AERODYNAMICS (R15A2104)

COURSE FILE

II B. Tech II Semester

(2017-2018)

Prepared By

Ms. Swetha Bala MNVS, Assoc. Prof

Department of Aeronautical Engineering

MALLA REDDY COLLEGE OF ENGINEERING & TECHNOLOGY

(Autonomous Institution – UGC, Govt. of India)

Affiliated to JNTU, Hyderabad, Approved by AICTE - Accredited by NBA & NAAC – 'A' Grade - ISO 9001:2015 Certified
Maisammaguda, Dhulapally (Post Via. Kompally), Secunderabad – 500100, Telangana State, India.

MRCET VISION

- To become a model institution in the fields of Engineering, Technology and Management.
- To have a perfect synchronization of the ideologies of MRCET with challenging demands of International Pioneering Organizations.

MRCET MISSION

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

MRCET QUALITY POLICY.

- To pursue continual improvement of teaching learning process of Undergraduate and Post Graduate programs in Engineering & Management vigorously.
- To provide state of art infrastructure and expertise to impart the quality education.

PROGRAM OUTCOMES

(PO's)

Engineering Graduates will be able to:

1. **Engineering knowledge**: Apply the knowledge of mathematics, science, engineering fundamentals, and an engineering specialization to the solution of complex engineering problems.
2. **Problem analysis**: Identify, formulate, review research literature, and analyze complex engineering problems reaching substantiated conclusions using first principles of mathematics, natural sciences, and engineering sciences.
3. **Design / development of solutions**: Design solutions for complex engineering problems and design system components or processes that meet the specified needs with appropriate consideration for the public health and safety, and the cultural, societal, and environmental considerations.
4. **Conduct investigations of complex problems**: Use research-based knowledge and research methods including design of experiments, analysis and interpretation of data, and synthesis of the information to provide valid conclusions.
5. **Modern tool usage**: Create, select, and apply appropriate techniques, resources, and modern engineering and IT tools including prediction and modeling to complex engineering activities with an understanding of the limitations.
6. **The engineer and society**: Apply reasoning informed by the contextual knowledge to assess societal, health, safety, legal and cultural issues and the consequent responsibilities relevant to the professional engineering practice.
7. **Environment and sustainability**: Understand the impact of the professional engineering solutions in societal and environmental contexts, and demonstrate the knowledge of, and need for sustainable development.
8. **Ethics**: Apply ethical principles and commit to professional ethics and responsibilities and norms of the engineering practice.
9. **Individual and team work**: Function effectively as an individual, and as a member or leader in diverse teams, and in multidisciplinary settings.
10. **Communication**: Communicate effectively on complex engineering activities with the engineering community and with society at large, such as, being able to comprehend and write effective reports and design documentation, make effective presentations, and give and receive clear instructions.
11. **Project management and finance**: Demonstrate knowledge and understanding of the engineering and management principles and apply these to one's own work, as a member and leader in a team, to manage projects and in multi disciplinary environments.
12. **Life- long learning**: Recognize the need for, and have the preparation and ability to engage in independent and life-long learning in the broadest context of technological change.

DEPARTMENT OF AERONAUTICAL ENGINEERING

VISION

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

MISSION

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

QUALITY POLICY STATEMENT

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

PROGRAM EDUCATIONAL OBJECTIVES – Aeronautical Engineering

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

PROGRAM SPECIFIC OUTCOMES – Aeronautical Engineering

1. To mould students to become a professional with all necessary skills, personality and sound knowledge in basic and advance technological areas.
2. To promote understanding of concepts and develop ability in design manufacture and maintenance of aircraft, aerospace vehicles and associated equipment and develop application capability of the concepts sciences to engineering design and processes.
3. Understanding the current scenario in the field of aeronautics and acquire ability to apply knowledge of engineering, science and mathematics to design and conduct experiments in the field of Aeronautical Engineering.
4. To develop leadership skills in our students necessary to shape the social, intellectual, business and technical worlds.

MALLA REDDY COLLEGE OF ENGINEERING & TECHNOLOGY

II Year B. Tech, ANE-II Sem

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4	1/-/-	3

(R15A2104) AERODYNAMICS

Objectives:

- To introduce the concepts of mass, momentum and energy conservation relating to aerodynamics.
- To make the student understand the concept of vorticity, irrotationality, theory of airfoils and wing sections.
- To introduce the basics of viscous flow.

UNIT - I

Basics of Aerodynamics: Review of Fluid Mechanics, Developments in aerodynamics, Fundamental aerodynamics variables, Nomenclature of Airfoil - Aerodynamic forces and moments and coefficients, Pressure distribution on an airfoil, Types of drag, Estimation of lift, Drag and pitching moment coefficient from the pressure distribution. Governing equations - Continuity, momentum and Energy equations in differential form.

UNIT - II

Inviscid Incompressible Flows: Angular Velocity, Vorticity and circulation, Kelvin Theorem and irrotational flow velocity potential, Stream function, Laplace equation, boundary condition at infinity and wall, Elementary flows and their combinations, Magnus effect, D'Alembert's Paradox, Kutta - Joukowsky theorem, kutta condition. Kelvin's circulation theorem & starting vortex, concept of small perturbation & thin airfoil theory - linearization of the boundary condition, resolution of thin airfoil problem into lifting & non-lifting cases, their solutions by method of singularity distribution, the aerodynamic center.

UNIT - III

Viscous Flow and Boundary Layer: Role of viscosity in fluid flow. Boundary layer growth along a flat plate and nearly flat surface, displacement thickness and patching of inviscid external flow to viscous boundary layer flow, laminar boundary layer, transition and turbulent boundary layer, factors influencing boundary layer separation - adverse pressure gradient and sharp bending / turning of surface. Real (viscous) flow and importance of skin friction drag airfoils. Blasius solution for the flat plate problem. Definition of momentum thickness & derivation of Von karman's momentum equation.

UNIT - IV

Inviscid Flow over Wings & Panel Methods: Vortex filament statement of Helmholtz's vortex theorems, Biot - Savart Law, starting, bound & trailing vortices of wings, Prandtl's Lifting line theorem - downwash and induced drag, Elliptic loading & wings of elliptic platforms, expression for induced drag, minimum induced drag for Elliptic platform. Source and vortex panel methods for airfoils.

UNIT - V

Applied Aerodynamics: Drag reduction & lift augmentation - Sweep, winglets, Flaps, slats and vortex generators. Airfoil design for high $C_{l\ max}$, Multiple lifting surfaces, Circulation control, Streamwise vorticity, Secondary flows, Vortex lift strakes.

Text books:

1. Aerodynamics for Engineers, fourth edition, Bertin, J.J., Pearