spin. There will be some sideslip and the aircraft will be rotating about all three axes. For simplicity, but without suggesting that it is possible for all aircraft to achieve this stable condition, the steady spin is qualified by a steady rate of rotation and a steady rate of descent.

6. **The Recovery**. The recovery is initiated by the pilot by actions aimed at first opposing the autorotation and then reducing the angle of attack (α) so as to unstall the wings. The aircraft may then be recovered from the ensuing steep dive.

The Steady Erect Spin

7. While rotating, the aircraft will describe some sort of ballistic trajectory dependent on the entry manoeuvre. To the pilot this will appear as an unsteady, oscillatory phase until the aircraft settles down into a stable spin with steady rate of descent and rotation about the spin axis. This will occur if the aerodynamic and inertia forces and moments can achieve a state of equilibrium. The attitude of the aircraft at this stage will depend on the aerodynamic shape of the aircraft, the position of the controls and the distribution of mass throughout the aircraft.

Motion of the Aircraft

8. The motion of the centre of gravity in a spin has two components:

   a. A vertical linear velocity (rate of descent = V fps).

   b. An angular velocity (Ω radians per sec) about a vertical axis, called the spin axis. The distance between the CG and the spin axis is the radius of the spin (R) and is normally small (about a wing semi-span).

The combination of these motions results in a vertical spiral or helix. The helix angle is small, usually less than 10°. Fig 1 shows the motion of the aircraft in spin.

9. As the aircraft always presents the same face to the spin axis, it follows that it must be rotating about a vertical axis passing through the centre of gravity at the same rate as the CG about the spin axis. This angular velocity may be resolved into components of roll, pitch and yaw with respect to the aircraft body axes. In the spin illustrated in Fig 1b the aircraft is rolling right, pitching up and yawing right. For convenience the direction of the spin is defined by the direction of yaw.

10. In order to understand the relationship between these angular velocities and aircraft attitude it is useful to consider three limiting cases:

   a. **Longitudinal Axis Vertical**. When the longitudinal axis is vertical the angular motion will be all roll.

   b. **Lateral Axis Vertical**. For the aircraft to present the same face (pilot's head) to the spin axis, the aircraft must rotate about the lateral axis. The angular motion is all pitch.

   c. **Normal Axis Vertical**. For the aircraft to present the same face (inner wing tip) to the axis of rotation, the aircraft must rotate about the normal axis at the same rate as the aircraft rotates about the axis of rotation. Thus the angular motion is all yaw.

11. Although these are hypothetical examples which may not be possible in practice, they illustrate the relationship between aircraft attitude and angular velocities. Between the extremes quoted in the previous paragraph, the motion will be a combination of roll, pitch and yaw, and depends on:

   a. The rate of rotation of the aircraft about the spin axis.

   b. The attitude of the aircraft, which is usually defined in terms of the pitch angle and the wing tilt angle. Wing tilt angle, often confused with bank angle, involves displacement about the normal and the longitudinal axes.

12. The aircraft's attitude in the spin also has an important effect on the sideslip present (see Fig 1c). If the wings are level, there will be outward sideslip; that is, the relative airflow will be from the direction of the outside wing (to port in the diagram). If the attitude of the aircraft is changed such that the outer wing is raised relative to the horizontal, the sideslip is reduced. This attitude change can only be due to a rotation of the aircraft about the normal axis. The angle through which the aircraft is rotated, in the plane containing the lateral and

longitudinal axes, is known as the wing tilt angle and is positive with the outer wing up. If the wing tilt can be increased sufficiently to reduce the sideslip significantly, the pro-spin aerodynamic rolling moment will be reduced.

Table 1 Sign Conventions Used in this Chapter

AXIS (Symbol)	LONGITUDINAL (x)	LATERAL (y)	NORMAL (z)
Positive Direction	Forwards	To right	Downwards
ANGULAR VELOCITY Designation Symbol	 Roll p	 Pitch q	 Yaw r
Positive Direction **MOMENT OF INERTIA**	to right A	nose-up B	to right C
MOMENTS			
Designation	rolling moment	pitching moment	yawing moment
Symbol	L	M	N
Postive Direction	to right	nose-up	to right

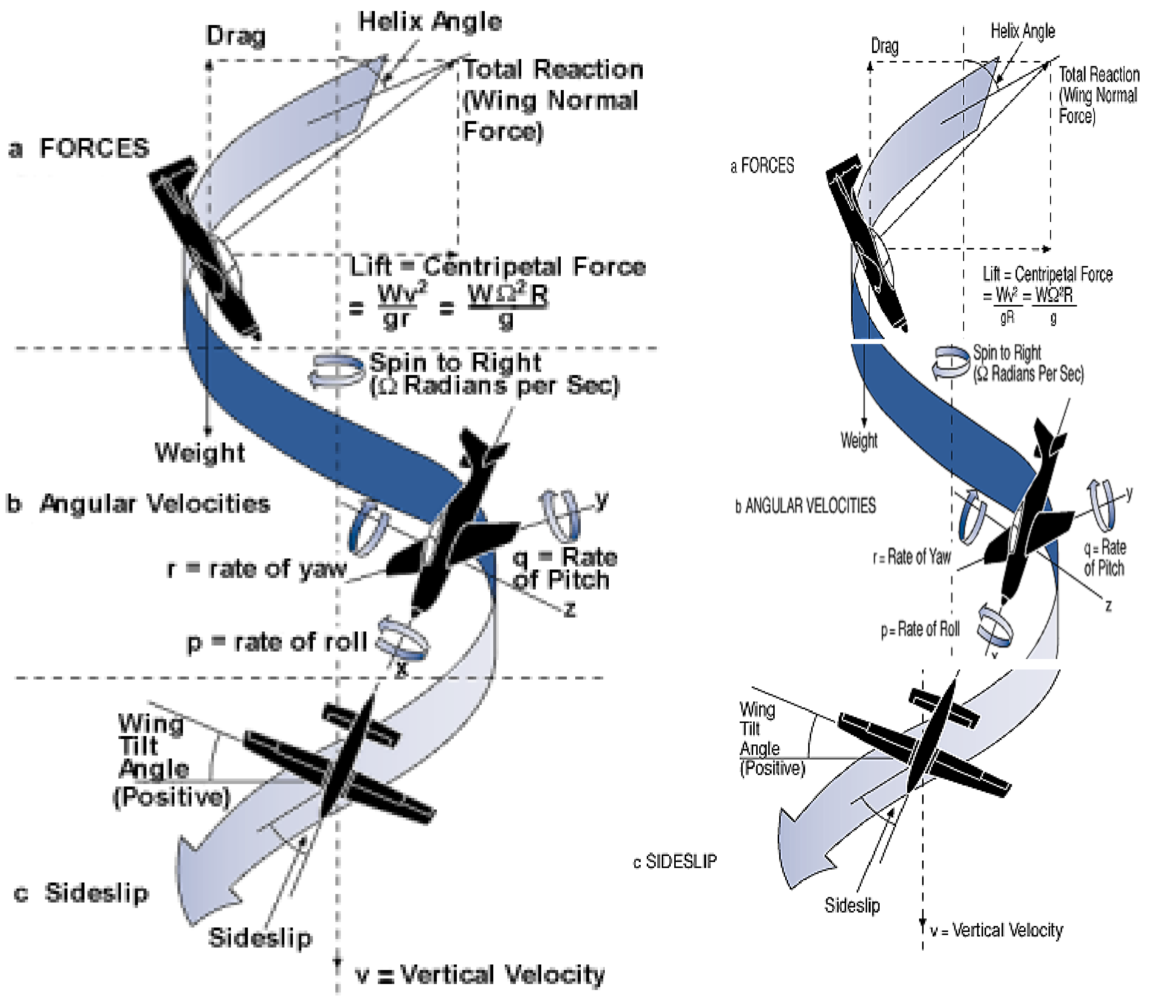


Fig 1 The Motion of an Aircraft in an Erect Spin to the Right

Balance of Forces in the Spin

13. Only two forces are acting on the centre of gravity while it is moving along its helical path (see Fig 1a).

a. Weight (W)

b. The aerodynamic force (N) coming mainly from the wings.

The resultant of these two forces is the centripetal force necessary to produce the angular motion.

14. Since the weight and the centripetal force act in a vertical plane containing the spin axis and the CG, the aerodynamic force must also act in this plane, ie it passes through the spin axis. It can be shown that, when the wing is stalled, the resultant aerodynamic force acts approximately perpendicular to the wing. For this reason it is sometimes called the wing normal force.

15. If the wings are level (lateral axis horizontal), from the balance of forces in Fig 1a:

a. $\text{Weight} = \text{Drag} = C_D \tfrac{1}{2}\rho V^2 S$

$$V = \sqrt{\frac{W}{C_D \frac{1}{2}\rho S}}$$

b. $\text{Lift} = \text{Centripetal force}$

$$C_D \frac{1}{2}\rho V^2 S = \frac{W\Omega^2 R}{g}$$

$$R = \frac{g C_L \frac{1}{2}\rho V^2 S}{W\Omega^2}$$

Where: R = spin radius, S = area

V = rate of descent, W = weight

If the wings are not level, it has been seen that the departure from the level condition can be regarded as a rotation of the aircraft about the longitudinal and normal axes. Usually this angle, the wing tilt angle, is small and does not affect the following reasoning.

Effect of Attitude on Spin Radius

16. If for some reason the angle of attack is increased by a nose-up change in the aircraft's attitude, the vertical rate of descent (V) will decrease because of the higher C_D (para 15a). The increased alpha on the other hand, will decrease C_L which, together with the lower rate of descent, results in a decrease in spin radius, (para 15b). It can also be shown that an increase in pitch increases the rate of spin, which will decrease R still further.

17. The two extremes of aircraft attitude possible in the spin are shown in Fig 2. The actual attitude adopted by an aircraft will depend on the balance of moments.

18. The effects of pitch attitude are summarized below: an increase in pitch (eg flat spin) will:

a. Decrease the rate of descent.

b. Decrease the spin radius.

c. Increase the spin rate.

It can also be shown that an increase in pitch will decrease the helix angle.

Angular Momentum

19. In a steady spin, equilibrium is achieved by a balance of aerodynamic and inertia moments. The inertia moments result from a change in angular momentum due to the inertia cross-coupling between the three axes.

20. The angular momentum about an axis depends on the distribution of mass and the rate of rotation. It is important to get a clear understanding of the significance the spinning characteristics of different aircraft and the effect of controls in recovering from the spin.

Moment of Inertia (I)

21. A concept necessary to predict the behaviour of a rotating system is that of moment of inertia. This quantity not only expresses the amount of mass but also its distribution about the axis of rotation. It is used in the same way that mass is used in linear motion. For example, the product of mass and linear velocity measures the momentum or resistance to movement of a body moving in a straight line. Similarly, the product of moment of inertia (mass distribution) and angular velocity measures the angular momentum of a rotating body. Fig 3 illustrates how the distribution of mass affects angular momentum.

22. The concept of moment of inertia may be applied to an aircraft by measuring the distribution of mass about each of the body axes in the following way:

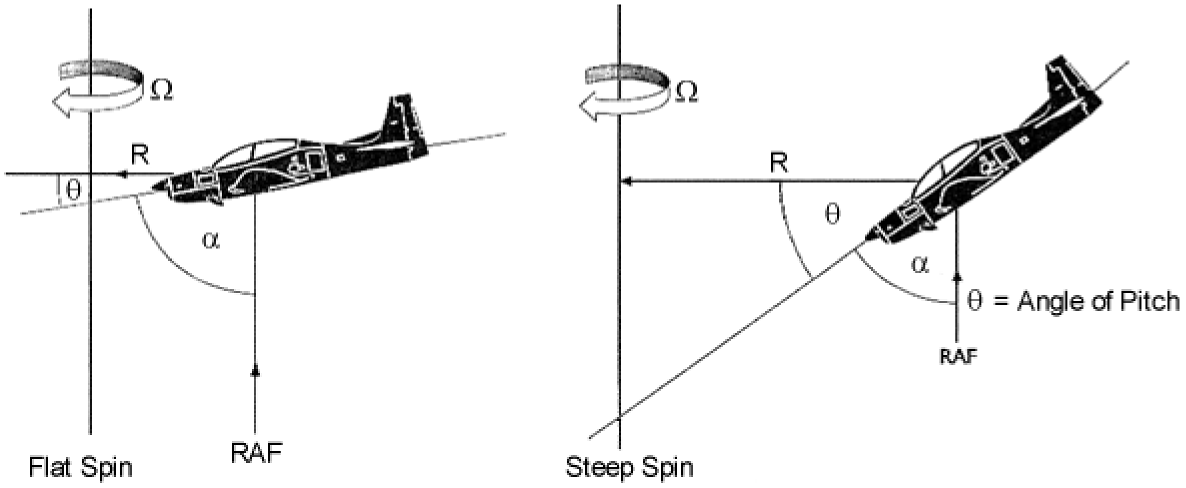


Fig 2 Simplified Diagram of Pitch Attitude

a. **Longitudinal Axis.** The distribution of mass about the longitudinal axis determines the moment of inertia in the rolling plane which is denoted by A. An aircraft with fuel stored in the wings and in external tanks will have a large value of A, particularly if the tanks are close to the wing tips. The tendency in modern high speed aircraft towards thinner wings has necessitated the stowage of fuel elsewhere and this, combined with lower aspect ratios, has resulted in a reduction in the value of A for those modern high performance fighter and training aircraft.

b. **Lateral Axis**. The distribution of mass about the lateral axis determines the moment of inertia in the pitching plane which is denoted by B. The increasing complexity of modern aircraft has resulted in an increase in the density of the fuselage with the mass being distributed along the whole length of the fuselage and a consequent increase in the value of B.

c. **Normal Axis.** The distribution of mass about the normal axis determines the moment of inertia in the yawing plane which is denoted by C. This quantity will be approximately equal to the sum of the moments of inertia in the rolling and pitching planes. C, therefore, will always be larger than A or B.

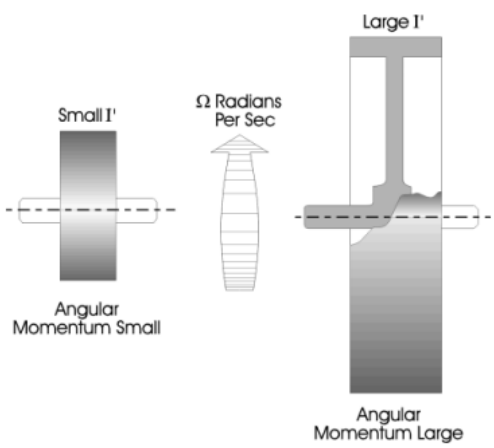


Fig 3 Two Rotors of the Same Weight and Angular Velocity

23. These moments of inertia measure the mass distribution about the body axes and are decided by the design of the aircraft. It will be seen that the values of A, B and C for a particular aircraft may be changed by altering the disposition of equipment, freight and fuel.

Inertia Moments in a Spin

24. The intertia moments generated in a spin are described below by assessing the effect of the concentrated masses involed. Another explanation using a gyroscropic analogy, is given in the Annex.

a. **Roll**. It is difficult to represent the rolling moments using concentrated masses, as is done for the other axes. For an aircraft in the spinning attitude under consideration (inner wing down pitching nose up), the inertia moment is anti-spin, ie tending to roll the aircraft out of the spin. The equation for the inertia rolling moment is:

$$L = - (C-B)\, rq$$

b. **Pitch**. The imaginary concentrated masses of the fuselage, as shown in Fig 4, tend to flatten the spin. The equation for the moment is:

$$M = (C-A)\, rp$$

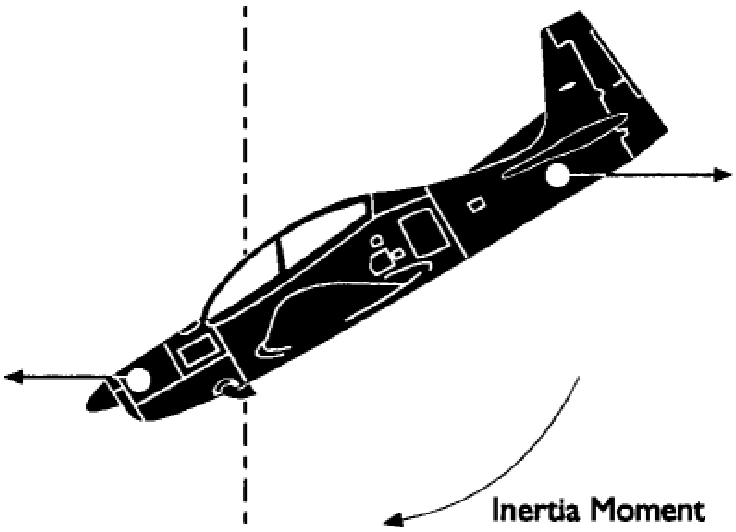


Fig 4 Inertia Pitching Moment

c. **Yaw**. The inertia couple is complicated by the fact that it comprises two opposing couples caused by the wings and the fuselage, see Fig 5. Depending on the dominant component, the couple can be of either sign and varying magnitude. The inertia yawing moment can be expressed as:

$$N = (A-B)\, p$$

25. This is negative and thus anti-spin when B > A; positive and pro-spin when A > B.

26. The B/A ratio has a profound effect on the spinning characteristics of an aircraft.

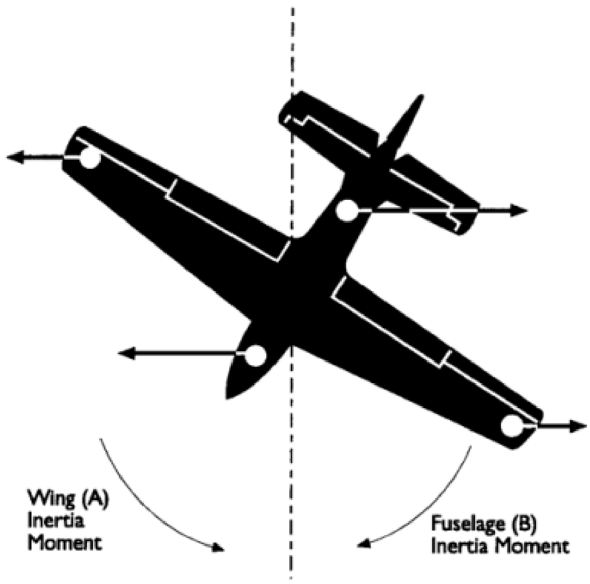


Fig 5 Inertia Yawing Moments

Aerodynamic Moments

27. It is now necessary to examine the contributions made by the aerodynamic factors in the balance of moments in roll, pitch and yaw. These are discussed separately below.

28. **Aerodynamic Rolling Moments**. The aerodynamic contributions to the balance of moments about the longitudinal axis to produce a steady rate of roll are as follows:

a. **Rolling Moment due to Sideslip**. The design features of the aircraft which contribute towards positive lateral stability produce an aerodynamic rolling moment as a result of sideslip. It can be shown that, even at angles of attack above the stall, this still remains true and the dihedral effect induces a rolling moment in the opposite sense to the sideslip. In the spin the relative airflow is from the direction of the outer wing (outward sideslip) and the result is a rolling moment in the direction in which the aircraft is spinning; this contribution is therefore pro-spin.

b. **Authoritative Rolling Moment**. In Chap 9 it is shown that the normal damping in roll effect is reversed at angles of attack above the stall. This contribution is therefore pro-spin.

c. **Rolling Moment due to Yaw**. The yawing velocity in the spin induces a rolling moment for two reasons:

(1) **Difference in Speed of the Wings**. Lift of the outside wing is increased and that of the inner wing decreased inducing a pro-spin rolling moment.

(2) **Difference in Angle of Attack of the Wings**. In a spin the direction of the free stream is practically vertical whereas the direction of the wing motion due to yaw is parallel to the longitudinal axis. The yawing velocity not only changes the speed but also the angle of attack of the wings. Fig 6 illustrates

the vector addition of the yawing velocity to the vertical velocity of the outer wing. The effect is to reduce the angle of attack of the outer wing and increase that of the inner wing. Because the wings are stalled (slope of CL curve is negative), the CL of the outer wing is increased and the CL of the inner wing decreased thus producing another pro-spin rolling moment.

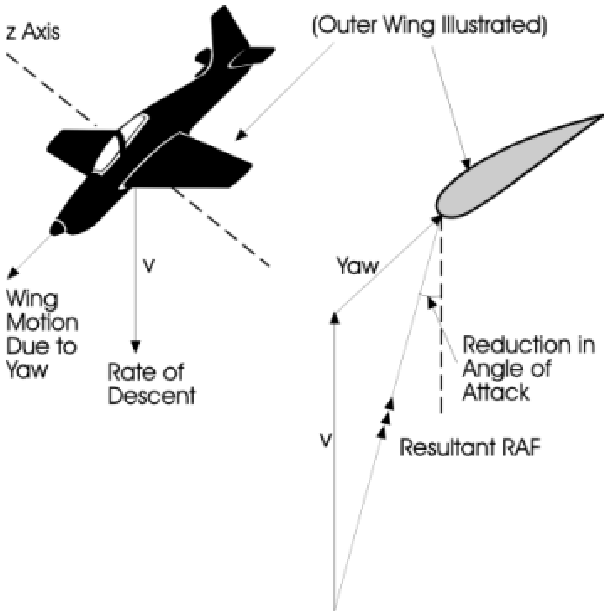


Fig 6 Change in Angle of Attack due to Yaw (Outer Wing)

d. **Aileron Response**. Experience has shown that the ailerons produce a rolling moment in the conventional sense even though the wing is stalled.

29. **Aerodynamic Pitching Moments**. The aerodynamic contributions to the balance of moments about the lateral axis to produce a steady rate of pitch are as follows:

a. **Positive Longitudinal Static Stability**. In a spin the aircraft is at a high angle of attack and therefore disturbed in a nose-up sense from the trimmed condition. The positive longitudinal stability responds to this disturbance to produce a nose-down aerodynamic moment. This effect may be considerably reduced if the tailplane lies in the wing wake.

b. **Damping in Pitch Effect**. When the aircraft is pitching nose-up the tailplane is moving down and its angle of attack is increased (the principle is the same as the damping in roll effect). The pitching velocity therefore produces a pitching moment in a nose-down sense. The rate of pitch in a spin is usually very low and consequently the damping in pitch contribution is small.

c. **Elevator Response**. The elevators act in the conventional sense. Down-elevator increases the nose-down aerodynamic moment whereas up-elevator produces a nose-up aerodynamic moment. It should be noted, however, that down-elevator usually increases the shielded area of the fin and rudder.

30. **Aerodynamic Yawing Moments**. The overall aerodynamic yawing moment is made up of a large number of separate parts, some arising out of the yawing motion of the aircraft and some arising out of the sideslipping motion. The main contributions to the balance of moments about the normal axis to produce a steady rate of yaw are as follows:

a. **Positive Directional Static Stability**. When sideslip is present keel surfaces aft of the CG produce an aerodynamic yawing moment tending to turn the aircraft into line with the sideslip vector (ie directional static stability or 'weathercock effect'). This is an anti-spin effect, the greatest contribution to which is from the vertical fin. Vertical surfaces forward of the CG will tend to yaw the aircraft further into the spin, ie they have a pro-spin effect. In a spin outward sideslip is present which, usually produces a net yawing moment towards the outer wing; ie in an anti-spin sense. Because of possible shielding effects from the tailplane and elevator and also because the fin may be stalled, the directional stability is considerably reduced and this anti-spin contribution is usually small.

b. **Damping in Yaw Effect**. Applying the principle of the damping in roll effect to the yawing velocity, it has been seen that the keel surfaces produce an aerodynamic yawing moment to oppose the yaw. The greatest contribution to this damping moment is from the rear fuselage and fin. In this respect the cross-sectional shape of the fuselage is critical and has a profound effect on the damping moment. The following figures give some indication of the importance of cross-section:

Cross-Section	Damping Effect (anti-spin)
Circular	1
Rectangular	2.5
Elliptical	3.5
Round top/flat bottom	1.8
Round bottom/flat top	4.2
Round bottom/flat top with strakes	5.8

$$\text{Damping effect} = \frac{\text{Damping from body of given cross-section}}{\text{Damping from circular cylinder}}$$

Fuselage strakes, are useful devices for improving the spinning characteristics of prototype aircraft. The anti-spin damping moment is very dependent on the design of the tailplane/fin combination. Shielding of the fin by the tailplane can considerably reduce the effectiveness of the fin. In extreme cases a low-set tailplane may even change the anti-spin effect into pro-spin.

c. **Rudder Response**. The rudder acts in the conventional sense, ie the in-spin rudder produces pro-spin yawing moment and out-spin rudder produces anti-spin yawing moment. Because of the shielding effect of the elevator (para 29c), it is usual during recovery to pause after applying out-spin rudder so that the anti-spin yawing moment may take effect before down-elevator is applied.

Balance of Moments

31. In para 16 it was seen that the balance of forces in the spin has a strong influence on the rate of descent. It does not, however, determine the rate of rotation, wing tilt or incidence at which the spin occurs: the balance of moments is much more critical in this respect. The actual attitude, rate of descent, sideslip, rate of rotation and radius of a spinning aircraft can only be determined by applying specific numerical values of the aircraft's aerodynamic and inertia data to the general relationships discussed below.

32. **Rolling Moments**. The balance of rolling moments in an erect spin is:

a. **Pro-spin**: The following aerodynamic rolling moments in an erect spin is:

(1) Autorotative rolling moment.

(2) Rolling moment due to sideslip.

(3) Rolling moment due to yaw.

b. **Anti-spin**. The inertia rolling moment, - (C - B) rq, is anti-spin.

These factors show that autorotation is usually necessary to achieve a stable spin. A small autorotative rolling moment would necessitate larger sideslip to increase the effect of rolling moment due to sideslip. This, in turn, would reduce the amount of wing tilt and make the balance of moments in yaw more difficult to achieve, however the balance of moments in this axis is not as important as in the other two.

33. **Pitching Moments**. In para 25 it was seen that the inertia pitching moment, (C – A) rp, of the aircraft is always nose-up in an erect spin. This is balanced by the nose-down aerodynamic pitching moment. The balance between these two moments is the main factor relating angle of attack to rate of rotation in any given case and equilibrium can usually be achieved over a wide range. It can be shown that an increase in pitch will cause an increase in the rate of rotation (spin rate). This, in turn, will decrease the spin radius (para 16).

34. **Yawing Moments**. The balance of yawing moments in an erect spin is:

a. Pro-spin.

(1) Yawing moment due to applied rudder.

(2) A small contribution from the wing, due to yaw, is possible at large angles of attack.

(3) Yawing moment due to sideslip (vertical surfaces forward of CG).

(4) Inertia yawing moment, (A - B)pq, if A > B.

b. Anti-spin.

(1) Inertia yawing moment, (A-B)pq, if B>A.

(2) Yawing moment due to sideslip (vertical surfaces aft of the CG).

(3) Damping in yaw effect.

It can be seen that in-spin rudder is usually necessary to achieve balance of the yawing moments and hold the aircraft in a spin.

35. **Normal Axis**. For conventional aircraft (A and B nearly equal), it is relatively easy to achieve balance about the normal axis and the spin tends to be limited to a single set of conditions (angle of attack, spin rate, attitude). For aircraft in which B is much larger than A, the inertia yawing moment can be large and, thus difficult to balance. This is probably the cause of the oscillatory spin exhibited by these types of aircraft.

36. **Yaw and Roll Axis.** The requirements of balance about the yaw and roll axes greatly limit the range of incidences in which spinning can occur and determine the amount of sideslip and wing tilt involved. The final balance of the yawing moments is achieved by the aircraft taking up the appropriate angle of attack at which the inertia moments just balance the aerodynamic moments. This particular angle of attack also has to be associated with the appropriate rate of spin required to balance the pitching moments and the appropriate angle of sideslip required to balance the rolling moments.

SPIN RECOVERY

Effect of Controls in Recovery from a Spin

37. The relative effectiveness of the three controls in recovering from a spin will now be considered. Recovery is aimed at stopping the rotation by reducing the pro-spin rolling moment and/or increasing the anti-spin yawing moment. The yawing moment is the more important but, because of the strong cross-coupling between motions about the three axes through the inertia moments, the rudder is not the only means by which yawing may be

induced by the pilot. Once the rotation has stopped the angle of attack is reduced and the aircraft recovered.

38. The control movements which experience has shown are generally most favourable to the recovery from the spin have been known and in use for a long time, ie apply full opposite rudder and then move the stick forward until the spin stops, maintaining the ailerons neutral. The rudder is normally the primary control but, because the inertia moments are generally large in modern aircraft, aileron deflection is also important. Where the response of the aircraft to rudder is reduced in the spin the aileron may even be the primary control although in the final analysis it is its effect on the yawing moment which makes it work.

39. The initial effect of applying a control deflection will be to change the aerodynamic moment about one or more axes. This will cause a change in aircraft attitude and a change in the rates of rotation about all the axes. These changes will, in turn, change the inertia moments.

Effect of Ailerons

40. Even at the high angle of attack in the spin the ailerons act in the normal sense. Application of aileron in the same direction as the aircraft is rolling will therefore increase the aerodynamic rolling moment. This will increase the roll rate (p) and affect the inertia yawing moment, (A - B)pq. The effect of an increase in p on the inertia yawing moment depends on the mass distribution or B/A ratio:

a. **B/A > 1**. In an aircraft where B/A > 1, the inertia yawing moment is anti-spin (negative) and an increase in p will decrease it still further, ie make it more anti-spin. The increase in anti-spin inertia yawing moment will tend to raise the outer wing (increase wing tilt) which will decrease the outward sideslip. This will restore the balance of rolling moments by decreasing the pro-spin aerodynamic moment due to lateral stability. The increase in wing tilt will also cause the rate of pitch, q, to increase, which, in turn:

(1) Causes a small increase in the anti-spin inertia rolling moment, - (C - B) rq, (C > B) and thus helps to restore balance about the roll axis (para 32).

(2) Further increases the anti-spin inertia yawing moment.

b. **B/A < 1**. A low B/A ratio will reverse the effects described above. The inertia yawing moment will be pro-spin (positive) and will increase with an increase in p.

41. Due to secondary effects associated with directional stability, the reversal point actually occurs at a B/A ratio of 1.3 Thus:

a. *B/A > 1.3*. Aileron with roll (in-spin) has an anti-spin effect.

b. *B/A < 1.3*. Aileron with roll (in-spin) has a pro-spin effect.

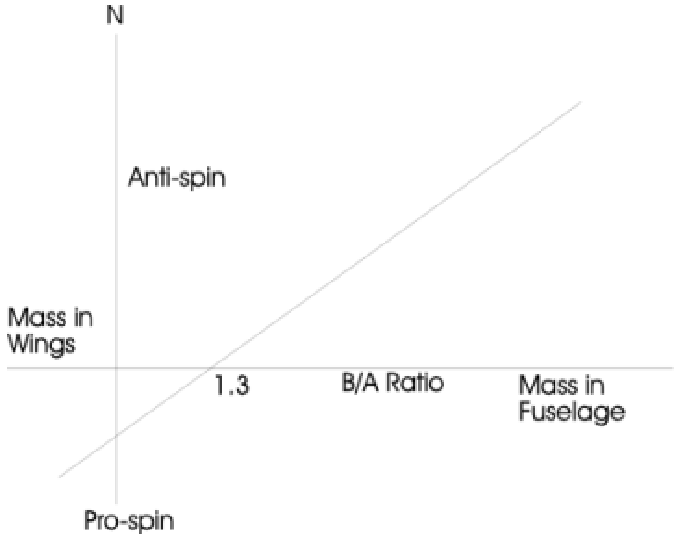


Fig 7 Yawing Moment (N) per degree of Aileron

42. Some aircraft change their B/A ratio in flight as stores and fuel are consumed. The pilot has no accurate indication of the value of B/A ratio and, where this value may vary either side of 1.3, it is desirable to maintain ailerons neutral to avoid an unfavourable response which may delay or even prohibit recovery.

43. An additional effect of aileron applied with roll is to increase the anti-spin yawing moments due to aileron drag.

Effect of Elevators

44. In para 29 it was seen that down-elevator produces a nose-down aerodynamic pitching moment. This will initially reduce the nose-up pitching velocity (q). Although this will tend to reduce alpha, the effect on the inertia yawing and rolling moments is as follows:

a. **Inertia Yawing Moment (A - B)pq**. If B > A, the inertia yawing moment is anti-spin. A reduction in q will make the inertia yawing moment less anti-spin, ie a pro-spin change. When A > B, however, down-elevator will cause a change in inertia yawing moment in the anti-spin sense.

b. **Inertia Rolling Moment -(C - B)rq**. The inertia rolling moment is always anti-spin because C > B. A reduction in q will therefore make it less anti-spin which is again a change in the pro-spin sense.

The result of these pro-spin changes in the inertia yawing and rolling moments is to decrease the wing tilt thus increasing the sideslip angle (Fig 1) and rate of roll. It can also be shown that the rate of rotation about the spin axis will increase.

45. Although the change in the inertia yawing moment is unfavourable, the increased sideslip may produce an anti-spin aerodynamic yawing moment if the directional stability is positive. This contribution will be reduced if the down elevator seriously increases the shielding of the fin and rudder.

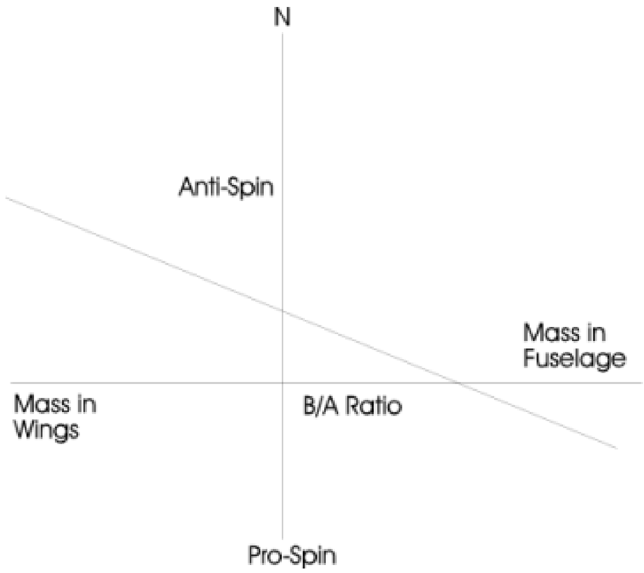


Fig 8 Yawing Moment (N) per Degree of Down Elevator

46. The overall effect of down-elevator on the yawing moments therefore depends on:

a. The pro-spin inertia moment when B > A.

b. The anti-spin moment due to directional stability.

c. The loss of rudder effectiveness due to shielding.

In general, the net result of moving the elevators down is beneficial when A > B and rather less so when B > A, assuming that the elevator movement does not significantly increase the shielding of the fin and rudder.

Effect of Rudder

47. The rudder is nearly always effective in producing an anti-spin aerodynamic yawing moment though the effectiveness may be greatly reduced when the rudder lies in the wake of the wing or tailplane. The resulting increase in the wing tilt angle will increase the anti-spin inertia yawing moment (when B > A) through an increase in pitching velocity. The overall effect of applying anti-spin rudder is always beneficial and is enhanced when the B/A ratio is increased.

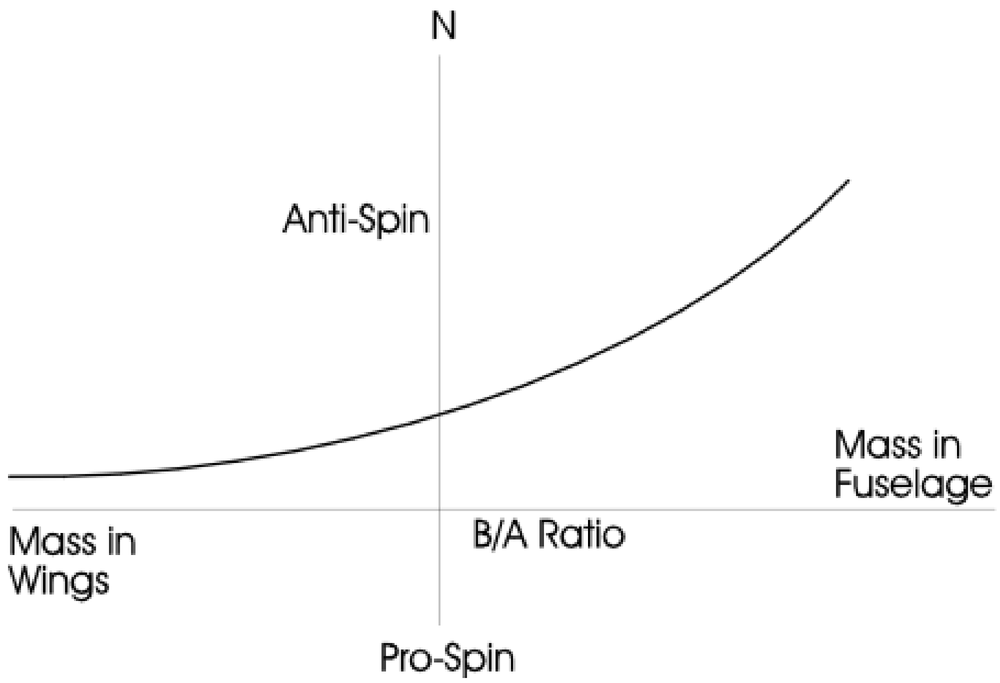


Fig 9 Yaw Moment (N) per Degree of Anti-spin Rudder

48. The effect of the three controls on the yawing moment is illustrated in Figs 7, 8 and 9.
Inverted Spin

49. Fig 10 shows an aircraft in an inverted spin but following the same flight path as in Fig 1. Relative to the pilot the motion is now compounded of a pitching velocity in the nose-down sense, a rolling velocity to the right and a yawing velocity to the left. Thus roll and yaw are in opposite directions, a fact which affects the recovery actions, particularly if the aircraft has a high B/A ratio.

50. The inverted spin is fundamentally similar to the erect spin and the principles of moment balance discussed in previous paragraphs are equally valid for the inverted spin. The values of the aerodynamic moments, however, are unlikely to be the same since, in the inverted attitude, the shielding effect of the wing and tail may change markedly.

51. The main difference will be caused by the change in relative positions of the fin and rudder and the tailplane. An aircraft with a low-mounted tailplane will tend to have a flatter erect spin and recovery will be made more difficult due to shielding of the rudder. The same aircraft inverted will respond much better to recovery rudder since it is unshielded and the effectiveness of the rudder increased by the position of the tailplane. The converse is true for an aircraft with a high tailplane.

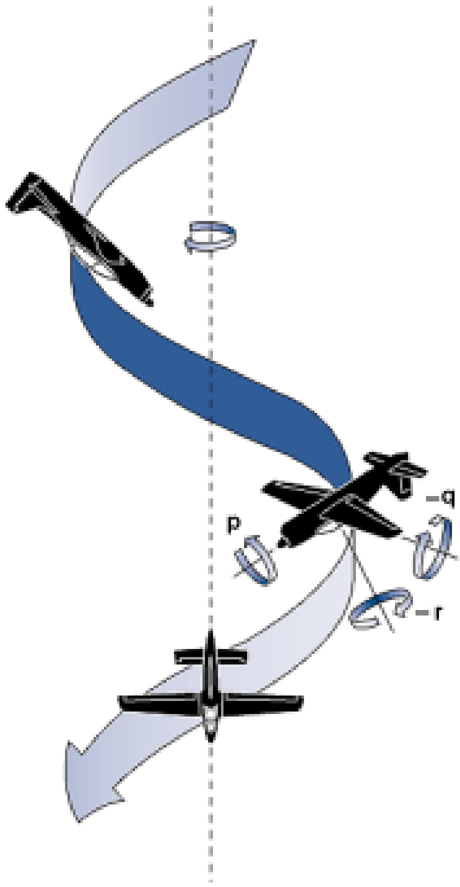


Fig 10 The Inverted Spin

52. The control deflections required for recovery are dictated by the direction of roll, pitch and yaw, and the aircraft's B/A ratio. These are:

a. Rudder to oppose yaw as indicated by the turn needle.

b. Aileron in the same direction as the observed roll, if the B/A ratio is high.

c. Elevator up is generally the case for conventional aircraft but, if the aircraft has a high B/A ratio and suffers from the shielding problems previously discussed, this control may be less favourable and may even become pro-spin.

<u>Oscillatory Spin</u>

53. A combination of high wing loading and high B/A ratio makes it difficult for a spinning aircraft to achieve equilibrium about the yaw axis. This is thought to be the most probable reason for the oscillatory spin. In this type of spin the rates of roll and pitch are changing during each oscillation. In a mild form it appears to the pilot as a continuously changing angle of wing tilt, from outer wing well above the horizon back to the horizontal once each turn; the aircraft seems to wallow in the spin.

54. In a fully-developed oscillatory spin the oscillations in the rates of roll and pitch can be quite violent. The rate of roll during each turn can vary from zero to about 200 degrees per second. At the maximum rate of roll the rising wing is unstalled which probably accounts for the violence of this type of spin. Large changes in attitude usually take place from fully nose-down at the peak rate of roll, to nose-up at the minimum rate of roll.

55. The use of the controls to effect a change in attitude can change the characteristics of an oscillatory spin quite markedly. In particular:

a. Anything which increases the wing tilt will increase the violence of the oscillations, eg in-spin aileron or anti-spin rudder.

b. A decrease in the wing tilt angle will reduce the violence of the oscillations, eg out-spin aileron or down-elevator.

The recovery from this type of spin has been found to be relatively easy, although the shortest recovery times are obtained if recovery is initiated when the nose of the aircraft is falling relative to the horizon.

Conclusions

56. The foregoing paragraphs make it quite clear that the characteristics of the spin and the effect of controls in recovery are specific to type. In general the aerodynamic factors are determined by the geometry of the aircraft and the inertial factors by the distribution of the mass.

57. The aspects of airmanship applicable to the spin man oeuvre are discussed in detail in AP 3456 Vol 5 Part 2, Sec 1, Chap 3, but in the final analysis the only correct recovery procedure is laid down in the Aircrew Manual for the specific aircraft.

TOPIC-4
BASIC PRINCIPLES OF HELICOPTER FLIGHT

ROTOR AERODYNAMICS

Introduction

1. The same basic laws govern the flight of both fixed and rotary wing aircraft and, equally, both types of aircraft share the same fundamental problem; namely that the aircraft is heavier than air and must, therefore, produce an aerodynamic lifting force to overcome the weight of the aircraft before it can leave the ground. In both types of aircraft the lifting force is obtained from the aerodynamic reaction resulting from a flow of air over an aerofoil section. The important difference lies in the relationship of the aerofoil to the fuselage. In the fixed-wing aircraft, the aerofoil is fixed to the fuselage as a wing whilst in the helicopter, the aerofoil has been removed from the fuselage and attached to a centre shaft which, by one means or another, is given a rotational velocity.

2. Helicopters have rotating wings, which are engine-driven in normal flight. The rotor provides both lift and horizontal thrust.

Rotor Systems

3. Helicopters may be single or multi-rotored, each rotor having several blades, usually varying from two to six in number. The rotor blades are attached by a rotor head to a rotor shaft which extends approximately vertically from the fuselage. They form the rotor which turns independently through the rotor shaft, see Fig 1. The axis of rotation is the axis through the main rotor shaft and about which the rotor blades are permitted to rotate. The plane of rotation is at right-angles to the axis of rotation at the head of the main rotor shaft. The rotor blades are connected to the rotor head, at an angle to the plane of rotation, called the pitch angle, see Fig 2.

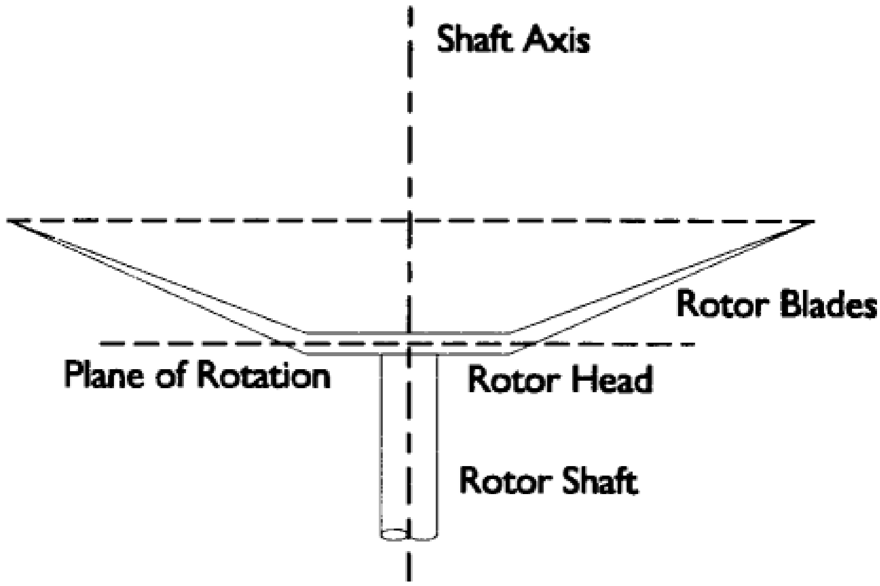


Fig 1 The Rotor Head Arrangement

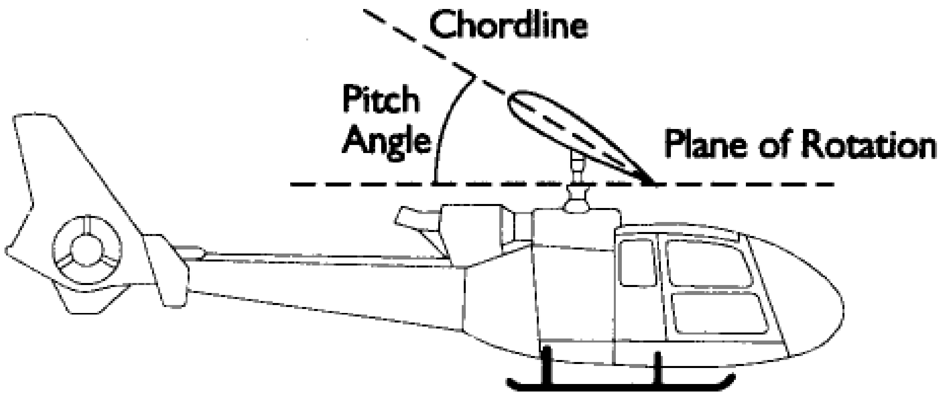


Fig 2 Blade Pitch Angle

4. The axis of rotation, which is perpendicular to the plane of rotation, is a line through the rotor head about which the blades rotate. Under ideal conditions the axis of rotation will coincide with the shaft axis. This however is not usually so since the rotor is tilted under most flight conditions, see Fig 3.

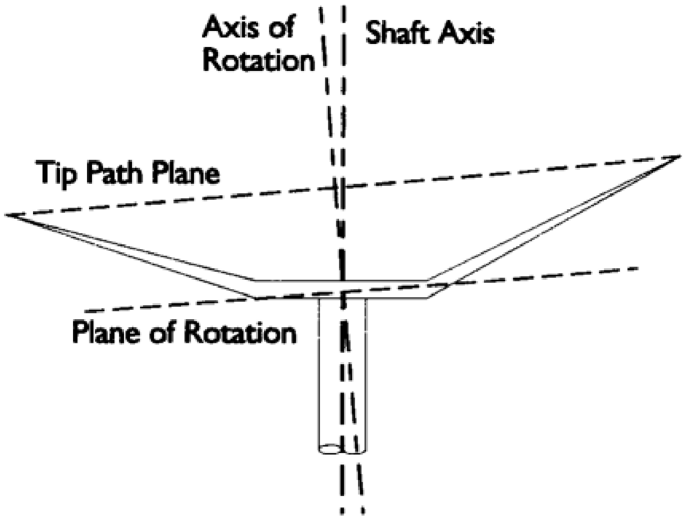


Fig 3 The Rotor Disc Tilted

5. The tip path plane, shown in Fig 3, is the path described by the rotor blades during rotation and is at right angles to the axis of rotation and parallel to the plane of rotation. The area contained within this path is known as the rotor disc.

<u>Forces on an Aerofoil</u>

6. The airflow around the aerofoil gives rise to a pressure distribution. The pressure differences produce a force distribution which can be represented by total reaction, see Fig 4. Total reaction may be resolved into a force perpendicular to the relative airflow (RAF) called lift and a force parallel to the RAF called drag. The angle which the chord line makes with the RAF is the angle of attack.

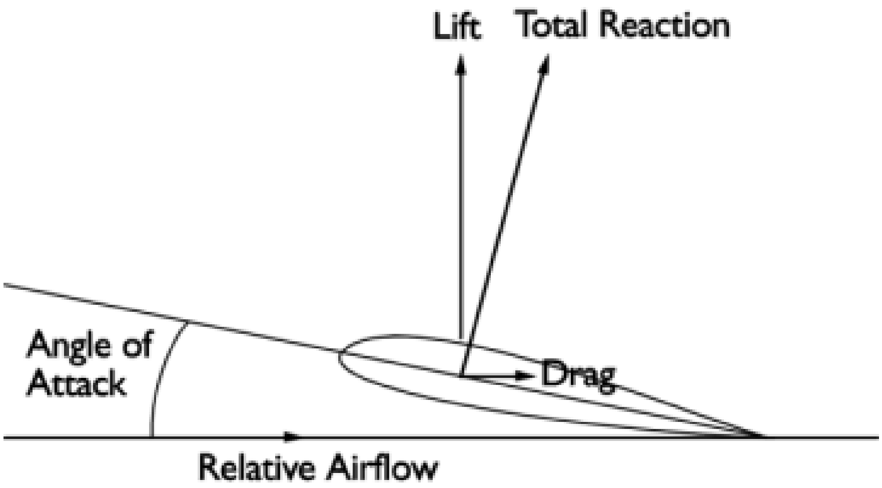


Fig 4 Total Reaction

The magnitude of lift is given by $\mathrm{LIFT} = C_L \times \frac{1}{2} \rho V^2 S$

where ρ = Air density

V = Velocity

S = Plan area of aerofoil

C_L = Coefficient of lift

The magnitude of drag is given by $\mathrm{DRAG} = C_D \times \frac{1}{2} \rho V^2 S$

where C_D = Coefficient of drag.

Blade Design

7. The design requirements of a rotor blade are complicated:

a. The combined area of the blades is small compared to the wings of an aeroplane of similar weight, so high maximum C_L is needed.

b. Power to weight ratio problems can be minimized by use of blades having a good lift to drag ratio.

c. The pitch angle of a blade is held by a control arm and a large pitching moment caused by movement of the centre of pressure would cause excessive stress in this component. A symmetrical aerofoil has a very small pitching moment and is also suitable for relatively high blade tip speeds.

d. Torsional stiffness is required so that pitching moment changes are minimized. A typical blade has an extruded alloy D spar leading edge with a fabricated trailing edge. It is symmetrical, with a thickness ratio of about 1:7 and is rectangular in plan, see Fig 5. Later designs of blade incorporate torsional stiffness, opposing pitching moments, and aerodynamic and planform balancing to allow cambered and high speed sections to be used to improve the overall performance of the blades.

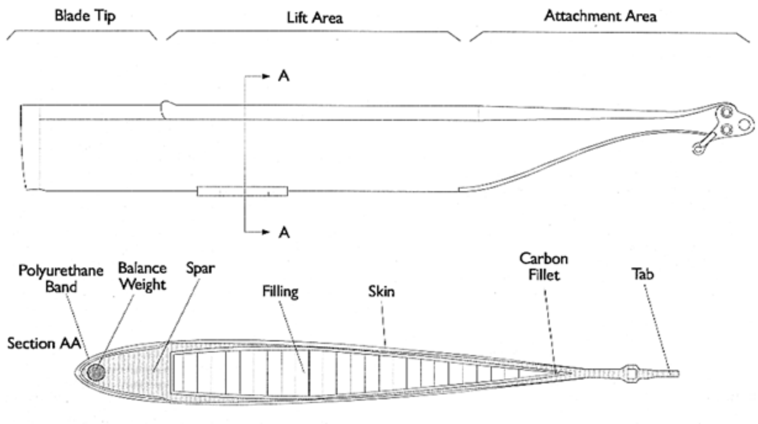


Fig 5 Typical Rotor Blade Section

Relative Flow

8. If a rotor blade is moved horizontally through a column of air, the effect will be to displace some of the air downwards. If a number of rotor blades are travelling along the same path in rapid succession then the column of air will eventually become a column of descending air. This downward motion of air is known as induced flow (IF), see Fig 6. The direction of the airflow relative to the blade (RAF) is the resultant of the blade's horizontal travel through the air and the induced flow, see Fig 7. The angle between the Relative air Flow and the Chord line is the angle of attack.

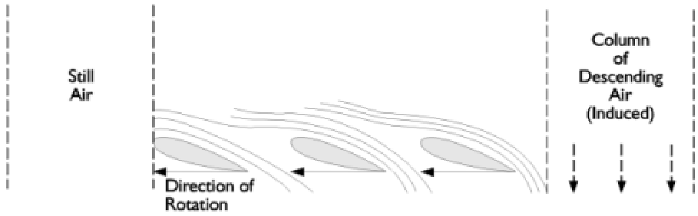


Fig 6 Induced Airflow

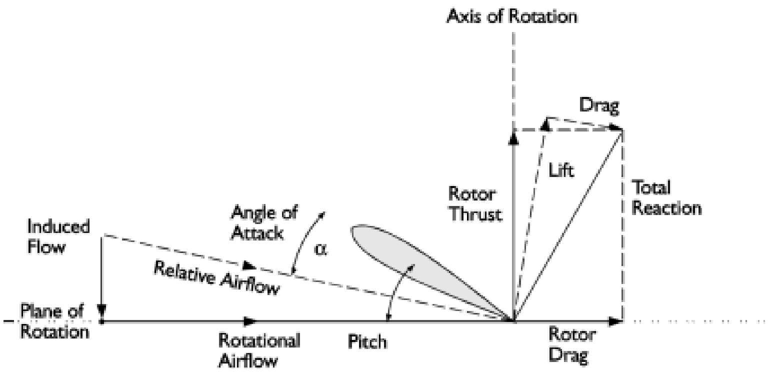


Fig 7 Forces Acting on a Rotor Blade

Lift and Drag

9. The Total Reaction is the vector resultant of lift, which is produced by the relative air flow passing over the blade at an angle of attack, and drag, which is perpendicular to the lift, or parallel to the RAF. The Total Reaction may be split into components; the Rotor Thrust acting along the axis of rotation, and the Rotor Drag acting parallel to the plane of rotation.

Total Rotor Thrust

10. The rotor thrusts of each blade are added together and make up the total rotor thrust. The total rotor thrust is defined as the sum of all the blade rotor thrusts and acts along the axis of rotation through the rotor head, see Fig 8.

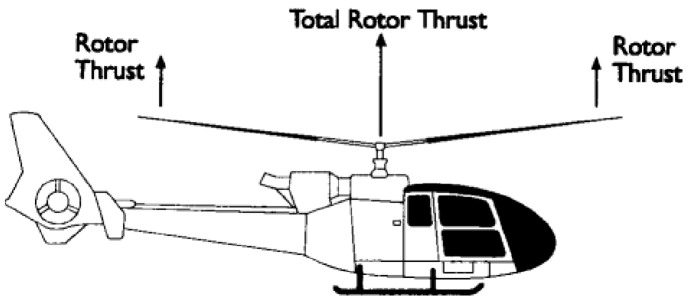


Fig 8 Total Rotor Thrust

Washout

11. The rotational velocity of each part of a rotor blade varies with its radius from the rotor head; the blade tip will always experience a greater velocity of airflow than the root. Lift, and hence rotor thrust, is proportional to V^2 and will be much greater at the blade tip than at the root - an unequal distribution of lift which would cause large bending stresses in the rotor blade. 'Washout' is a designed twist in the blade which reduces blade pitch angle from root to tip giving a more uniform distribution of lift - see Fig 9. The angle of attack, and hence rotor thrust, is decreased with the pitch angle at the tip.

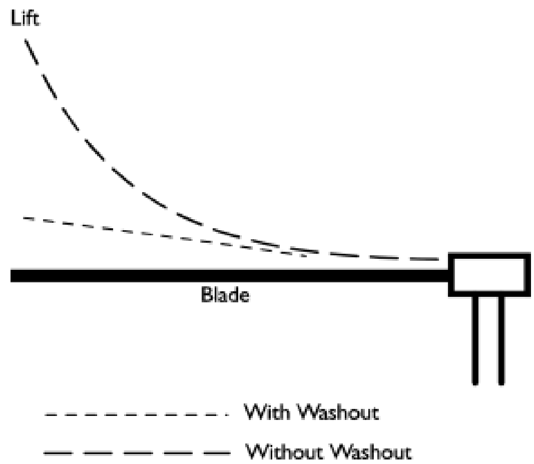


Fig 9 Lift Distribution with Washout

CONTROL

Introduction

12. For various stages of flight the total rotor thrust requirements will change. Although rotor rpm (Nr), and hence rotational velocity, can be changed, the reaction time is slow and the range of values is small. The other controllable variable is pitch angle; a change in pitch angle will cause a change in angle of attack and, therefore, total rotor thrust.

Collective Pitch Changes

13. The pitch angle of a rotor blade is changed by turning it about a sleeve and spindle bearing on its feathering hinge by means of a pitch operating arm connected to a rotating swash plate. The rotating plate may be raised and lowered or have its angle changed by a non rotating swash plate below, which is connected to the collective pitch lever and cyclic control stick in the cockpit by rods which are usually hydraulically assisted, see Fig 10.

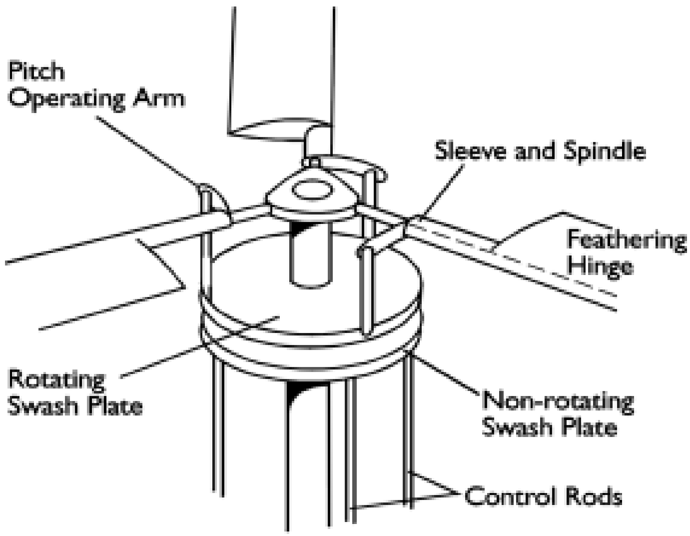


Fig 10 Rotor-Head Detail

The pitch angle is thus increased or decreased collectively by the pilot raising or lowering the collective pitch lever or changed cyclically by movement of the cyclic control stick.

Control of Rotor RPM (Nr)

14. Changes in total rotor thrust will produce corresponding changes in rotor drag. Engine power must, therefore, be controlled to maintain Nr when altering total rotor thrust.

15. Most helicopters have automatic devices to sense the slightest variation in rotor speed and to compensate by altering the fuel supply to the engine to maintain constant Nr. Such control is usually provided by a fuel computer or a hydro-mechanical governor.

Flapping

16. Flapping is the angular movement of the blade above and below the plane of the hub. Flapping relieves bending stresses at the root of the blade which might otherwise be caused by cyclic and collective pitch changes or changes in the speed and direction of the airflow relative to the disc. In a rigid rotor system bending stresses are absorbed by designed deformation of the rotor/hub combination. In an articulated rotor, bending stresses are avoided by allowing the blade to flap about the flapping hinge, see Fig 11.

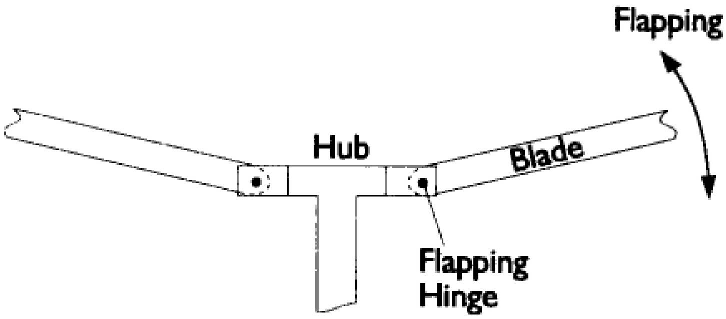


Fig 11 Flapping Hinge

Coning

17. Rotor thrust will cause the blades to rise about the flapping hinges until they reach a position where their upward movement is balanced by the outward force of centrifugal reaction being produced by the rotation of the blades, see Fig 12. In normal operation the blades are said to be coned upwards, the coning angle being measured between the spanwise length of the blade and the blades tip path plane. The coning angle will vary with combinations of rotor thrust and Nr, see Fig 12. If rotor thrust is increased and Nr remains constant, the blades cone up. If Nr is reduced, centrifugal force decreases and if rotor thrust remains constant, the blades again cone up. The weight of the blade will also have some effect but for any given helicopter this will be constant.

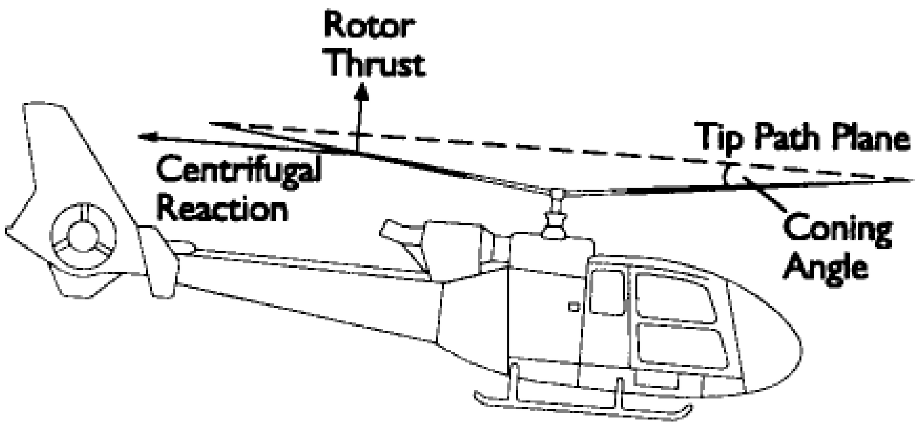


Fig 12 Centrifugal Reaction

Limits of Rotor RPM

18. Because the area of the rotor disc reduces as the coning angle increases the coning angle must never be allowed to become too big. As centrifugal force gives a measure of control of the coning angle through Nr, providing the Nr is kept above a laid down minimum, the coning angle will always be within safe operating limits. There will also be an upper limit to Nr due to transmission considerations and blade root loading stresses. Compressibility, due to high blade tip speeds, is also a limiting factor. Nr limits are to be found in the appropriate Aircrew Manual.
Overtorqueing

19. Overtorqueing can be avoided by careful monitoring of the torque gauge and careful use of the helicopter controls. The condition is described in Vol 5 Part 2 Section 3 Chapter 1.

Overpitching

20. Overpitching is a dangerous condition reached following the application of pitch to the rotor blades without sufficient engine power to compensate for the extra rotor drag. The condition is described fully in Vol 5 Part 2 Section 3 Chapter 1.

HOVERING

Take-Off and Climb to a Free Air Hover

1. To lift a helicopter off the ground, a force must be produced greater than the weight which acts vertically downwards through the aircraft's centre of gravity (CG). On the ground with minimum pitch set, the total Rotor Thrust is small, and on some aircraft can even be negative, and the aircraft remains on the ground. As the collective lever is raised blade pitch and the angle of attack are increased and the Total Rotor Thrust becomes equal to AUW and the helicopter is resting only lightly on the ground. A further increase in angle of attack causes Total Rotor Thrust to exceed the AUW and the helicopter accelerates vertically (in still air conditions), Fig 1.

2. As the Rate of Climb (ROC) increases there is a relative airflow down through the rotor. This adds to and increases the induced airflow. The Angle of Attack and Total Rotor Thrust are automatically reduced by the increased IF and the acceleration decreases until a steady ROC is achieved with TRT = AUW, see Fig 2.

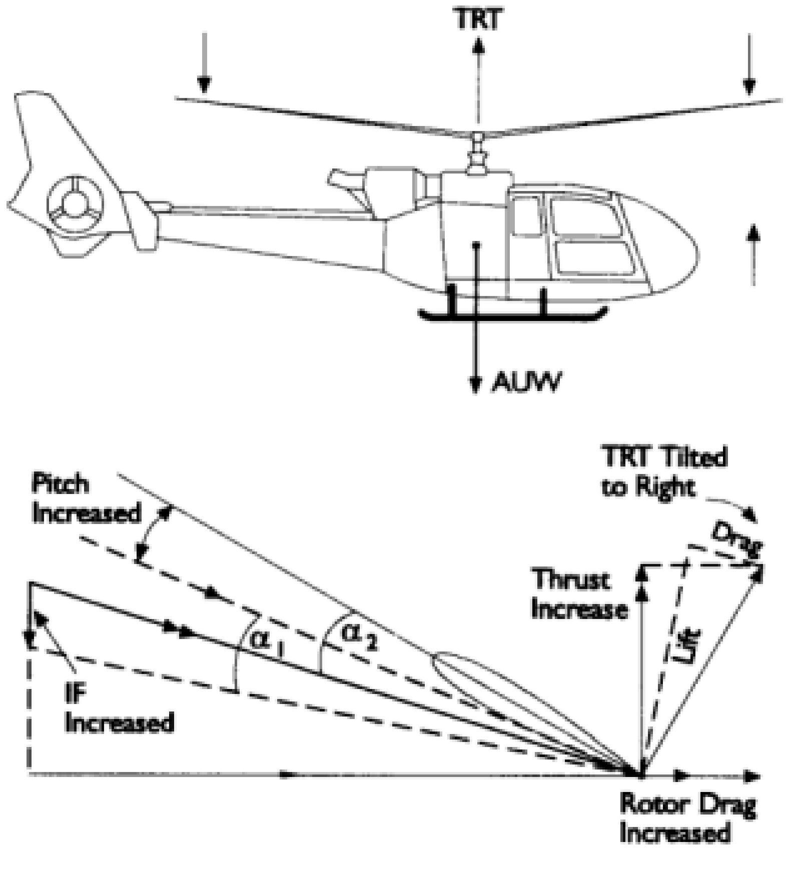


Fig 1 Forces in the Take-off and Climb

3. In the climb the Total Reaction Vector is tilted away from the axis of rotation because the direction of the RAF has changed. Rotor drag is increased and more power is required to maintain Nr.

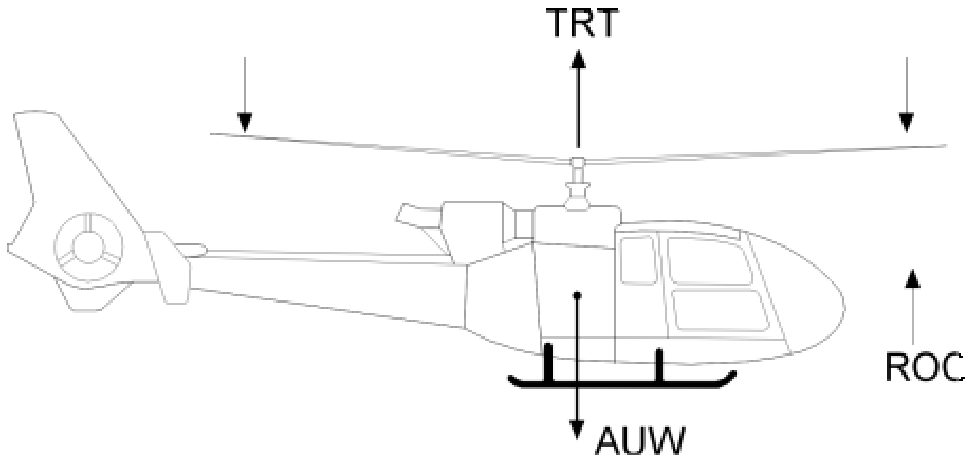


Fig 2 Steady Rate of Climb

4. To stop the climb, collective pitch and angle of attack are reduced and the TRT is now less than AUW. The helicopter's ROC decreases, IF reduces, angle of attack re-increases and TRT increases until a steady hover is achieved with TRT equal to AUW. The helicopter is now said to be in a Free Air Hover.

Vertical Descent

5. At low rates of descent the sequence is the reverse of the vertical climb, that is, due to downward movement, IF will be opposed and angle of attack will increase, see Fig 3. At higher rates of descent airflow is more complex and is discussed in detail in chapter 5, paras 4 to 10.

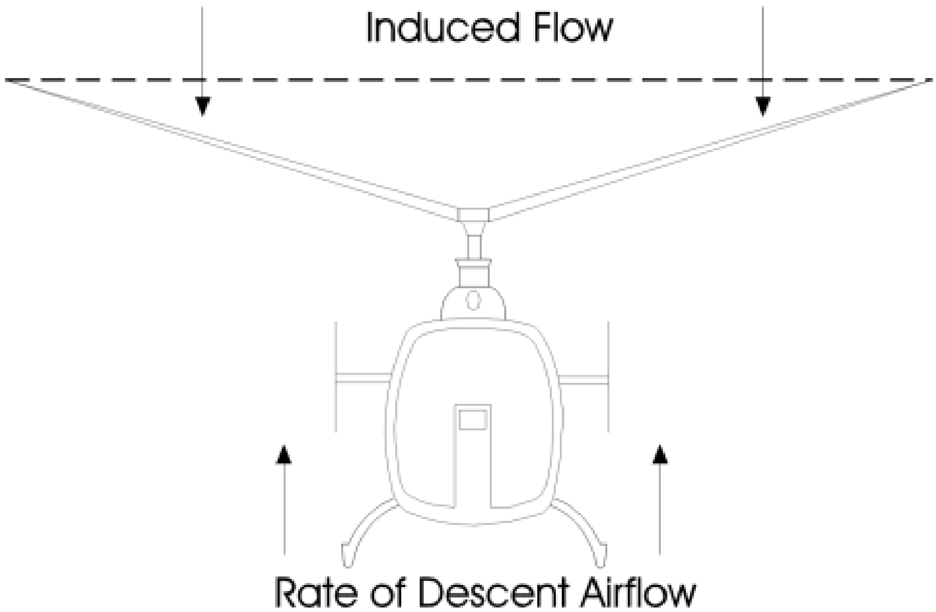


Fig 3 Vertical Descent

6. When climbing or descending there will be some parasite drag from the fuselage but the amount is small since a ROC or ROD of 1200ft/min is barely 12Kt.

Ground Effect

7. In a free air hover the airflow through the rotor disc begins at zero velocity some distance above and accelerates through the disc and into the air below. There is little resistance to the downward movement of air. If the helicopter is hovered close to the ground the downwash meets the ground, is opposed, and escapes horizontally. A divergent duct is produced causing an increase in pressure, see Fig 4. The increased pressure of the air beneath the helicopter opposes and reduces the IF so that angle of attack and hence TRT are increased for a given pitch setting, see Fig 5. In order to remain at a constant height the collective pitch must be reduced, to reduce the angle of attack and keep the TRT equal to AUW see Fig 6. The TR will have moved closer to the axis of rotation producing a reduction in rotor drag in power required to hover is Ground Effect. Helicopters are said to hover Inside Ground Effect (IGE) or, when in free air hover, Outside Ground Effect (OGE).

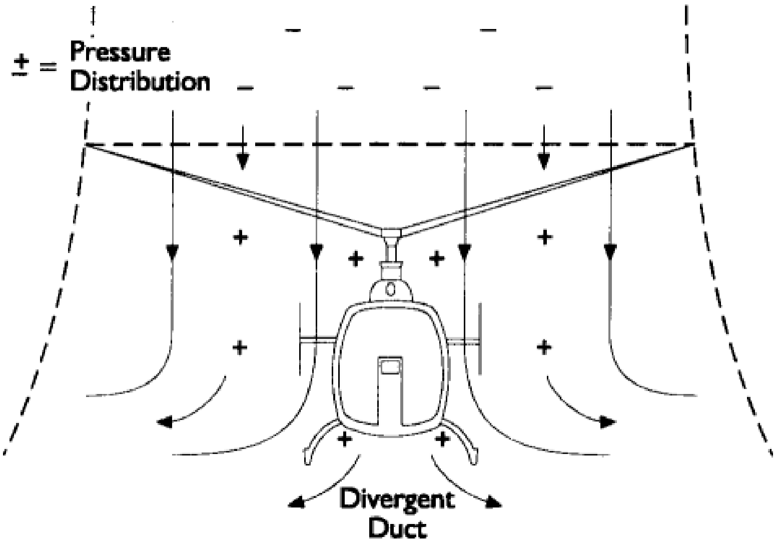


Fig 4 Hover in Ground Effect

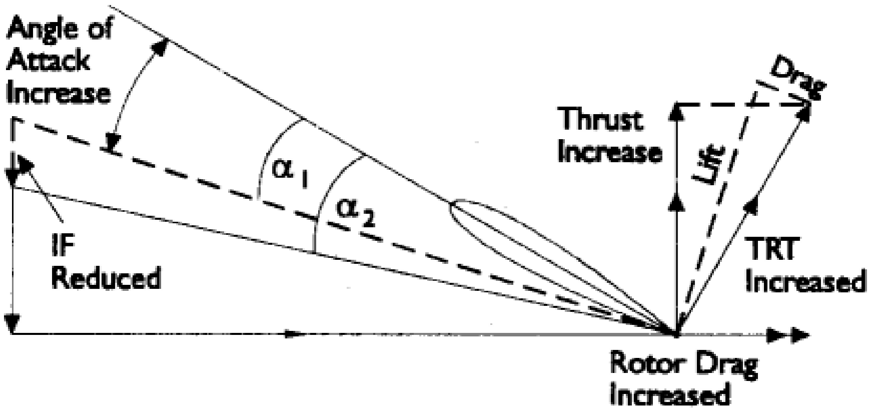


Fig 5 Angle of Attack and Total Rotor Thrust Increase

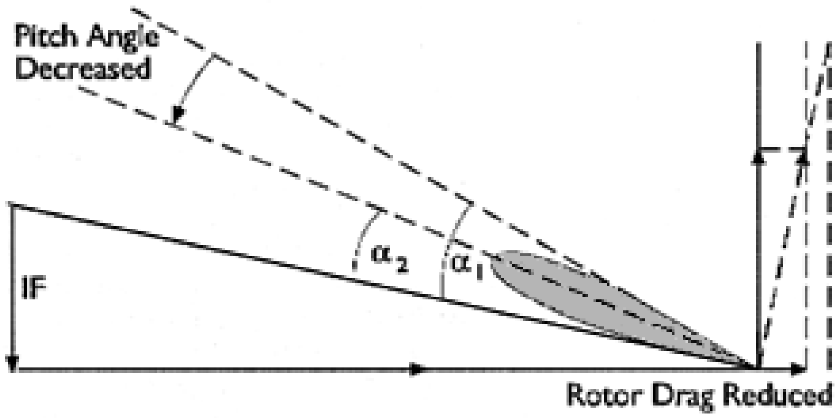


Fig 6 Collective Pitch Decreasing

8. **Factors affecting Ground Effect.** Ground effect is affected by the following factors:

a. **Height**. The reduction in IF is greater when the rotor is close to the ground. Ground effect reduces with increase in height until it is negligible above 2/3 rotor diameter distance from the ground.

b. **Slope**. On sloping ground much of the air flows downhill and there is reduced ground effect because there is no development of a divergent duct.

c. **Nature of the Ground**. Rough ground will tend to disrupt the air flow preventing a divergent duct from being formed.

d. **Wind**. The ground effect is displaced downwind reducing ground effect. However, as wind speed increases IF is reduced by translational lift which is described in chapter 3.

Recirculation

9. Whenever a helicopter is hovering near the ground some of the air passing through the disc is recirculated and it would appear that the recirculated air increases speed as it passes through the disc a second time, see Fig 7. This local increase in IF near the tips gives rise to a loss of rotor thrust. Some recirculation is always taking place, but over a flat, even surface the loss of rotor thrust due to recirculation is more than compensated for by ground effect. If a helicopter is hovering over tall grass or similar types of surface the loss of lift due to recirculation will increase and, in some cases the effect will be greater than ground effect and more power would be required to hover near the ground than in free air; see Fig 8 heavy helicopters can experience this phenomenon hovering over water.

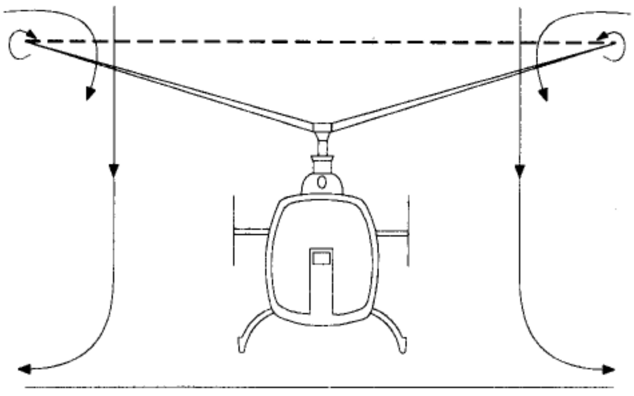


Fig 7 Increased IF Near the Blade Tips

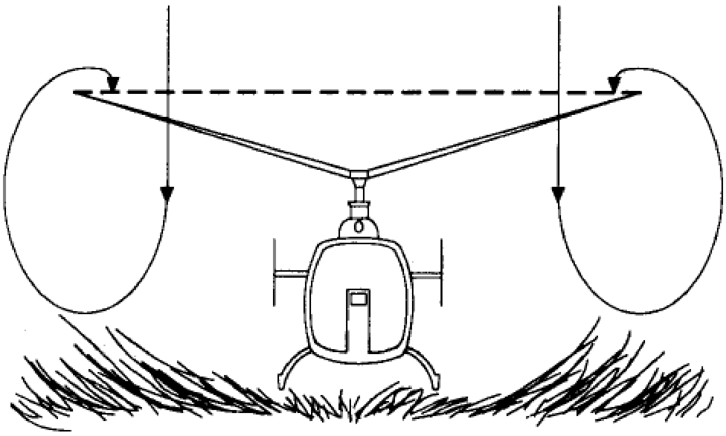


Fig 8 Increased Recirculation due to Long Grass

10. Recirculation will increase when any obstruction on the surface or near where the helicopter is hovering prevents the air from flowing evenly away. Hovering close to a building, wire link fencing or cliff face may cause severe recirculation, see Fig 9.

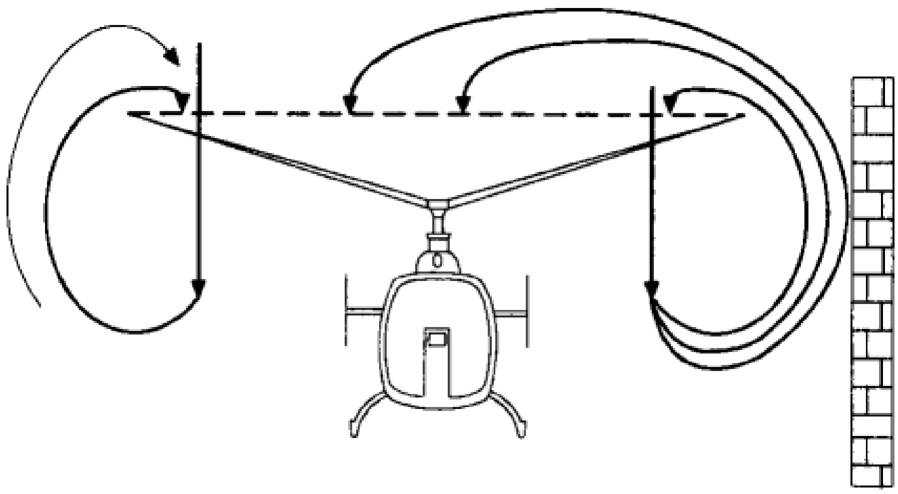


Fig 9 Recirculation Near a Building

HORIZONTAL MOVEMENT

Cyclic Pitch Changes

11. For a helicopter to move horizontally the rotor disc must be tilted so that the total rotor thrust vector has a component in the direction required, see Fig 10. To enable the rotor disc to tilt the swash plates are tilted so that the pitch angle on one side of the disc increases causing the blade to rise, while the pitch angle on the other side of the disc must, at the same time, be decreased by the same amount, causing the blade to descend. The tilting of the swash plates is controlled by the pilot moving the cyclic stick.

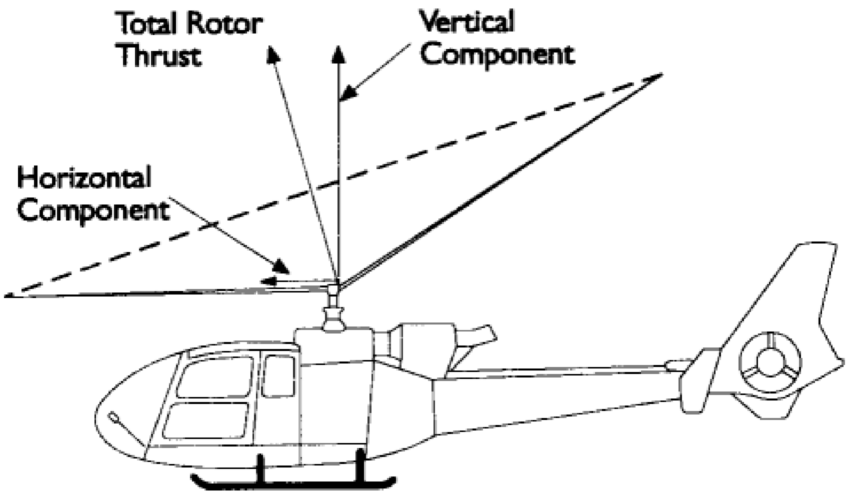


Fig 10 Producing Horizontal Movement

Flapping to Equality

12. A cyclic pitch change does not markedly alter the magnitude of total rotor thrust but simply changes the disc attitude. This is achieved by the blades flapping to equality of rotor thrust. If a blade in a hover has an angle of attack, a, see Fig 11a, a cyclic stick movement will decrease the blade pitch and, assuming that initially the direction of the RAF remains unchanged, the reduction in pitch will reduce both the blade's angle of attack (α) and rotor thrust, see Fig 11b. The blade cannot maintain horizontal flight and will now begin to flap down, causing an automatic increase in the blade's angle of attack. When the angle returns to a, the blade thrust will return to its original value and the blade will continue to follow the new path required to keep the angle of attack constant, see Fig 11c. Thus cyclic pitch will alter the plane in which the blade is rotating, but the angle of attack remains unchanged. The reverse takes place when a blade experiences an increase in cyclic pitch. It should be remembered that when a cyclic pitch change is made, the blades continuously flap to equality as they travel through 360° of movement.

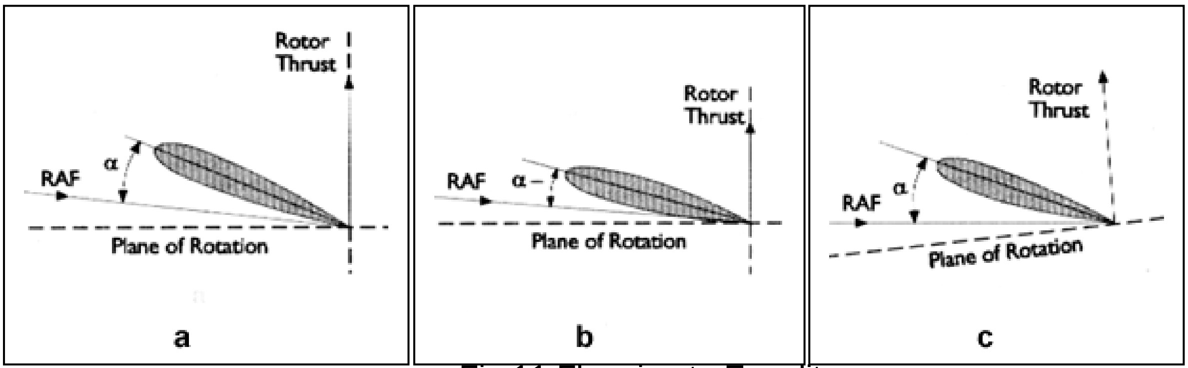


Fig 11 Flapping to Equality

Control Orbit

13. In its simplest form of operation, movement of the cyclic stick causes a flat plate, or non rotational swash plate, mounted centrally on the rotor shaft to tilt, the direction being controlled by the direction in which the cyclic stick is moved. Rods of equal length, known as pitch operating arms (POA) or pitch change rods connect the swash plate to the rotor blades. When the swash plate is tilted the pitch operating arms move up or down, increasing or decreasing the pitch on the blades, see Fig 12. The amount by which the pitch changes, and which blades are affected, depends on the amount and direction in which the swash plate is tilted. The swash plate can be more accurately described as a control orbit because it represents the plane in which the pitch operating arms are rotating.

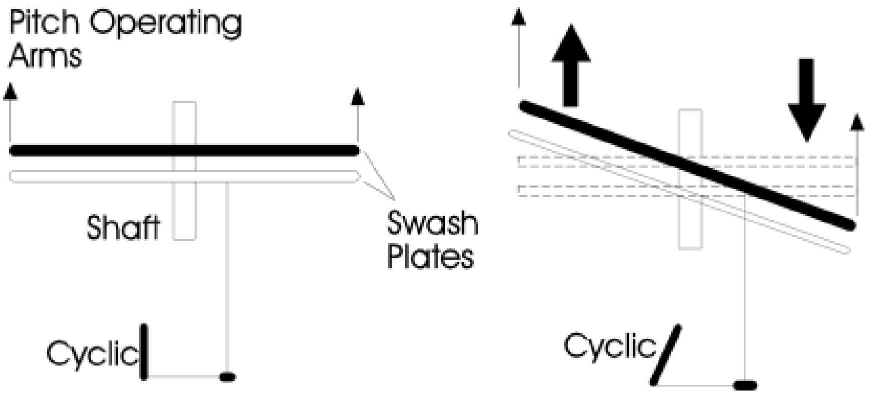


Fig 12 Control Orbit

Pitch Operating Arm Movement

14. Now consider the effect of the movement of the POA when the control orbit has been tilted 2 (assuming that the control orbit tilts in the same direction as the stick is being moved), see Fig 13a. A Plan view, Fig 13b, shows clearly the amount by which the control orbit has been tilted at four positions, A, B, C and D. If the movement of the POA through 360° of travel is plotted on a simple graph, the result would be as shown in Fig 14. The rate at which the POA is moving up and down is not uniform. This can be shown more clearly as a comparison is made between the control orbit in plan view and the control orbit inside elevation; and noting how much movement takes place in each 30° of travel over a range of 90°, see Fig 15.

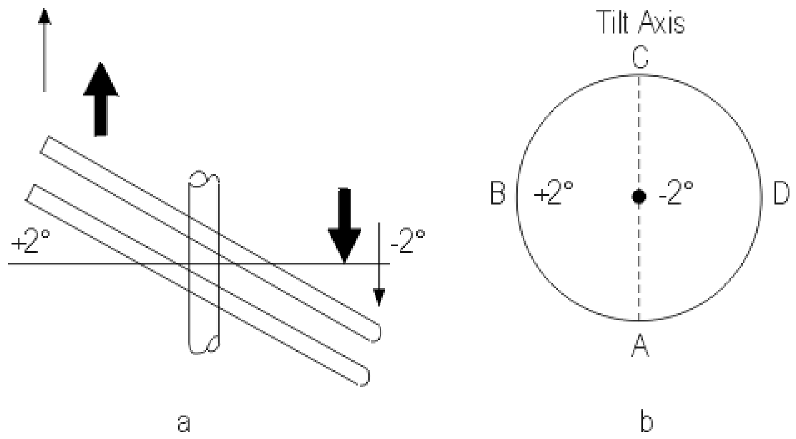


Fig 13 Pitch Operating Arm Movement

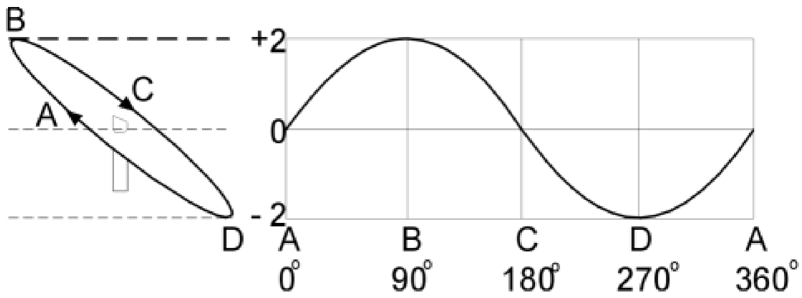


Fig 14 Movement of Pitch Operating Arms Through 360°

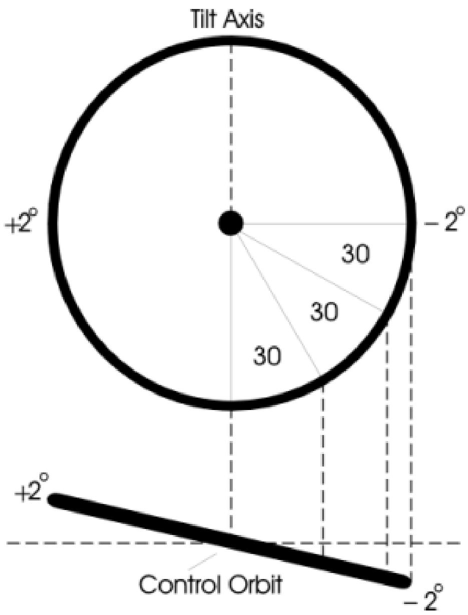


Fig 15 Rate of Movement of Pitch Operating Arms

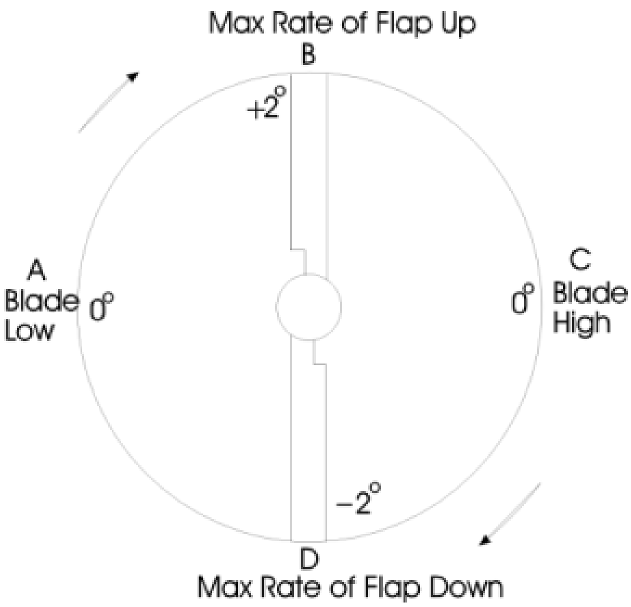


Fig 16 Relationship of Blade Position to Control Orbit Position

15. **Resultant Change in Disc Attitude.** In order to determine the resultant change in disc attitude, the movement of each blade is followed through four points A,B,C and D during 360° of movement. The control orbit has been tilted by the cyclic stick and hence the pitch operating arms move so that a maximum pitch of +2° is applied at point B; a minimum pitch, -2°, at point D, and zero pitch at points A and C, see Fig 16. As the blade moves clockwise from A it will experience an increase in pitch and the blade will begin to flap up. The rate of flapping will vary with the amount of pitch change so the blade will be experiencing its greatest rate of flapping as it passes B, the point of maximum pitch change. In its next 90° of travel the pitch is returned from +2° to 0 at point C and the rate at which the blade is flapping will slowly reduce to reach zero at point C. Flapping up, however, will have continued past B and the blade will be at its highest point at C. The exact reverse will take place after C, resulting in the blade being at its lowest at point A. The disc will now be tilted along the axis B-D. This is 90° out of phase with the maximum and minimum pitch positions, see Fig 17.

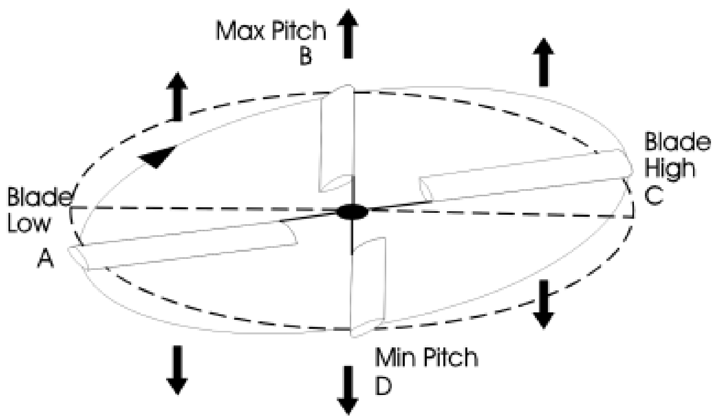


Fig 17 High and Low Blade Position

Phase Lag

16. When cyclic pitch is applied the blades will automatically flap to equality and, in so doing, the disc attitude will change, the blade reaching its highest and lowest positions 90° later than the point where it experiences the maximum increase and decrease of cyclic pitch. The variation between the tilt of the control orbit in producing this cyclic pitch change and subsequent tilt of the rotor is known as phase lag. Phase lag will also occur when the blades experience a cyclic variation resulting from a change in speed or direction of the RAF, as occurs in horizontal flight.

Advance Angle

17. Phase lag, if uncorrected, would have the effect that movement of the cyclic stick would cause the rotor to tilt in a direction 90° out of phase with the direction in which the cyclic stick is moved. Thus moving the cyclic stick forward would have the effect of moving the helicopter sideways. This undesirable feature is overcome by arranging for the blade to receive the maximum alteration in cyclic pitch change 90° before the blade is over the highest and lowest points on the control orbit, see Fig 18. The angular distance that the

POA is positioned on the control orbit in advance of the blade to which it relates is known as the advance angle.

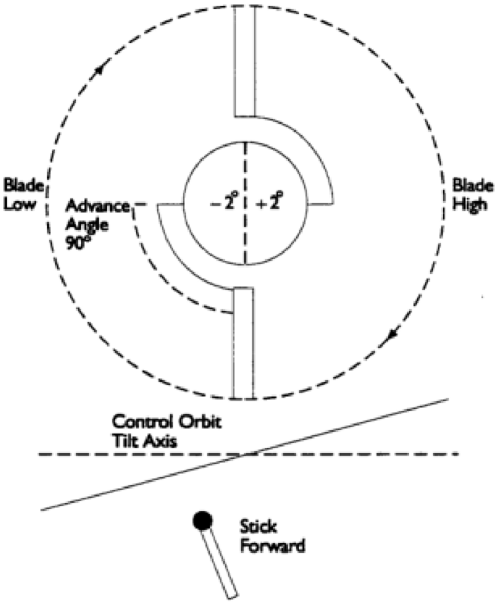


Fig 18 90 degree Advance Angle

When the control orbit tilts to follow the stick, to compensate fully for phase lag, the advance angle would have to be 90°. If the control orbit is 45° out of phase with stick movement, then the advance angle needs to be only 45° to make full compensation for phase lag, see Fig 19.

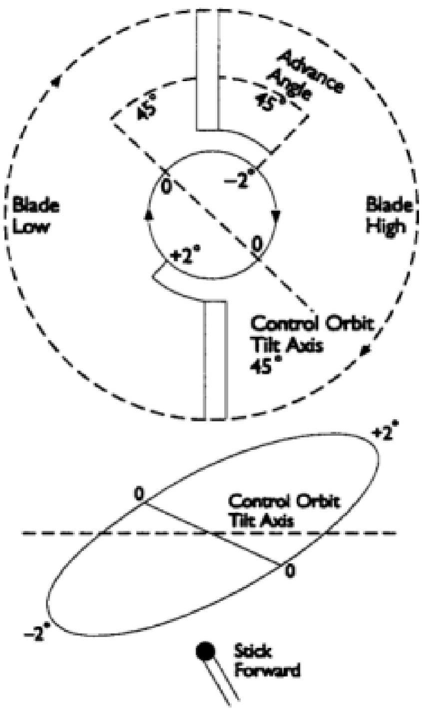


Fig 19 45 degree Advance Angle

Dragging

18. Dragging is the freedom given to each blade to allow it to move in the plane of rotation independently of the other blades. To avoid bending stresses at the root, the blade is allowed to lead or lag about a dragging hinge, see Fig 20, but rate of movement is restricted by some form of drag damper to avoid undesirable oscillations. Dragging is caused by:

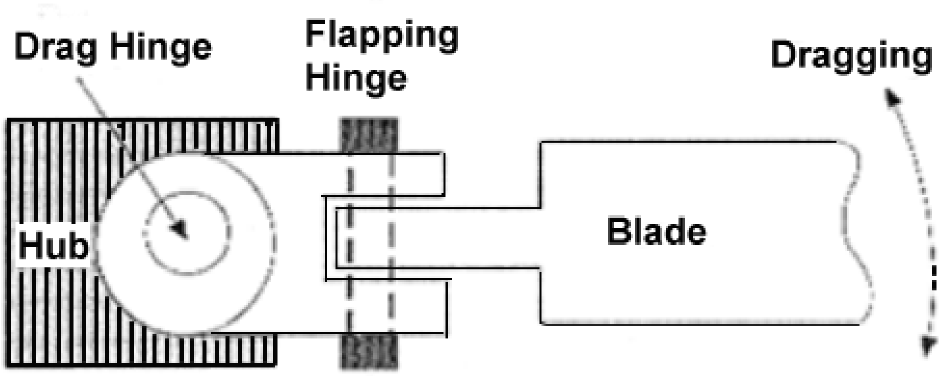


Fig 20 Dragging Hinge

a. **Periodic Drag Changes**. When the helicopter moves horizontally, the blade's angle of attack is continually changing during each complete revolution to provide symmetry of rotor thrust. The variation in angle of attack results in variation in rotor drag and consequently the blade will lead or lag about the dragging hinge.

b. **Conservation of Angular Momentum**. If a helicopter is stationary on the ground in still air conditions, rotor running, the radius of the blade's CG relative to the axis of rotation/shaft axis will be constant. If the cyclic stick is now moved the blades will flap to produce a change in disc attitude. The axis or rotation will no longer be coincident with the shaft axis and this results in a continual change of the CG radius relative to the shaft axis through 360° of travel. The radius variation will cause the blades to speed up or slow down depending on whether the radius is reducing or increasing, see Fig 21.

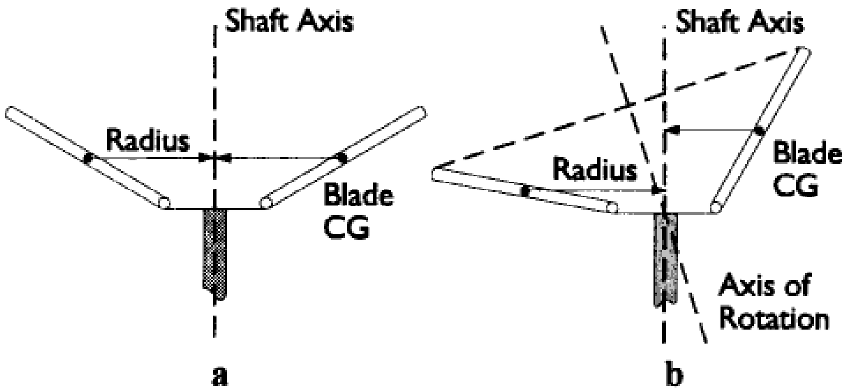


Fig 21 Variation in Radius of Blade CG Resulting from Flapping

c. **Hooke's Joint Effect.** Hooke's joint effect is the movement of a blade to reposition itself relative to the other blades when cyclic stick is applied; its effect is very similar to the movement of the blades CG relative to the hub. If a rotor is hovering in still air, see Fig 22a and b, when viewed from above the shaft axis the blades A,B,C and D appear equally spaced relative to the shaft axis. When a cyclic tilt of the disc occurs, Fig 22c and d, the cone axis will have tilted but, if still viewed from the shaft axis, which has not tilted, blade A will appear to have increased its radius and blade C decreased its radius. Blades B and D must maintain position as in Fig 22c in order to achieve their true positions on the cone. It follows therefore that they must move in the plane of rotation to position themselves as in Fig 22d.

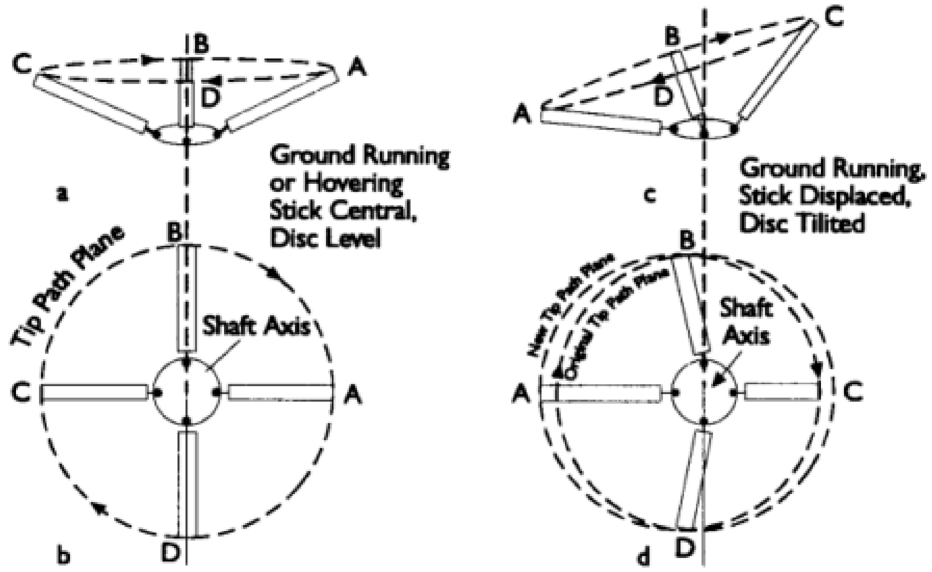


Fig 22 Hooke's Joint Effect

TOPIC – 5 : NAVIGATION

THE EARTH AND ITS REPRESENTATION

The Earth, Distance, and Direction

THE EARTH

The Form of the Earth

1. For most navigational purposes the Earth is assumed to be a perfect sphere,although in reality it is not. For many centuries man has been concerned about the shape of the Earth; the early Greeks in their speculation and theorizing ranged from the flat disc to the sphere, and even cylindrical and rectangular Earths have been propounded.

2. The basic shape of the Earth is almost spherical, being slight flattened at the poles. This shape is more properly termed an oblate spheroid, which is the figure generated by the revolution of an ellipse about its minor axis. Because of this flattening, the Earth's polar diameter is approximately 27 statute miles shorter than its average equatorial diameter.

3. The ratio between this difference and the equatorial diameter is termed the compression of the Earth, and indicates the amount of flattening. This ratio is approximately 1/300 but geodetic information obtained from satellite measurements indicates that the Earth is very slightly "pear-shaped", the greater mass being in the southern hemisphere.

4. **The Poles**. The extremities of the diameter about which the Earth rotates are called poles. In Fig 1a these are represented by P and P1.

5. **East and West**. East is defined as the direction in which the Earth is rotating. This direction, anti-clockwise to an observer look down on the pole P, is shown by the arrows in Fig 1a and b. West is the direction opposite to East.

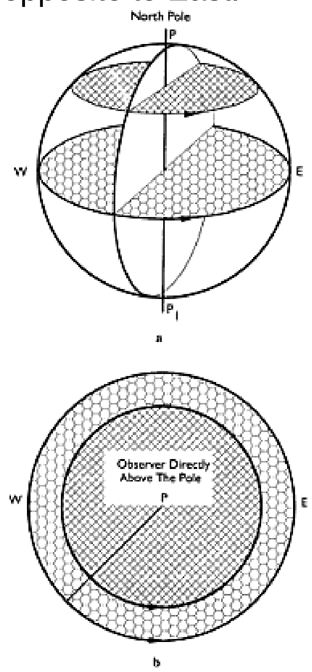


Fig 1 Earth References

6. **North and South**. The two poles are distinguished arbitrarily; the North pole (P in Fig 1a) is said to be the pole which lies to the left of an observer facing East. North is therefore that direction in which an observer would have to move in order to reach the North pole; it is at right angles to the East-West direction. The other pole (P1 in Fig 1a) is known as the South pole. The directions, East, West, North and South are known as the cardinal directions.

Lines Drawn on the Earth

7. The shortest distance between two points is the length of the straight line joining them. It is, however, impossible to draw a straight line on a spherical surface and so all lines drawn on the Earth are curved, some regularly and others irregularly. The regularly curved imaginary lines on the Earth which are of interest to the navigator are described below.

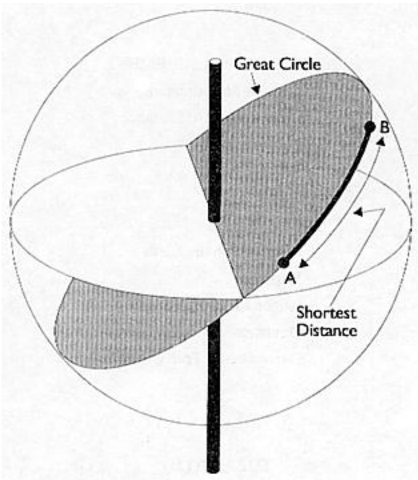


Fig 2 Great Circle

8. **Great circle**. A great circle is a circle on the surface of a sphere whose centre and radius are those of the sphere itself. Because its plane passes through the centre of the sphere, the resulting section is the largest that can be obtained, hence the name great circle. Only one great circle may be drawn through two places on the surface of a sphere which are not diametrically opposed. The shortest distance between any two points on the surface of a sphere is the smaller arc of the great circle joining them (see Fig 2).

9. **Small Circle**. A small circle is a circle on the surface of a sphere whose centre and radius are not those of the sphere. All circles other than great circles on the surface of a sphere are small circles (see Fig 3).

10. **The Equator**. The Equator is the great circle whose plane is perpendicular to the axis of rotation of the Earth. Every point on the equator is therefore equidistant from both poles. The equator lies in an East-West direction and divides the Earth into northern and southern hemispheres.

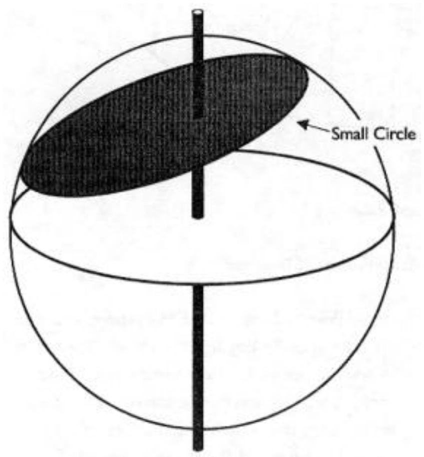


Fig 3 Small Circle

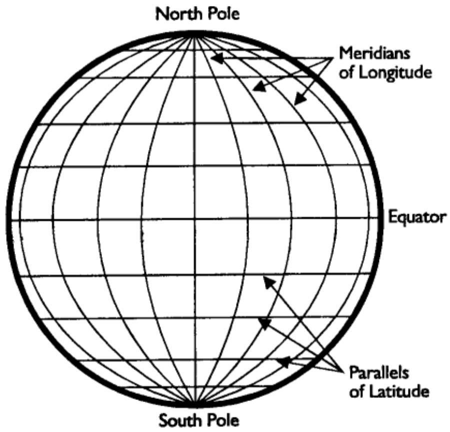


Fig 4 Equator, Meridians and Parallels

11. **Meridians.** Meridians are semi-great circles joining the poles; every great circle joining the poles forms a meridian and its anti-meridian. All meridians indicate North-South directions.

12. **Parallels of Latitude**. Parallels of latitude are small circles on the surface of the Earth whose planes are parallel to the plane of the equator. They therefore lie in an East-West direction (see Fig 4).

13. **Rhumb Line**. A rhumb line is a regularly curved line on the surface of the Earth cutting all meridians at the same angle. Only one such line may be drawn through any two points. Parallels of latitude are rhumb lines as are the meridians and the equator, though the latter two are special cases as they are the only examples of rhumb lines which are also great circles. Thus, when two places are situated elsewhere than on the equator or on the same meridian, the distance measured along the rhumb line joining them is not the shortest distance between them. However, the advantage of the rhumb line is that its direction is constant, therefore the rhumb line between two points may be followed more conveniently than the great circle joining them since the direction of the latter changes continuously with reference to the meridians. The saving in distance effected by flying a great circle rather than a rhumb line increases with latitude but it is appreciable only over great distances, consequently flights of less than 1,000 miles are usually made along the rhumb line. Rhumb lines are convex towards the equator (excepting parallels of latitude, the equator and meridians) and lie nearer the equator than the corresponding great circles (see Fig 5).

Earth Convergence

14. From Fig 5 it can be seen that the meridians are only parallel to one another where they cross the equator, elsewhere the angle of inclination between selected meridians increases towards the poles. This angle of inclination between selected meridians at a particular latitude is known variously as Earth convergence, true convergence, meridian convergence and convergency.

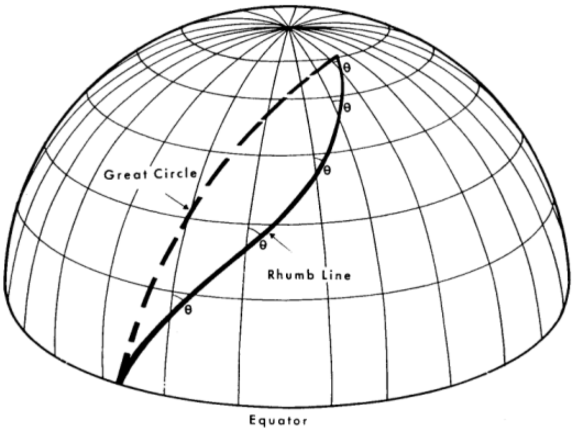


Fig 5 Rhumb Line

UNITS OF MEASUREMENT

Angular Measurement

15. The sexagesimal system of measuring angles is universally employed in navigation. In this system the angle subtended at the centre of a circle by an arc equal to the 360th part of the circumference is called a degree; each degree is subdivided into 60 minutes (') and each minute into 60 seconds ("). Thus the size of any angle may be expressed in terms of degrees, minutes and seconds.

16. In spherical calculations it is frequently convenient to express spherical distances (ie, great circle distances) in terms of angular measurement rather than in linear units. This is possible because of a simple relationship between the radius, arc, and angle at the centre of a circle. Thus the length of the arc of a great circle on the Earth might be expressed as 10° 38'; this would convey little unless there were some ready means of converting angular units to linear units. This difficulty of converting from angular to linear units has been overcome by the definition of the standard unit of linear measurement on the Earth, the nautical mile.

Measurement of Distance

17. Assuming the Earth to be a true sphere, a nautical mile is defined as the length of the arc of a great circle which subtends an angle of one minute at the centre of the Earth. Thus the number of nautical miles in the arc of any great circle equals the number of minutes subtended by that arc at the centre of the Earth. The conversion of an angular measurement of spherical distance to linear units requires only the reduction of the angle to minutes of arc; the number of minutes is equal to the spherical distance in nautical miles.

18. In Fig 6a, if AB, the arc of a great circle, subtends an angle at the Earth's centre of 40°20', AB is said to be 40° 20' in length. Forty degrees 20 minutes is equivalent to 2,420 minutes of arc which is equal to a length of 2,420 nautical miles.

19. Because of the Earth's uneven shape the actual length of the nautical mile is not constant, but varies with latitude from 6,046 feet at the equator to approximately 6,108 feet at the poles. A more accurate definition of the nautical mile than that given in para 17 is that it is the length of the arc on the Earth's surface that subtends an angle of one minute at its own centre of curvature. In Fig 6b the arc of BC is on a comparatively "flat" part of the spheroid and the distance to the centre of curvature is relatively long (AB or AC); therefore an angle φ is subtended by a comparatively long arc BC. The arc YZ is at a comparatively curved part of the spheroid, the distance to the centre of curvature (XY or XZ) is shorter and the angle φ is subtended by a shorter arc length. However, for the purpose of navigation a fixed unit of measurement is helpful. Until 1 March 1971 this was the UK Standard Nautical mile of 6,080 feet. Since that time the International Nautical Mile of 1,852 metres (6,076.1 feet) has been adopted as the standard for air navigation.

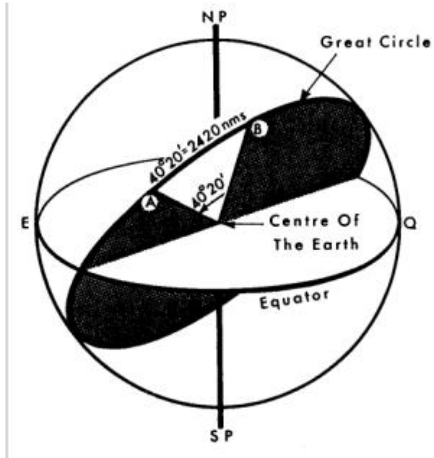


Fig 6a Angular Distance

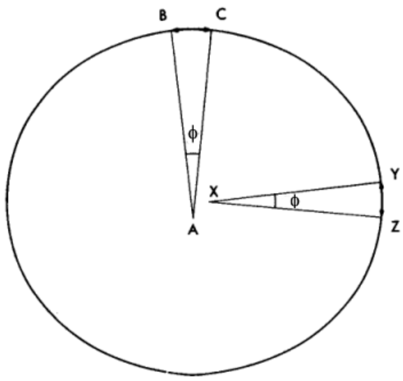


Fig 6b Nautical Mile

20. The other mile unit in common use is the statue mile (so called because its length is determined by law; this is 5,280 feet in length. It is a purely arbitrary unit of measurement and, unlike the nautical mile, is not readily converted into angular measurement terms.

21. **Metric Units**. The kilometer is the SI unit of distance. This unit is the length of 1/10,000th part of the average distance between the equator and either pole; it is equivalent to 3,280 feet.

Speed

22. Speed is the rate of change of position. It is usually expressed in linear units per hour. As there are three main linear units, there are three expressions of speed:

a. Knots, or nautical miles per hour (kt)

b. Miles per hour ie statute miles per hour (mph).

c. Kilometres per hour (km/hr).

DIRECTION

Direction on the Earth

23. In order to fly in a given direction it is necessary to be able to refer to a datum line or fixed direction whose orientation is known or can be determined. The most convenient datum is the meridian through the current position, since it is the North-South line. By convention direction is measured clockwise from North, to the nearest degree, ie from 000° to 360°. It is always expressed as a three-figure group; thus East, which is 90° from North, is written 090°, and West 270°.

24. **True Direction**. Direction measured with reference to True North, the direction of the North geographic pole, is said to be the True direction. True direction has the advantages of being a constant directional reference (ie True direction about a point does not change with time), of being the basis of nearly all maps and charts, and of being directly and continuously output by inertial systems. However, magnetic direction continues to be used as an aircraft heading reference and as the basic direction

25. **Magnetic Direction**. The Earth acts as if it is a huge magnet whose field is strong enough to influence the alignment of a freely suspended magnetic needle anywhere in the world. The poles of this hypothetical magnet are known as North and South magnetic poles and, like those of any magnet, they can be considered to be connected by lines of magnetic force. Although the magnetic and geographic poles are by no means coincident (the respective North poles are separated by approximately 900 n miles), the lines of force throughout the equatorial and temperate regions are roughly parallel to the Earth's meridians. A freely suspended magnetic needle will take up the direction indicated by the Earth's lines of force and thus assume a general North-South direction; the actual direction in which it points, assuming no other influences are acting upon it, is said to be Magnetic North. With such a datum available it is possible to measure magnetic direction. Thus knowing the angle by which the direction of Magnetic North differs from True North at any given point (an angle which is accurately measured on the ground and displayed on plotting charts), it is possible to convert Magnetic direction, which can be measured, into True direction which is required.

Variation

26. The angular difference between the direction of True North and Magnetic North at any given point, and therefore between all True directions and their corresponding Magnetic directions at that point, is called Variation. Variation is measured in degrees and is named East (+) or West (−) according to whether the North-seeking end of a freely-suspended magnetic needle, influenced only by the Earth's field, lies to the East of West of True North at any given point. The algebraic sign given to Variation indicates how it is to be applied to magnetic direction to convert it to True direction. At any point, therefore, the True direction can be determined by measuring Magnetic direction and then applying the local Variation. A useful mnemonic is:

"Variation East, Magnetic least, Variation West, Magnetic best."

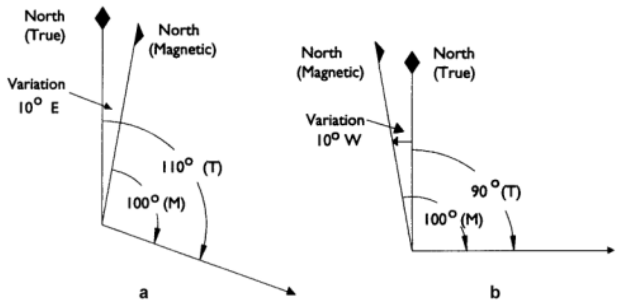


Fig 7 Variation

Direction 100° (M)
Magnetic
Variation 10°E(+)

Direction True 110° (T) **(see Fig 7a)**

Direction 100° (M)
Magnetic
Variation 10°W(−)

Direction True 090° (T) **(see Fig 7b)**

Isogonals

27. Variation is not constant over the Earth's surface but varies from place to place. The change is gradual and follows a moreor less regular pattern. By means of a magnetic survey the variation at numerous points is accurately measured and tabulated. From such a survey it is possible to discover a number of points where variation has the same value. Lines joining these points of equal variation are known as isogonals and these lines are printed on maps and charts.

28. The variation at any given point is not a fixed quantity but is subject to gradual change with the passage of time because the magnetic axis of the Earth is constantly changing. This change, which is indicated in the margin of the chart, is not large but in certain places may amount to as much as one degree in five years. It is important, therefore, that charts indicate the date to which variation values apply, and also the annual change, so that the isogonal values may be updated.

Deviation

29. When a freely-suspended magnetic needle is influenced only by the Earth's magnetic field, the direction it assumes is known as Magnetic North. If such a needle is placed in an aircraft, it is subject to a number of additional magnetic fields created by various electrical circuits and magnetized pieces of metal within the aircraft; consequently its North-seeking end deviates from the direction of magnetic North and indicates a direction known as compass North.

30. The angular difference between the direction of Magnetic North and that of Compass North, and therefore all Magnetic directions and their corresponding Compass directions, is called Deviation. Deviation is measured in degrees and is named East (+) or West (−) according to whether the North-seeking end of a compass needle, under various disturbing influences, lies to the East or West of Magnetic North. The algebraic sign given to deviation indicates how it is to be applied to compass direction to convert it to Magnetic direction.

31. Deviation is not, as might be imagined, a constant value for a given compass; instead it varied with the heading of the aircraft. Nor is the deviation experienced by two different compasses likely to be the same under identical conditions. Thus in order to convert the directions registered by a particular compass to Magnetic directions, a tabulation of the deviations of that compass, found on various headings, is required. Such a tabulation of the deviation, usually in the form of a card, must be provided and placed near the compass to which it applies.

32. The deviation of a compass will change as its position in the aircraft is changed. Deviation will also change, over a period of time, due to changing magnetic fields within the aircraft. Moreover, as the aircraft flies great distances over the Earth, changes occur in deviation because of the Earth's changing magnetic field. It is not sufficient, therefore, to prepare a deviation card and expect it to last indefinitely, the card must be renewed at frequent intervals in order that it may always record the deviation as accurately as possible. A useful mnemonic for the application of deviation is:

"Deviation East, compass least, deviation West, compass best."

Direction Compass 100° (C)
Deviation 4°E(+)

Direction Magnetic 104° (M) (Fig 8a)

Direction Compass 100° (C)
Deviation 4°W(−)

Direction Magnetic 096° (M) (Fig 8b)

Derivation of True Direction

33. It is possible therefore to express a direction given with regard to a particular compass needle as True direction, provided that deviation and variation are known.

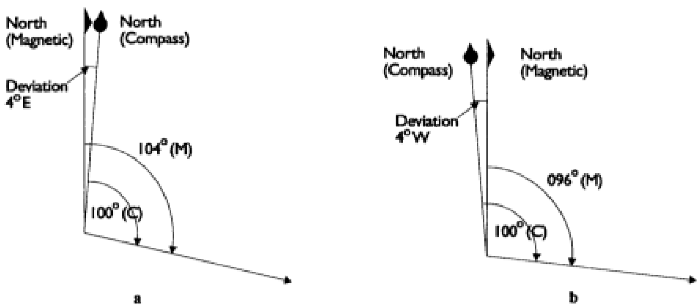


Fig 8 Deviation

To avoid the complications arising from the changing values of variation and deviation during flight, plotting is usually carried out using true directions. In Fig 9:

Compass direction 225° (C)
Deviation 2°W(−)

Magnetic direction 223°(M)
Variation 12°W(−)

True direction 221° (T)

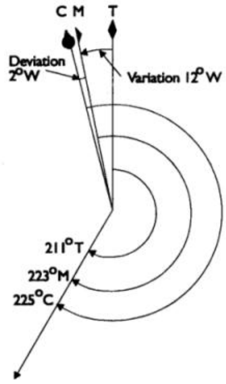


Fig 9 Three Expressions for Direction

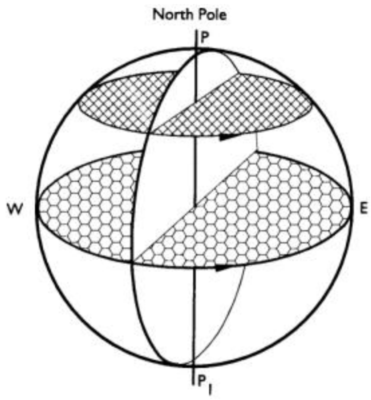


Fig 1a

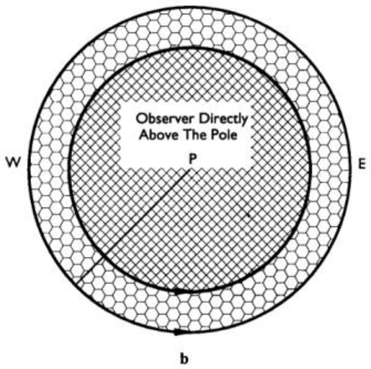


Fig 1b

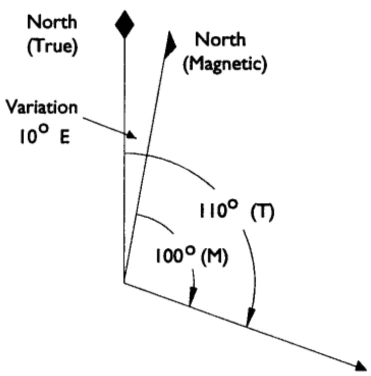


Fig 7a

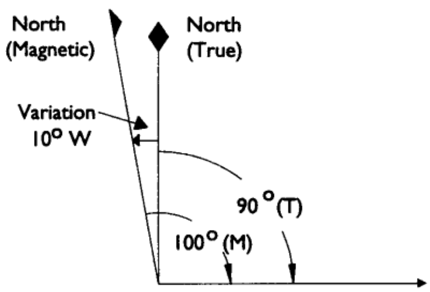


Fig 7b

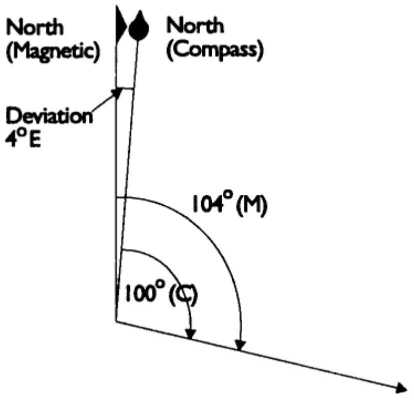

North
(Magnetic)
North
(Compass)
Deviation
4°E
104° (M)
100° (C)

Fig 8a

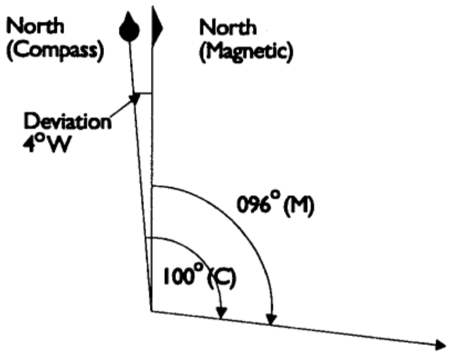

North
(Compass)
North
(Magnetic)
Deviation
4°W
096° (M)
100° (C)

Fig 8b

DISTANCE, DIRECTION AND POSITION

POSITION

Introduction

1. Since air navigation is the process of directing an aircraft from one point to another, it is essential to be able to define these points as positions on the Earth's surface.

2. Mathematically, a point can be defined by reference to two mutually perpendicular axes. Thus the point P (Fig 1a) is defined in general terms, by the Cartesian coordinates +x and +y, which have linear values. Similarly point R is positioned by the coordinates x', y'.

3. When the point P lies on a sphere (Fig 1b), a similar system may be employed but the coordinates may have either linear (x, y) or angular units of measurement (β°, α°).

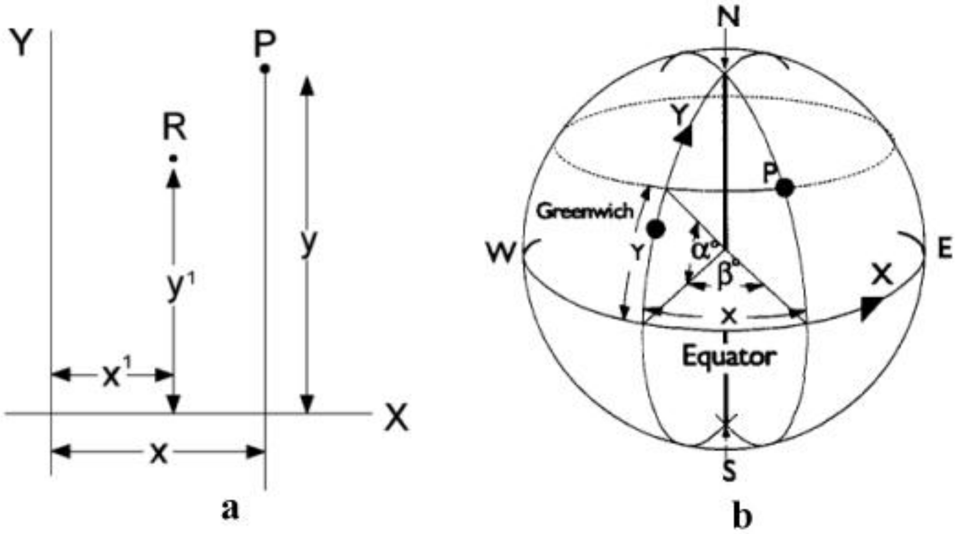


Fig 1 Coordinates Systems Introduction

LATITUDE AND LONGITUDE

General

4. On the Earth position is normally defined by a reference system known as latitude and longitude. The chosen axes are the equator (X) and the meridian of Greenwich (Y) - the prime meridian.

Latitude

5. Latitude is defined as the angular distance from the equator to a point, measured northward or southward along the meridian through that point. This quantity is expressed in degrees, minutes and seconds and is annotated N or S according to whether the point lies North or South of the equator (see Fig 2).

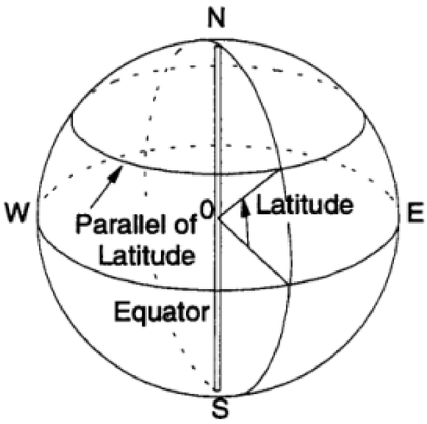
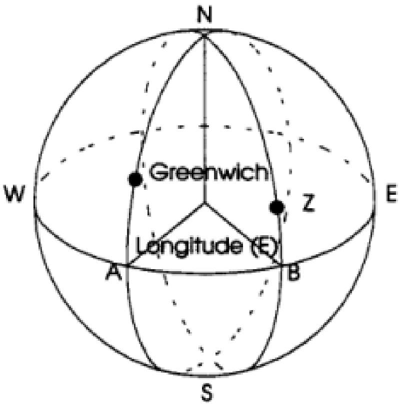


Fig 2 Latitude

Longitude

6. The longitude of any point is the shorter angular distance along the equator between the prime meridian and the meridian through the point (Fig 3). It is expressed in degrees minutes and seconds, and is annotated E or W according to whether the point lies to the East or West of the prime meridian. As the plane of the Greenwich Meridian bisects the Earth, longitude cannot be greater than 180° East or West (Fig 4).



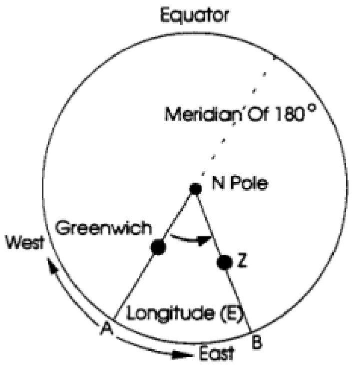


Fig 3 Longitude

Fig 4 Extremes of Longitude

Recording Position

7. In air navigation it is usually sufficient to express latitude and longitude in degrees and minutes only. By convention, the group of figures representing latitude is always written first and is followed by the figures expressing longitude. To avoid ambiguity there are always two figures used to denote degrees of latitude, those below ten being preceded by the digit 0. Similarly, three figures are used to denote degrees of longitude, employing leading zeros as necessary. The letters N, S E, and W are used to indicate the sense of the latitude and longitude coordinates. Thus the position of a point situated in latitude 53 degrees 21 minutes North and in longitude zero degrees 5 minutes East, is written: 53 21 N 000 05 E, the spaces being optional.

Change of Latitude

8. The change of latitude (ch lat) between two points is the arc of a meridian intercepted between their parallels of latitude. It is annotated N or S according to the direction of the change from the first point to the second.

9. If the two points are on the same side of the equator, as in Fig 5a, the ch lat is found by subtracting the lesser latitude, that of A, from the greater, that of B. If A and B are on opposite sides of the equator, as in Fig 5b, the ch lat is equal to the sum of the latitudes of A and B. In Fig 5a the ch lat of point B from an observer at point A is annotated N, in Fig 5b the ch lat of point B from point A is annotated S.

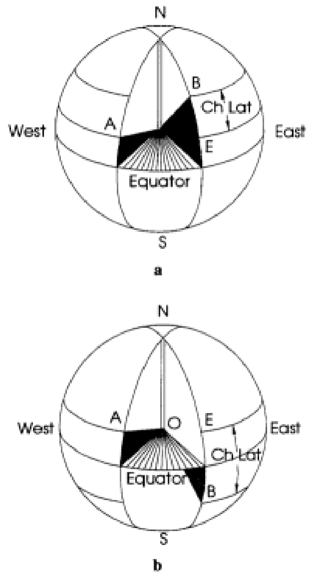


Fig 5 Change of Latitude

Change of Longitude

10. The change of longitude (ch long) between two points is the smaller arc of the equator intercepted by the meridians through the two points. It is annotated E or W according to the direction of the change from the first point to the second.

11. In Fig 6a since the longitudes of B and A are of the same sign the change of longitude is the difference between them, and the change of longitude of A from B is easterly. In Fig 6b the change of longitude of A from B is again easterly and, as the longitudes are of opposite sign, the change of longitude is the sum of the longitudes of B and A. In Fig 6c the change of longitude of A from B is westerly and its amount is 360° minus the sum of the longitudes of B and A. This is the smaller arc of the equator intercepted by the meridians of B and A.

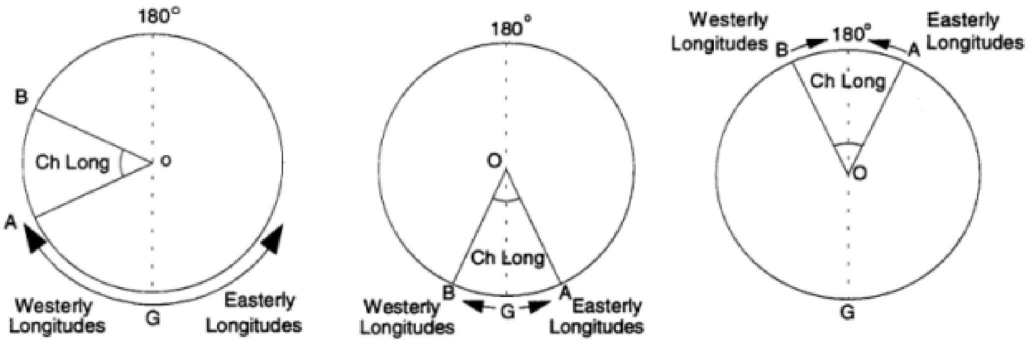


Fig 6 Change of Longitude

Departure

12. The distance between two given meridians, measured along a stated parallel and expressed in nautical miles, is called departure. In general terms it is defined as the East-West component of the rhumb line distance between two points. The value of departure between two meridians varies with latitude, decreasing with increasing latitude (Fig 7); the change of longitude between these meridians of course remains the same, irrespective of the latitude.

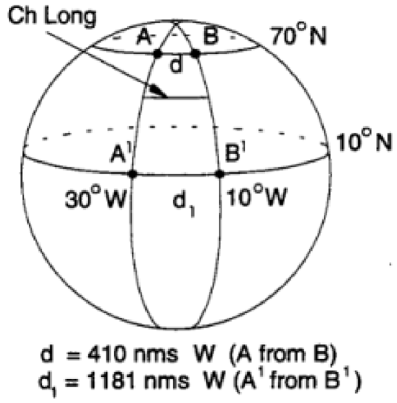


Fig 7 Departure and Change of Longitude

13. The departure between any two points is thus a function of their latitudes and the change of longitude, and the relationship is given by:

Departure (nms) = ch long (mins) x cos mean lat:

where mean lat = lat A + lat B

Disadvantages of the Latitude and Longitude Reference System

14. The latitude and longitude method of reporting position suffers from certain disadvantages:

a. The possibility of confusion in areas close to the equator and the prime meridian.

b. The necessity of giving an 11 figure group to obtain positional accuracy of 1 min eg 5136 N 00125 W or 5136 N 10125 W.

c. One minute of latitude and one minute of longitude represent different distances on the earth, except at the equator, and the distance represented by one minute of longitude decreases with increasing latitude.

15. To overcome these disadvantages military forces have, since the first World War, used reporting systems based on networks of lines (grids) which are a fixed distance apart and cut each other at right angles. Examples of these systems discussed in this chapter are:

a. The National Grid System.
b. The Universal Transverse Mercator Grid (UTM).
c. Geographical Reference System (GEOREF).

AIR SPEED INDICATOR

Introduction

1. A knowledge of the speed at which an aircraft is travelling through the air, i.e. the air speed, is essential both to the pilot for the safe and efficient handling of the aircraft and to the navigator as a basic input to the navigation calculations. The instrument, which displays this information is called Air Speed Indicator or ASI.

Aim

2. To know the principle, construction and errors of ASI.

Principle

3. An aircraft stationary on the ground is subject to normal atmosphere or static pressure which acts equally on all parts of the aircraft structure. In flight the aircraft experiences an additional pressure on its leading surfaces due to a build up of the air through which the aircraft is travelling. The additional pressure due to the aircrafts forward motion is known a dynamic pressure and is dependent upon the forward speed of the aircraft and the density of the air. According to the following formula:

$$p_t = \tfrac{1}{2}\rho v^2 + p$$

Where, p_t = The pitot pressure (also known as total head pressure or stagnation pressure)

p = The static pressure.

ρ = The air density.

v = The velocity of the aircraft.

Rearranging the formula, the difference between the pitot and the static pressure is equal to $\tfrac{1}{2}\rho v^2$ (the dynamic pressure). The air speed indicator measures this pressure difference and provides a display indication graduated in units of speed.

4. Fig 1 illustrates the principle, in its most simple form, on which all air speed indicators function. The ASI is a sensitive differential pressure gauge operated by pressure picked up by a pressure head, which is mounted in suitable position of the airframe. The simplest pressure head consists of an open ended tube the pilot tube, aligned with the

direction of flight and a second tube the static tube, which is closed and streamlined at the forward end but which has a series of small holes drilled radically along its length.

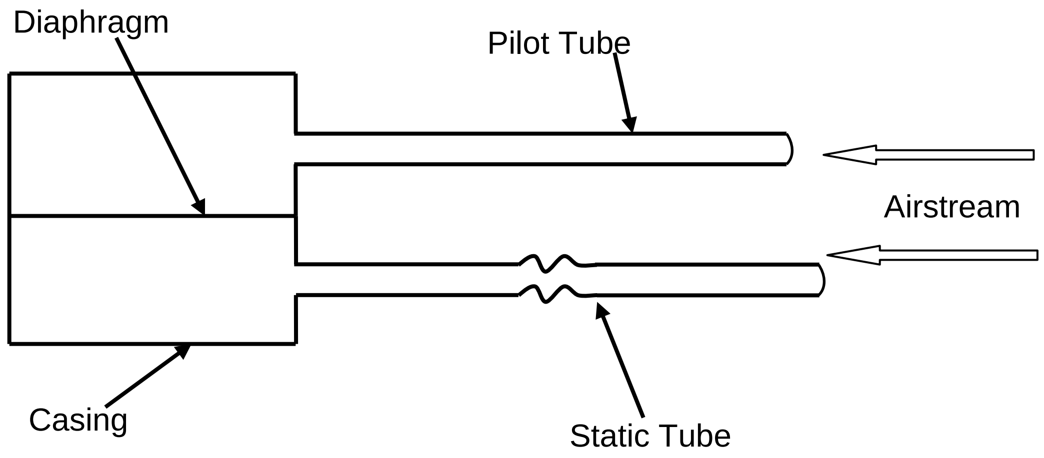


Fig 1: Principle of Air Speed Indicator

5. When moved through the air, the pitot tube will pick up pitot pressure made up of static pressure and dynamic pressure. The pitot pressure is led through a pipeline to one side of a sealed chamber, divided by a thin flexible diaphragm. The static tube is unaffected by dynamic pressure as its end is closes, however, the small holes will pick up local static pressure. The static pressure is led through a second pipe line to the other side of the diaphragm.

6. The diaphragm is subjected to the two opposing pressure, However, the static pressure component of the pitot pressure is balanced by the static pressure on the other side of the diaphragm, so that any diaphragm movement is determined solely by the dynamic, or pitot excess pressure. Movement of the diaphragm is transmitted through a mechanical linkage to a pointer on the face of the ASI where the pitot excess pressure (p_t – p) is indicated in terms of speed.

7. In some installations the pitot tube and the static tube are combined into a single pressure head with the pitot tube built inside the, static tube. A heater is placed between the pitot and static tubes to prevent ice forming and causing a blockage. Drain holes in the head allow moisture to escape and various traps may be used to prevent dirt and water from affecting the instrument. A combined pressure head is shown in Fig 2.

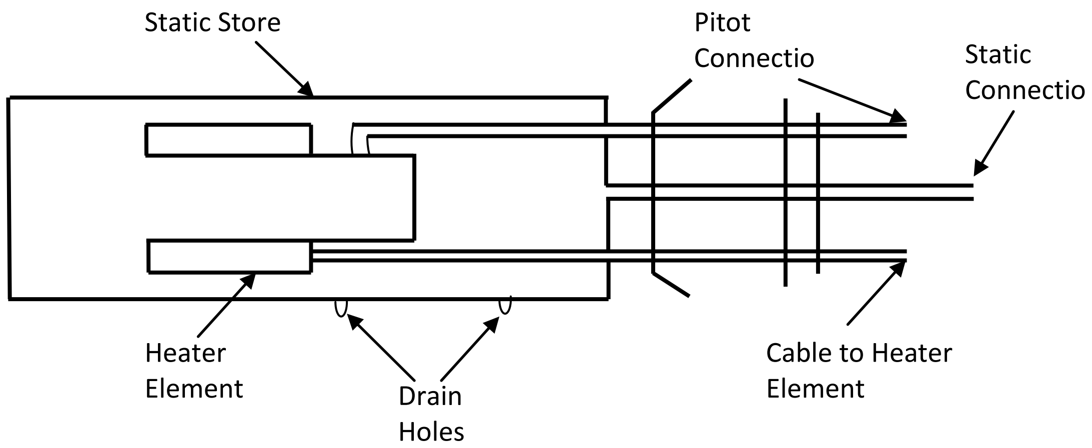


Fig 2: A Combined Pressure Head Element

Construction

8. Most air speed indicators, in current use have a capsule instead of the changer and diaphragm. However, the principle of operation is exactly the same. The capsule acting as the pressure sensitive elements is mounted in an airtight case. Pitot pressure is fed into the capsule and static pressure is fed to the interior of the case, which thus contains the lower pressure. A pressure difference will cause the capsule to open out the movement being proportional to pressure. A link quadrant and pinion can be used to transfer this movement to a pointer and dial calibrated in knots.

9. As stated in Para 3, the pitot excess pressure varies with the square of the speed and a liner pressure/deflection characteristic in the capsule produces an uneven speed/deletion characteristic of the pointer mechanism, giving unequal pointer movements for equal speed changes. To produce a linear scale between the capsule and pointer it is necessary to control the characteristics of the capsule and/or the mechanism. Control of the capsule is difficult due, among other reasons, to the magnification factor of the mechanism. It is more usual to control the mechanism to produce a linear scale shapes by changing the lever length as the points of construction will vary however, the basic principle holds good for all. A typical simple ASI is shown in Fig-3.

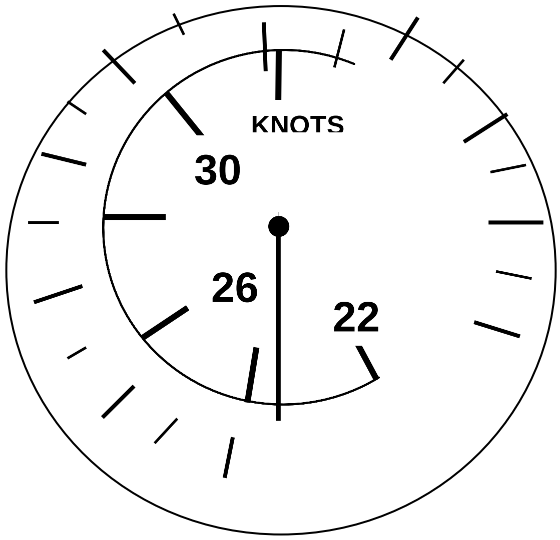


Fig 3: Typical Simple ASI

10. **The Sensitive and Servo Air Speed Indicators**. The sensitive and servo ASI's are identical in principle to the simple ASI and operate from the normal pitot/static system. Extra sensitively is achieved by an increase in the gear train from the capsule. So that two pointers may be moved over an evenly calibrated dial. Because of this increase in the gear train, more power is required to operate the gears and this is provided by a stack of capsule. This capsule assembly has a linear pressure/deflection characteristic which is more closely controlled than the single capsule used in the simple ASI. In a servo ASI the mechanical linkage is replaced by an electrical linkage utilizing error actuation and power amplification. A typical sensitive ASI display is shown in Fig-4.

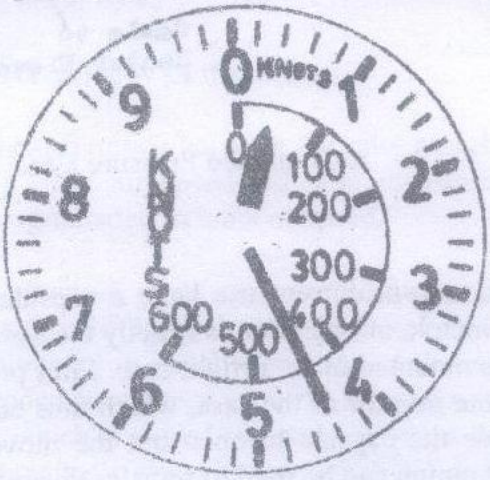


Fig 4 : A Two Pointer Sensitive ASI

Calibration

11. Since dynamic pressure varies with air speed and air density, and since air density varies with temperature and pressure, standard datum values have to be used for the calibrations of air speed indicators. The values used are the sea level values of the standard ICAO atmosphere. The formula given in para 3 is only an approximation and one of two formulae is used for calibration of particular ASI depending on the speed range of the instrument.

Errors of ASI

12. The ASI pointer registers the amount of capsule movement due to dynamic pressure, however, the dial is calibrated according to the formulae mentioned above which assume constant air density (Standard sea level density) and no instrument defects. Any departure from these conditions of disturbance in the pitot or static pressure being applied to the instrument will result in a difference between the indicated and the true air speed and thus an error in the display. There are four sources of error. These are:

a. Instrument error.

b. Pressure error.

c. Compressibility error.

d. Density error.

13. **Instrument Error.** Instrument error is caused by manufacturing tolerances in the construction of the instrument. The error is determined during calibration and any necessary correction is combined with that for pressure error (See para 14).

14. **Pressure Error.** Pressure error results from disturbance in the static pressure around the aircraft due to movement through the air. Size of the error depends upon:

a. The position of the pressure head, pitot head or static vent.

b. The angle of attack of the aircraft.

c. The speed of the aircraft.

d. The configuration of the aircraft (i.e. clean, flaps/gear/airbrakes etc).

e. The presence of sideslip.

Most of the error results from variations in the local static pressure caused by the airflow over the pressure head. In lower speed aircraft, the airflow over the pressure head or static head is often diversed from the pitot tube and positioned where the truest indication of static pressure is obtained e.g. on the fuselage midway between nose and tail. In such a case the static pipeline terminates at a hole in a flat brass plate known as the static vent. It is usual to have two static vents. One either side of the aircraft to balance out the effects of sideslip which produces an increase of pressure on one side of the aircraft and a corresponding decrease in pressure on the other side. The use of static vents eliminates almost all the error caused by the pressure head. Any remaining error is determined by flight trials. Unfortunately the use of static vent becomes less acceptable for high performance aircraft since, at Mach numbers exceeding 0.8, the flow of air around the static vent may be unpredictable. In such cases a high speed pitot head is used and, as before, pressure error is determined by flight trails. The correction for pressure error (PEC) is tabulated in the Aircrew Manual for the aircraft type and is also combined with that for instrument error (IFC) and recorded a correction card mounted adjacent to each ASI. The card correction (i.e. IEC+PEC) should be applied to the indicated air speed (IAS) to obtain rectified air speed (RAS).

15. **Compressibility Error.** The calibration formula contains a factor, which is a function of the compressibility of the air. At higher speeds this factor becomes significant. However, the calibration formula use standard mean sea level values and an error is introduced at any altitude where the actual values differ from those used in calibration. At altitude, the less dense air is more easily compressed than the denser air at sea level, resulting in a greater dynamic pressure which causes the ASI to over read. In addition compressibility increases with increase of speed, therefore compressibility error varies both with speed and altitude. Compressibility error and its correction can be calculated by using the circular slide rule of the DR computer MK 4A. Application of the compressibility error correction (CEC) to RAS produces equivalent air speed (EAS).

16. **Density Error.** As has already been explained, dynamic pressure varies with air speed and the density of the air. Standard mean sea level air density is used for calibration purposes. Thus, for any other condition of air density, the ASI will be in error. As altitude increase, density decreases and IAS, and thus EAS, will become progressively lower than true air speed (TAS). The necessary correction can be calculated from the formula:

$$\text{EAS} = \text{TAS}\sqrt{\frac{\rho}{\rho_0}}$$

where ρ = The air density at the height of the aircraft.

ρ_o = The air density at mean sea level.

In practice, the density error correction (DEC) is obtained from a graph or by the use of a circular slide rule such as the DR computer Mk 4A.

17. **Summary.** The relationship between the various air speeds and the associated errors can be summarized as follows :

$$CAS = IAS \pm PEC \pm IEC$$
$$EAS = CAS \pm CEC$$
$$TAS = EAS \pm DEC$$

Blocked or Leaking Pressure Systems

18. **Blockages**.

a. **Pitot**. If the pitot tube is blocked, e.g. by ice, the ASI will not react to changes of airspeed in level flight. However, the capsule may act as a barometer producing an indication of increases in speed if the aircraft climbs or a decrease in speed if the aircraft dives. If the pitot tube contains a small bleed hole for drainage, partial blockage of the nose of the tube (the most common effect of icing) will result in an under reading. More extensive icing will cause the reading to reduce towards zero as the dynamic pressure leaks away through the bleed hole.

b. **Static**. If the static tube is blocked, the ASI will over read at lower altitudes and under read at higher altitudes than that at which the blockage occurred.

19. **Leaks**.

a. **Pitot.** A leak in the pitot tube causes the ASI to under read.

b. **Static**. A leak in the static tube, where the pressure outside the pipe is lower than static (i.e. most un-pressurized aircraft), will cause the ASI to over read, where the outside air is higher than static (i.e. in a pressurized cabin) the ASI will under read.

Conclusion

20. ASI displays IAS and it is related to dynamic pressure. The error of ASI depends on the density of air, speed of the aircraft, wrong pressure entry into pitot-static tube etc. Due to blockage and leakage, ASI over reads or under reads. The under or over reading of ASI is potentially dangerous. The former may cause problem in adverse landing conditions(e.g. in a strong cross wind). And the later condition may result in an aircraft stall at a higher indicated airspeed than that specified for the aircraft.

ALTIMETER

Introduction

1. The purpose of the altimeter is to measure the height of the aircraft above a given reference plane. This information is vital for maintaining terrain clearance and separation from other aircraft. To use it effectively is instrument flying it is essential that you thoroughly understand the principle of operation, and the effect of barometric pressure on the altimeter.

Aim

2. a. To know the principle, construction and errors of altimeter.

   b. To know the altimeter setting procedure and different altitude.

Principle of Operation

3. Air is more dense at the surface of the earth than it is aloft. As altitudes increases, the atmospheric pressure deceases. This difference in pressure at various levels causes the altimeter to indicate changes in altitude. The pressure altimeter is simply a barometer that measures the pressure the atmosphere and presents an altitude indication in number of feet or meters.

4. A pressure altimeter consists basically of a thin corrugated metal capsule, which is partially evacuated and sealed. It is prevented from collapsing completely by means of a leaf spring, or in some cases, by its own rigidity. Equilibrium is maintained between the pressure of the atmosphere on the faces of the capsule and the tension of the spring Changes in atmosphere pressure alter this state of equilibrium and the capsule will expand for a decrease in pressure or contract for an increase in pressure, until a new balance is obtained. The movement of the capsule face is transmitter to a pointer moving over a scale granted according to one of the standard atmospheres.

5. Changes of pressure are measured relative to a datum pressure, usually that of mean sea level. To allow for variations in actual mean sea level pressure from that assumed by the standard atmosphere, a method of altering the datum pressure is required (obtained by datum setting knob).

Construction

6. A simple altimeter consists of a single capsule mounted in an airtight case, the case being fed with static pressure from the aircrafts static tube or vent.

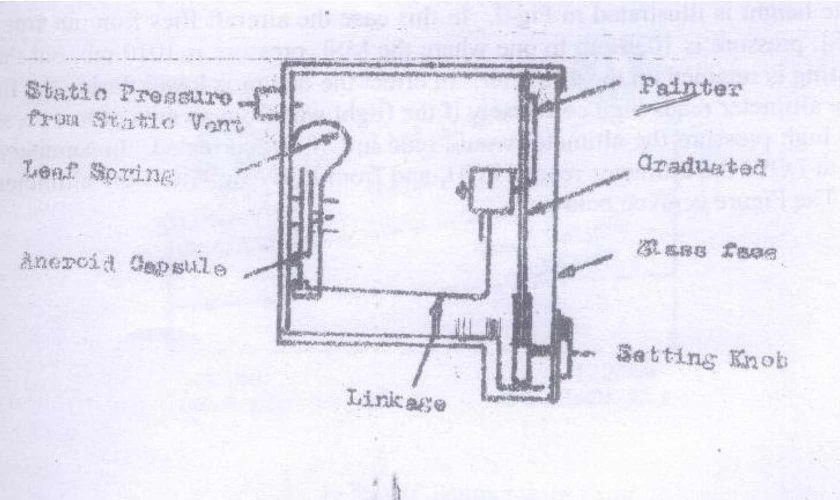


Fig 1 : Simple Altimeter

7. As the aircraft climbs, the pressure in the case falls, allowing the spring to pull the capsule face apart. Conversely a decreases in height compresses the capsule faces. This linear movement is magnified and transmitter to a pointer moving over a card graduated in feet in accordance with one of the standard atmospheres.

Errors of Altimeter

8. Pressure altimeter errors may be considered under two categories, instrument or installation errors, and errors causes by non standard atmospheric conditions.

9. The errors inherent in the instrument and installation are :

a. **Instrument Error**. Instrument error is caused by manufacturing tolerances. It is usually insignificant but if necessary a correction card can be provided.

b. **Pressure Error**. Pressure error occurs when the true external static pressure is not accurately transmitter to the instrument. A false static pressure can be created by the effect of the airflow passing over the static vent. Although the error is generally negligible at low speeds and altitudes, it can become significant at high speeds, or when services such as flaps airbrakes, or gear are operated. Avoidance or reduction of the effect is accomplished by careful probe or vent design and location Residual error is calibrated for each aircraft type and detailed in the Aircrew Manual or ODM, or automatically in an air data computer or pressure error corrector unit (PECU). Large transient errors can be caused by shock waves passing over the vent during acceleration or decelerations.

c. **Lag Error**. Since the response of the capsule and linkage is not instantaneous, the altimeter needle lags whenever height is changed rapidly causing an under read on climbs and an over read on descents. Clearly the latter situation could be dangerous and should be allowed for in rapid descents. The amount of lag varies with the rate of change of height. Time lag is virtually eliminated in servo assisted altimeters and may be reduced in others by the fitting of a vibration mechanism.

10. Variations from International Standard Atmosphere (ISA) conditions may be brought about by the development of weather systems, and local geographic effects. The resulting errors in ISA calibrated altimeters are:

a. **Barometric Error**. Barometric error occurs when the actual datum pressure differs from that to which the altimeter has been set and can be overcome simply by the correct setting of the millibar scale. The effect of the error on an altimeter which is not reset when flying from an area of high pressure to an area of low pressure at a constant indicate height is illustrated in Fig-2. In this case the aircraft flies from an area where the MSL pressure is 1030 mb to one where the MSL pressure is 1010 mb, but the 1030 mb setting is retained on the altimeter. In effect the datum is lower during the flight so that the altimeter reads high conversely if the flight was from an area of low pressure to one of high pressure the altimeter would read low if not corrected. In summary, from HIGH to LOW the altimeter reads HIGH, and from LOW to HIGH the altimeter reads LOW. The Figure is given below:

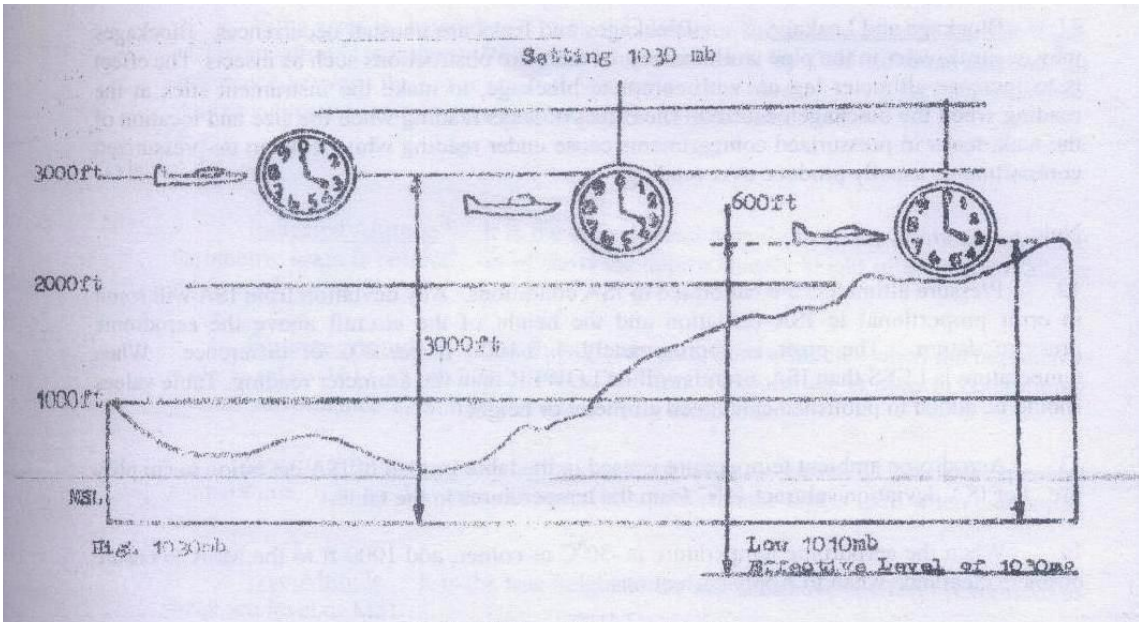


Fig 2 : Effect of Barometric Error

b. **Temperature Error**. Temperature error arises when the atmospheric conditions differ from those assumed by the standard atmosphere used to calibrate the altimeter. The ICAO standard atmosphere assumes a temperature lapse rate of 1.98°C per 1,000 ft up to 36,090 ft, with a constant temperature of –56.5°C above that. If the actual temperature lapse rate differs from the assumed ones as they very often do then the indicated height will be incorrect. In a cold air mass the density is greater than in a warm air mass, the pressure levels are more closely spaced and the altimeter will over read (Fig-3), the error being zero at sea level and increasing with altitude. The error is not easy to compensate for since in order to do so it would be necessary to have a knowledge of the temperature structure from the surface to the aircraft. The magnitude of the error is approximately 4ft/1,000 ft for every 1°C that the air generally differs from IAS. Corrections can be made for low altitudes by use of the table in the Flight Information Handbook and this may be necessary, for example when calculating decision height in arctic conditions. The table is reproduced in Fig-4 to give an indication of the magnitude of the error.

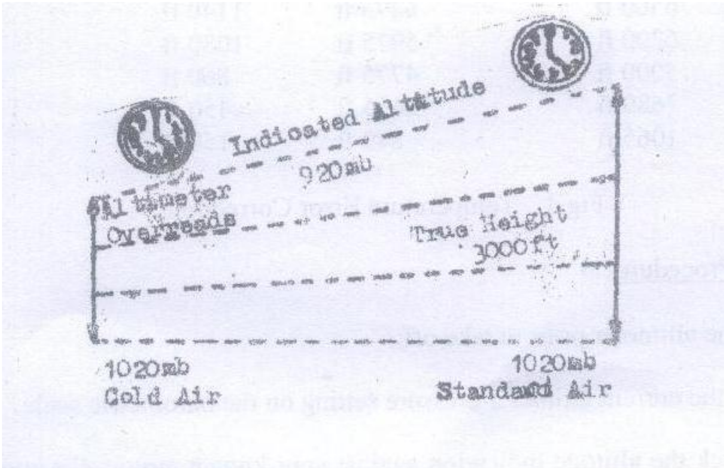


Fig 3 : Effect of Temperature Error

11. **Blockage and Leakage**. Blockages and leaks are unusual occurrences. Blockages may occur if water in the pipe work freezes, or there are obstructions such as insects. The effect is to increase altimeter lag or, with complete blockage, to make the instrument stick at the reading when the blockage occurred. The effect of leaks reading when the size and location of the leak, leaks in pressurized compartments cause under reading while leaks in un-pressurized compartments usually produce over reading.

Note

12. Pressure altimeters are calibrated to ISA conditions. Any deviation from ISA will result in error proportional to ISA deviation and the height of the aircraft above the aerodrome pressure datum. The error is approximately 4 ft/1000 ft per 0^oC of difference. When temperature is LESS than ISA aircraft will be LOWER than the altimeter reading. Table values should be added to published calculated altimeter or height.

13. Aerodrome ambient temperature is used in the table instead of ISA deviation to simplify use. For ISA deviation subtract 15^oC from the temperatures in the table.

14. When the aerodrome temperature is -30^oC or colder, add 1000 ft to the MSA to ensure obstacle clearance when to Apply corrections.

15. When the aerodrome temperature is 0^oC or colder, temperature error correction must be added to DH/DA or MDH/MDA step down fixes inside the FAF, and All low altitude approach procedures in mountainous regions (defined as terrain of 3000 ft AMSL or higher).

16. When pilots intends to apply corrections to the FAF crossing altitude, procedure turn or missed approach altitude, they must advise ATC of their intention and the correction to be applied.

17. IFR assigned altitudes may be refused if altimeter temperature error will reduce obstacle clearance below acceptable minimum. However, once an assigned altitude has been accepted it must subsequently be adjusted to compensate for temperature error.

Example

18. ILS Rwy Bardufoss, Elev 260 ft, Surface temp -30^{0}C, QNH used through out (Cat C aircraft) :

	Published Altitude	HAT	Add	Altitude to Fly
MSA	6700 ft	N/A	1000 ft	7700 ft
Min Hold	6500 ft	6275 ft	1140 ft	7640 ft
Proc Turn	6200 ft	5975 ft	1080 ft	7280 ft
MLV NDB Inbd	5000 ft	4775 ft	860 ft	5860 ft
OM	2680 ft	2455 ft	450 ft	3130 ft
DA	1065 ft	840 ft	150 ft	1215 ft

Fig 4: Temperature Error Correction

Altimeter Setting Procedure

19. To check the altimeter prior to take off:

a. a. Set the current altimeter pressure setting on the barometric scale.

b. Check the altitude indication against your known airport elevation and note the error.

c. If the error is beyond $\pm$ 75 feet, the altimeter should not be used for IFR flight. If the deviation is less than $\pm$ 75 feet, set the altimeter at the field elevation and note the difference between the tower altimeter setting and the reading in the kollsman window. Add or subtract this figure to all subsequent setting received.

Types of Altitude

20. a. **Indicated Altitude.** It is the altitude read directly from the altimeter when the barometric scale is correctly set to show the approximately height of the aircraft above mean sea level (MSL).

b. **Pressure Altitude.** It is the altitude read from altimeter when the barometric scale is set to 1013.25 mb/29.92 inches/760 mm. This altitude is used in determining aircraft performance TAS, true altitude, density altitude etc.

c. **Density Altitude.** It is the pressure altitude corrected for non standard temperature. It is used in take off and climb performance and is used when computing same.

d. **True Altitude**. It is the true height of the aircraft above sea level (expressed as mean sea level or MSL).

Summary

21. a. For normal operations (except to determine TAS, true altitude and related aircraft performance) pilots should disregard the effect of non standard temperature

since all aircraft operating with the same pressure adjustments are separated by pressure levels.

b. If the local altimeter setting is lower than that set in your kollsman window, the aircraft is lower than the altitude indicated. The reverse is true when the local pressure is higher than what is set into the altimeter.

c. How do you remember all this? When flying from a high to a low, or from hot to cold, look out below.

Conclusion

22. Altimeter is an aneroid barometer that measures the static pressure and relates its to height in the atmosphere. The lower the pressure, the greater the height. It is exposed to various types of error some of which are inherent. And others can be eliminated by setting the altimeter correctly.

VERTICAL SPEED INDICATOR

Introduction

1. A Vertical Speed Indicator (VSI) also known as a rate of climb and descent indicator (RCDI),is a sensitive differential pressure gauge, which displays a rate of change of atmospheric pressure in terms of a rate of climb or descent when the aircraft departs from level flight.

Aim

2. This chapter aims at the principle and errors of VSI (VVI).

Principle

3. The principle employed is that of measuring the difference of pressure between two chambers, one within the other, static atmosphere pressure is fed directly to the chamber or capsule and through a metering unit to the outer chamber which in effect forms the instrument case. The metering unit restricts the flow of air into and out of the case, whereas the flow to the inside of the capsule is unrestricted. Therefore, if the static pressure varies due to changing altitude the pressure change in the case lags that in the capsule. The resultant different pressure distorts the capsule and this movement is transmitted to the pointer by means of a mechanical linkage. A bleed valve is fitted in, so to prevent damage and to improve the instruments reaction time (by reducing lag) when leveling off from a high speed descent. The construction of a VSI is shown schematically in Fig-1 and a typical display is illustrated in Fig-2.

4. It is important that any pressure difference between the inside and outside of the capsule should represent the same rate of climb or descent, regardless of the ambient atmospheric, pressure and temperature variations with altitude. The function of the metering unit, in the manner in which it restricts the flow into the case, is to compensate for these changes in ambient conditions.

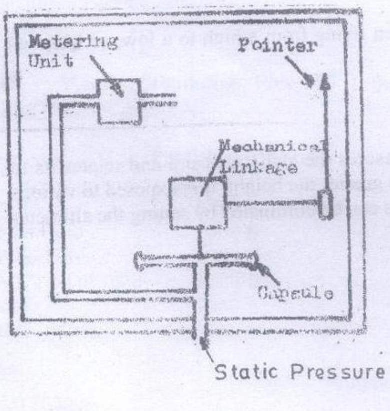


Fig 1: VSI Schematic Construction

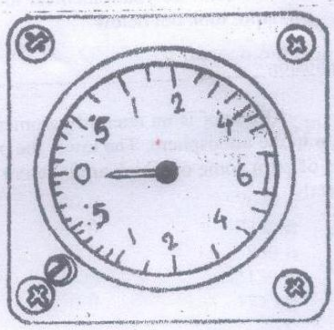


Fig 2 : VSI Typical Display

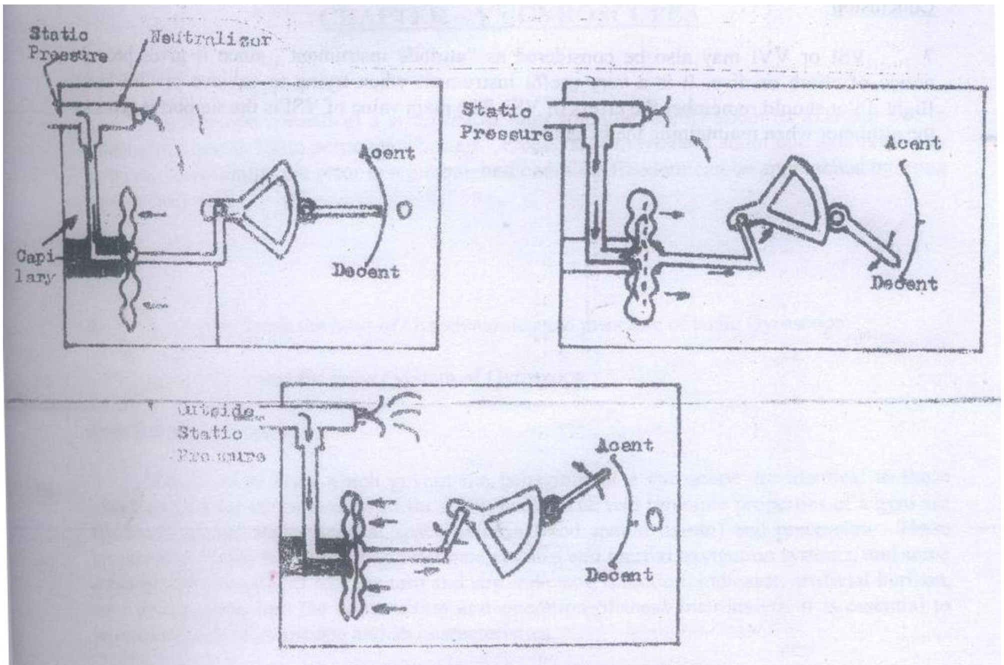


Fig 3 : Principle of Vertical Speed Indicator

5. In level flight the pressure inside the capsule and the case are the same and the pointer remains at the horizontal, zero, position. When the aircraft climbs, the static pressure decreases and the capsule collapses slightly, causing the pointer to indicate a rate of climb. The fall in pressure in the case lags behind that in the capsule until level flight is resumed and the pressures equalize. In a descent, the increase in pressure in the capsule and the capsule is expanded.

Errors of VSI

6. The VSI can suffer from the following errors :

a. **Pressure Error**. If the static head or vent is subject to a changing pressure error, the VSI may briefly indicate a wrong rate of climb or descent.

b. **Instrument Error**. Instrument error is the result of manufacturing tolerances and is usually insignificant.

c. **Transonic Jump**. Movement of a shockwave over the static vents results in a rapid change in static pressure which briefly produces a false reading on the VSI.

d. **Lag.** Because of the time required for the pressure difference to develop when an aircraft is rapidly maneuvered into a steady climb or descent there is a few seconds delay before the pointer settles at the appropriate rate of climb or descent. A similar delay in the pointer indicating zero occurs when the aircraft is leveled.

e. **Static Line Blockage.** If the static line or vent becomes block by ice or other obstruction, the VSI will be rendered unserviceable and the pointer will remain at zero regardless of the vertical speed.

Conclusion

7. VSI or VVI may also be considered as “attitude instrument”, since it gives prompt notice of climb or dive. It is a very useful instrument when trying to achieve precise level flight. Pilot should remember the errors of VSI. The main value of VSI is the support it gives to the altimeter when maintaining the height.

TOPIC- 6 : BASIC AERO ENGINE PROPULSION OF THEORY

Basic Theory and Principles of Propulsion

Introduction

1. When an aircraft is travelling through air in straight and level flight and at a constant true airspeed (TAS), the engines must produce a total thrust equal to the drag on the aircraft as shown in Fig 1. If the engine thrust exceeds the drag, the aircraft will accelerate, and if the drag exceeds the thrust, the aircraft will slow down.

2. Although a variety of engine types are available for aircraft propulsion, the thrust force must always come from air or gas reaction forces normally acting on the engine or propeller surfaces.

3. The two common methods of aircraft propulsion are:

a. The propeller engine powered by piston or gas turbine.
b. The jet engine.

Rotary wing aircraft are powered by turboshaft engines which produce shaft power to drive a gearbox and work on similar principles to gas turbine propeller engines (turboprops), except that all the available energy is absorbed by the turbine, with no residual jet thrust.

Fig 1 Arrangement of Thrust and Drag Forces

The Propeller Engine

4. With a propeller engine, the engine power produced drives a shaft which is connected to a propeller usually via a gearbox. The propeller cuts through the air accelerating it rearwards. The blade of a propeller behaves in the same way as the aerofoil of an aircraft; the air speeds up over the leading face of the propeller blade causing a reduced pressure with a corresponding increase of pressure on the rearward face (see Fig 2). This leads to a net pressure force over the propeller where Pressure X Area = Force thus providing thrust, eg:

Given Net Pressure of 40 kPa (Pa $=N/m^2$)

and a Blade area of 1 m^2

Thrust = 40 kPa X 1 m^2 = 40 kN

With gas turbine powered propeller engines, a small amount of thrust is produced by the jet exhaust which will augment the thrust produced by the propeller.

5. An alternative method of calculating the thrust produced by a propeller is provided by Newton's laws of motion which give:

Force = Mass X Acceleration

Thrust = Mass flow rate of air through Propeller X Increase in velocity of the air
= M X (V_j-V_a)

where,
M = Mass flow rate of air
V_j = Velocity of slipstream
V_a = Velocity of the aircraft (TAS)

This will give the same result as that given by the sum of pressure forces. In the case of the propeller, the air mass flow will be large, and the increase in velocity given to the air will be fairly small.

The Jet Engine

6. In all cases of the jet engine, a high velocity exhaust gas is produced, the velocity of which, relative to the engine, is considerably greater than the TAS. Thrust is produced according to the equation in para 5 ie:

$$\text{Thrust} = M (V_j - V_a)$$

where Vj is now the velocity of the gas stream at the propelling nozzle (see Fig 3). This represents a simplified version of the full thrust equation as the majority of thrust produced is a result of the momentum change of the gas stream.

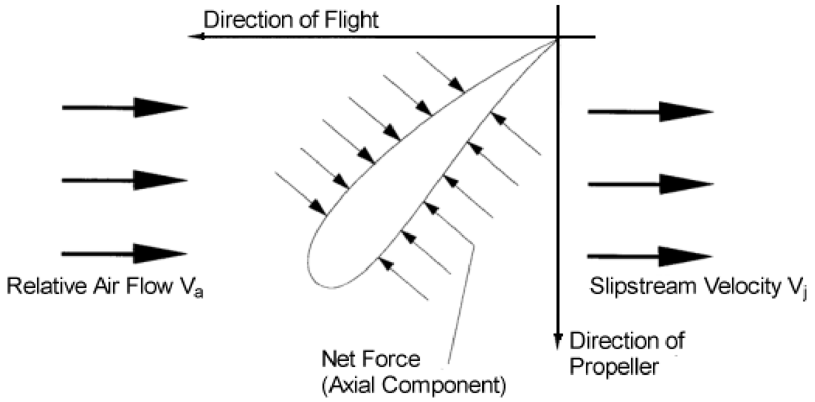


Fig 2 Propeller Thrust

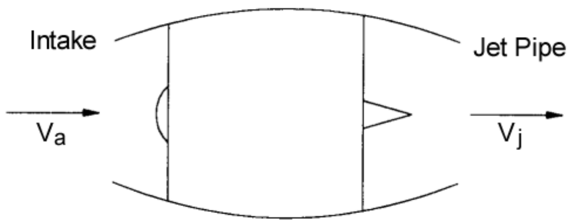


Fig 3 Jet Thrust - Relative Velocities

7. In the rocket engine (Fig 4) the gases which leave the engine are the products of the combustion of the rocket propellants carried; therefore no intake velocity term Va is required: The simplified version of the equation giving the thrust produced thus becomes:

Thrust = Mass flow rate of propellant X V_j

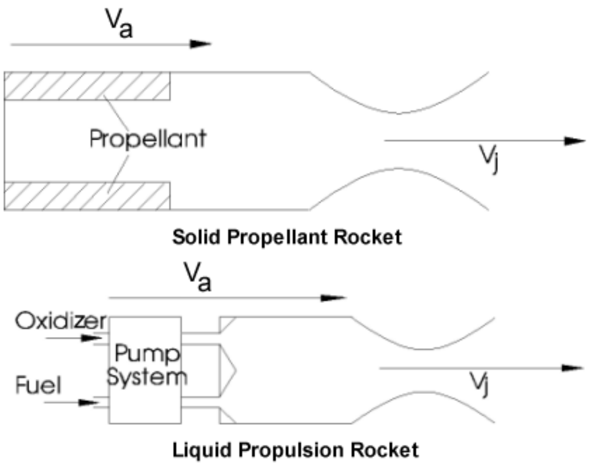


Fig 4 Rocket Engines

The Turbofan (By-pass) Engine

8. The Turbofan or by-pass engine (Fig 5) powers the vast majority of modern aircraft, and is likely to do so for the foreseeable future. It can be seen as the link between the Turbopropeller and the Turbojet engine. The thrust from a by-pass engine is derived from the mass air flow from the 'fan' plus the mass air flow from the core engine and can be exhausted separately or mixed prior to entering the jet pipe.

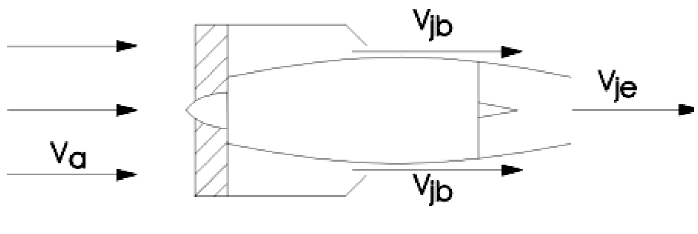


Fig 5 Turbofan Thrust

9. The thrust for a mixing turbofan engine can be treated in the same way as a simple turbojet, as the mass flows are mixed prior to entering a common exhaust and propelling nozzle. However, where the bypass air flow is exhausted separately the simplified thrust calculation becomes:

Thrust = Mass flow rate of air through fan duct X (V_{jb} - V_a) +
Mass flow rate of air through core engine X (V_{je} - V_a)
= M_{fan} X (V_{jb} - V_a) + M_{core} X (V_{je} - V_a)

The ratio M_{fan}/M_{core} is called the by-pass ratio and is quoted for both mixing and non-mixing turbofans; values below about 1.5 are termed low bypass ratio turbofans. With ratios above about 1.5, turbofans are considered high bypass.

Engine Efficiency

10. As the engine thrust propels the aircraft, propulsive power is being developed in proportion to the airspeed, ie:

Propulsive Power = Engine Efficiency X TAS

The power developed must be sufficient to overcome aircraft drag with an adequate margin to increase aircraft velocity as required. Fuel is consumed during combustion thus releasing energy to generate power. (1 kg of kerosene can produce 43 mJ of energy). The overall efficiency (ho) of the engine as a propulsive power plant is defined as:

$$\eta_0 = \frac{\text{Propulsive power developed}}{\text{Fuel power consumed}}$$

Thermal and Propulsive Efficiency of Gas Turbines

11. In the conversion of fuel power into propulsive power it is convenient to consider the conversion taking place in two stages:

a. The conversion of fuel power into gas power.

b. The conversion of gas power into propulsive power.

The air-breathing engine burns fuel to produce useful gas kinetic energy. Some of this energy is lost in the form of heat in the jet efflux, by kinetic heating, conduction to engine components, and friction. The ratio of the gas energy produced in the engine to the heat energy released by the fuel in unit time, determines the THERMAL efficiency (hth) of the engine, ie:

$$\eta_{th} = \frac{\text{Rate of increase in KE of gas stream}}{\text{[illegible]}}$$

12. Of the gas kinetic energy produced, some is converted into propulsive power, whilst the remainder is discharged to atmosphere in the form of wasted kinetic energy. The ratio of the propulsive power to the rate of increase in kinetic energy of the gas stream determines the PROPULSIVE efficiency (hp) of the engine, ie:

$$\eta_p = \frac{\text{Propulsive power developed}}{\text{[illegible]}}$$

13. An examination of the expressions derived for the thermal, propulsive and overall efficiencies shows that the following relationship exists:

$$\eta_0 = \eta_{th} \times \eta_p$$

14. Fig 6 shows a typical breakdown of the total fuel power produced from burning kerosene at a rate of 1.4 kg/s to produce a power potential of 60 MW.

By calculating the efficiencies of the above example viz:

η_{th} = 15/60 = 25%
η_p = 12/15 = 80%
η_0 = 12/60 = 20 %

it can be seen that the biggest single loss is through waste heat, the majority of which (75%) is lost without being converted to useful kinetic energy. A further loss (5%) is experienced by failing to convert all the remaining kinetic energy to useful propulsive power.

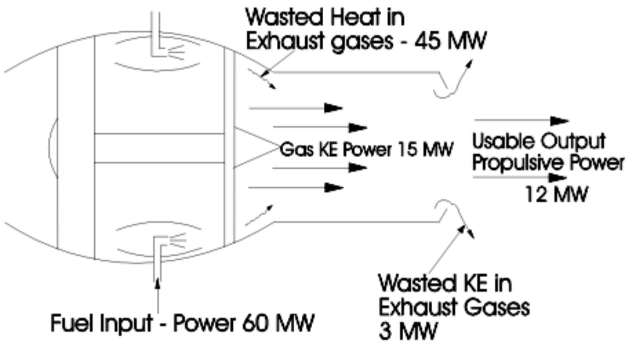


Fig 6 Representation of Energy Efficiency

15. The generation of thrust as shown in Fig 7, M X (V_{je} - V_a), is always accompanied by the rejection of power in the form of wasted kinetic energy (kinetic energy = ½ X M X (V_{je} - V_a)^2 with a consequent effect on the propulsive efficiency (η_p). For a given thrust, this wasted kinetic energy can be reduced by choosing a high value of air mass flow rate (M) and a low value of (V_{je} - V_a), since kinetic energy is proportional to the square of the velocity. This result is shown in Fig 8. Therefore, provided that the thermal efficiency remains constant, engines with a large mass flow and relatively low increase in gas velocity will be more efficient (see Fig 9).

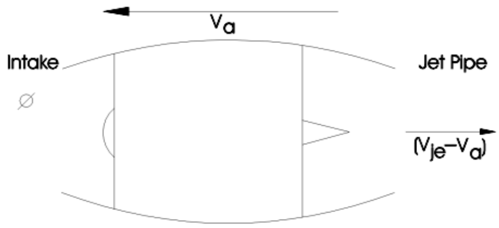


Fig 7 Gas Turbine Thrust - Absolute Velocity

16. The sudden drop in propulsive efficiency, shown in Fig 9, for a propeller aircraft is caused by the propeller tip speed approaching Mach 1.0, with a corresponding loss of effectiveness of the propeller, at aircraft speeds in excess of about 350 kt. Advanced propeller technology designs have produced propellers with a tip speed in excess of Mach 1.0, enabling aircraft speeds of over 430 kt at sea level.

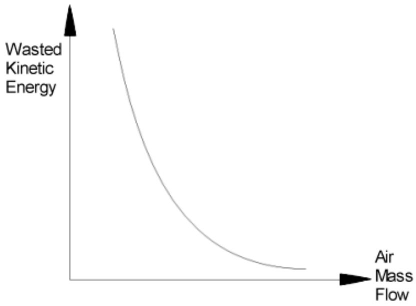


Fig 8 Variation in KE Loss with Mass Flow Rate at Constant Thrust

17. Fig 9 also shows the advantage of the propeller over other forms of power plant at low speeds. Similarly, the turbofan engines can be seen to have advantages over the turbojet. The low bypass mixing turbojet bridges the gap between high bypass turbofans and pure turbojets. The mixing of the two gas streams is theoretically more efficient than exhausting the gas streams separately, but on high bypass turbofans it is almost impossible to achieve efficient mixing. Many other factors affect the choice of powerplant (see para 23), and the decision becomes a complex one, often with no clear cut answer.

Specific Fuel Consumption and Overall Efficiency

18. For a turboprop or turboshaft engine, the specific fuel consumption (SFC) can be defined as either:

Mass flow rate of fuel or Mass flow rate of fuel , respectively

The SFC = Mass flow rate of fuel X Propeller efficiency

From which SFC α Propeller efficiency

Thus, Overall efficiency α Propeller efficiency

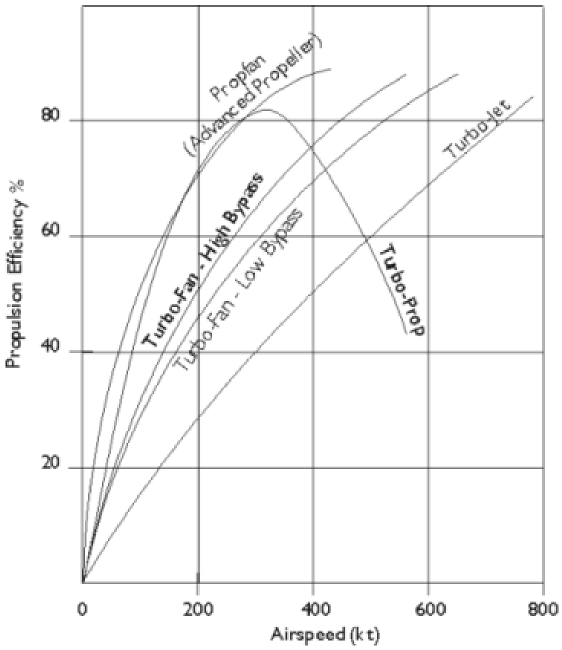


Fig 9 Comparison of Propulsive efficiencies

19. For a jet engine (including Turbofans):

SFC = Mass flow rate of fuel

i.e, SFC α Mass flow rate of fuel X Airspeed

Thus, Overall efficiency α TAS

Factors Affecting Thermal Efficiency of Piston Engines

20. The principle of operation of the spark ignition piston engine is described briefly in Sect 2. The thermal efficiency depends upon compression ratio, combustion chamber design, mixture strength, engine rpm, air inlet temperature, etc. Under normal operating conditions, there is little variation from engine to engine, a typical figure being 30%. In particular, there is little variation with engine size.

Factors Affecting Thermal Efficiency of Gas Turbine Engines

21. Gas turbine engines are widely used as turboprop, turboshaft, turbojet and turbofan engines. The thermal efficiency will vary considerably, not only from engine to engine, but also with operating conditions. The thermal efficiency of these powerplants depends mainly upon:

a. Compression ratio.
b. Component efficiency.
c. Air inlet temperature.
d. The turbine entry temperature.

The efficiency of the engine increases with increasing compression ratio (pressure ratio) so values in the order of 30:1 are now being produced. These high pressure ratios are more easily employed in larger engines, with the result that large gas turbines are usually more efficient than small ones. Thermal efficiencies of gas turbines are approximately in the range of 10 - 40% at normal operation.

Power Output of Gas Turbines

22. Gas or shaft power output from a gas turbine is mainly dependent upon:

a. Size.

b. Turbine entry temperature.

c. Component efficiencies.

d. Inlet air density.

e. Rpm.

The turbine inlet temperature will be limited to a certain maximum value by the properties of the turbine blade and the degree of blade cooling: current values of this temperature are in the region of 1800° K. The inlet density decreases with increasing altitude and ambient temperature and, therefore, adverse climatic conditions may have a serious effect on performance. Water injection may be used to compensate for loss of thrust under these conditions.

Choice of Aircraft Power plant

23. The factors which affect the choice of power plant for a particular aircraft include:

a. Power output.

b. Efficiency.

c. Power/weight and power/volume ratios.

d. Cost.

e. Reliability.

f. Maintainability.

g. Noise and pollution.

For low speed application, propeller engines are often chosen because of their overall high efficiency. Piston engines are used in small aircraft because of their advantages of efficiency and cost over the small gas turbine. For larger aircraft, turboprop engines have gained favour as they have good power/weight ratios and are easily maintained. For higher speeds, the propeller is replaced by the turbofan or turbojet.

24. For air transport application, where fuel efficiency is extremely important, high by-pass ratio turbofans are being used by the majority of large aircraft, with lower by-pass ratio turbofans and turboprops used in the smaller aircraft. The choice for training and combat aircraft is less clearcut. In the past, pure jets have been used for jet trainers, but have been replaced by low by-pass ratio turbofans and turboprops. Modern strike aircraft use low by-pass afterburning turbofans, which give a higher efficiency at subsonic speed and provide a greater thrust augmentation (>80%) in afterburning mode.

Introduction to Piston Engines

Introduction

1. The internal combustion piston engine consists basically of a cylinder (Fig 1) which is closed at one end, a piston which slides up and down inside the cylinder, and a connecting rod and crank by which reciprocating movement at the piston is converted to rotary movement of the crankshaft. In the closed end of the cylinder, known as the Cylinder Head, are inlet and exhaust valves and a sparking plug.

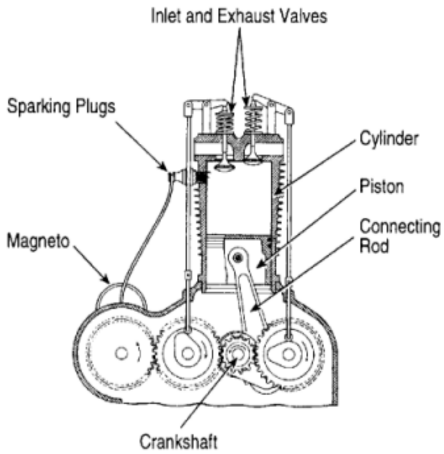


Fig 1 A Four-stroke Internal Combustion Engine

The Four Stroke Cycle

2. The sequence of operations by which the engine converts heat energy into mechanical energy is known as the four stroke or constant volume cycle, and is shown in Fig 2. A mixture of petrol and air is introduced into the cylinder during the induction stroke and compressed during the compression stroke (1-2). At this point the fluid is ignited, the heat generated causing a rapid increase in pressure (2-3) which drives the piston down on its power stroke (3-4). Finally, the waste products of combustion are ejected during the exhaust stroke (4-1). The four stroke cycle is illustrated in Fig 3.

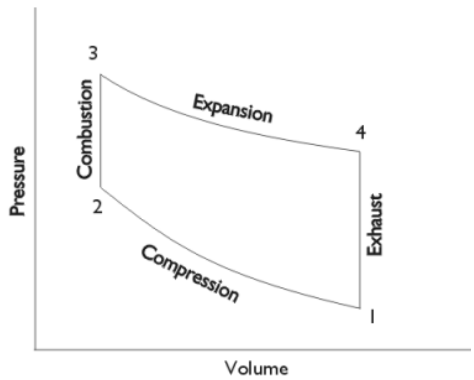


Fig 2 Constant Volume Diagram

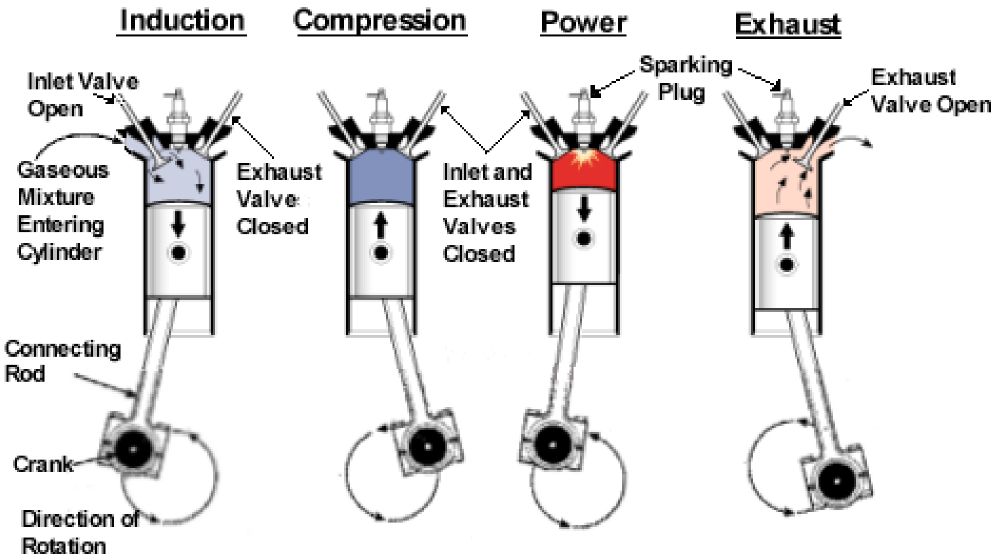


Fig 3 The Four Stroke Cycle

3. One of the most noticeable differences between car and aero-engines is that, with the exception of those fitted to light aircraft, the latter possess more cylinders. This is because it is impracticable, for various reasons, to obtain much more than 74.5 kW per cylinder; consequently a high output would not be developed by a scaled-up version of a low-power engine.

4. Even in engines of modest power it is often better to use a number of small cylinders in preference to fewer and larger, for not only does smoother operation result, but also, in many cases, a smaller frontal area can be obtained.

Timing

5. In theory, the opening and closing of the valves, and the supply of the spark are all timed to take place at either top dead centre (TDC) ie when the piston is at its highest point in the cylinder, or bottom dead centre (BDC) as appropriate. In practice however, the timing is modified to take into account the following facts:

a. There is a limit to the speed of which valves can be made to open/close, beyond which excessive stresses would be imposed on the valve operating gear.

b. When a valve is almost closed, the flow of gases is minimal.

c. There is an appreciable time between the ignition of the compressed fuel/air mixture, and the build up to a maximum pressure in the cylinder head.

6. As engine speed is increased, it is necessary for a spark to be further advanced (ie to be made to occur at a greater crank angle before TDC) so that the maximum combustion pressure will occur early in the power stroke. However, rich mixtures, such as are necessary when an engine is developing its full power, burn faster than normal or weak mixtures, and consequently it is usual for the spark to be slightly retarded at full throttle.

Cooling

7. If an engine were perfectly efficient all the heat produced in it would be turned into useful work, and the problem of cooling would not arise. This is impossible, however, and in practice less than 30% of the heat generated during combustion is converted into mechanical energy; about 40% passes out with the exhaust gases, while the reminder finds its way into the engine and, if no steps were taken to get rid of it, would cause mechanical deterioration and break-down of the oil.

8. There are two methods of cooling the cylinders, air cooling and liquid cooling, the difference being that in one case heat is transferred directly to the air through which the engine moves (Fig 4a), whereas in the other a liquid coolant circulates continuously between the cylinders and a radiator as in a car (Fig 4b). Each system has its merits, and each tends, though not exclusively, to a distinctive arrangement of the cylinders. Whichever method is used, however, a considerable degree of cooling is achieved by the lubricating oil circulating in the engine. The oil is pumped through an oil cooler to dispose of this absorbed heat.

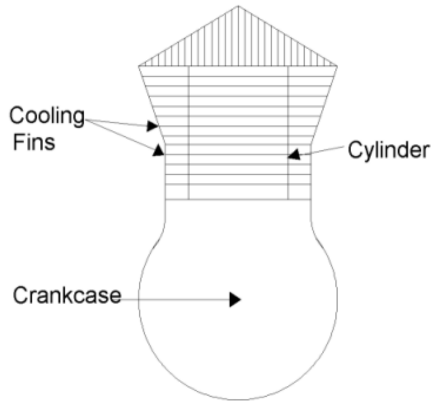


Fig 4a Air Cooled Engine

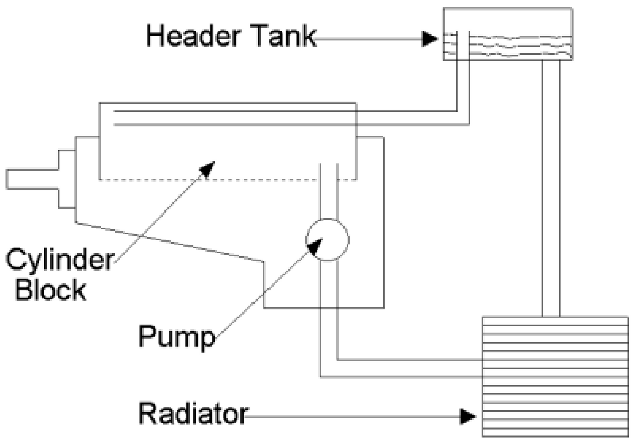


Fig 4b Liquid Cooled Engine

Ignition System

9. The aircraft engine ignition system is required to provide a rapid series of sparks of an intensity sufficient to ignite the weakest fuel/air mixtures normally used, correctly timed in rotation to each compression stroke, and arranged to fire each cylinder in the desired sequence. The following paragraphs describe briefly the main components of a simple system as shown in Fig 5.

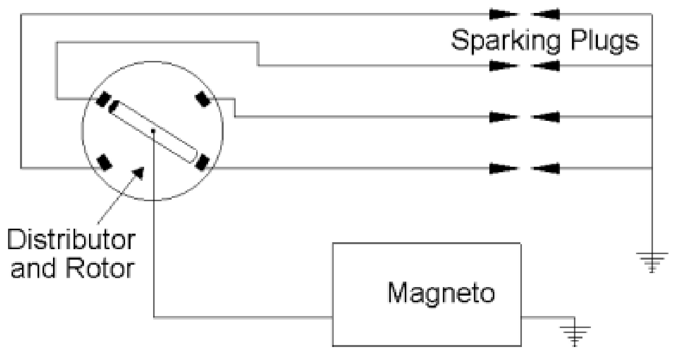


Fig 5 Ignition System Circuit Diagram

10. **Sparking Plugs.** The sparking plugs provide the air gap which produces the spark for ignition of the fuel/air mixture in the combustion chamber. There are two plugs to each cylinder, so that burning of the charge from two points will give more efficient burning and greater power and also provide an alternative source of ignition should one fail.

11. **Magneto**. The magneto is an engine driven electrical generator designed to supply high voltage current to the plugs in sequence, and at a precise time in the compression stroke.

12. **Distributor**. The distributor consists of two parts, a rotor and a distributor block. The rotor is attached to a distributor gear and rotates at a fixed ratio with respect to the magneto and crankshaft. As it rotates it comes opposite to, but does not actually make contact with, each of a number of electrodes in turn. These electrodes, which are insulated from each other and from the body of the magneto, are connected one to each of the plug leads. The rotor receives the high current from the magneto and passes it, via the electrodes and leads, to the appropriate sparking plug.

System Integrity

13. To guard against engine failure due to a defect in the ignition system, two entirely independent magnetos, with two sets of sparking plugs and connecting leads are fitted to each engine. The provision of two sparking plugs in each cylinder also ensures more efficient ignition of the charge, and it is for this reason that a small drop in rpm occurs when one magneto is switched off to test the ignition.

Carburation

14. Carburation is the process by which air and fuel vapour are mixed in suitable proportions and the supply of this mixture regulated according to the requirements at any given operating condition.

15. The mechanical means by which this mixture is achieved is by the use of a carburetter or fuel injector. Their purpose is to supply a well atomised and correctly proportioned mixture of fuel and air to the engine, and to provide a method of limiting the power output by limiting the flow of the mixture.

16. Liquid fuels will not burn unless they are mixed with oxygen. For the mixture to burn efficiently in an engine cylinder, the air/fuel ratio must be kept within a certain range, around 15:1 by weight. The ratio is expressed in weight because volume varies considerably with temperature and pressure

Icing

17. When flying in certain conditions of humidity and temperature, ice will quickly build up on the carburetter or injector air intakes. To obviate this, most aircraft are fitted with a shutter system to blank off entry of the cold air and obtain warm or hot air from inside the engine cowling, but the use of hot air will reduce engine performance and range unless there is air temperature compensation.

Lubrication

18. The primary purpose of a lubricant is to reduce friction between moving surfaces and to cool the surface. It is also used to dissipate heat from the moving parts, pistons and cylinders are particularly dependent on oil for cooling.

19. The internal friction of a fluid, its resistance to flow, is called viscosity. Viscosity varies not only between oils, but between the same oil at differing temperatures. When oil is cold it flows slowly and has a high viscosity making circulation extremely difficult. If the oil gets too hot the viscosity may become so low the film between the bearing surfaces breaks down, metal-to-metal contact occurs and rapid wear and heating results.

Oil Dilution

20. The object of oil dilution is to facilitate the starting of piston engines in cold weather. Fuel is added to the oil to reduce the viscosity, this reduces the torque necessary to turn the engine, and ensures an adequate supply of lubricant to all moving parts at approximately working pressure immediately after engine starting. If carried out regularly, irrespective of the atmospheric temperature prevailing, oil dilution also minimizes the accumulation of sludge deposits within the engine.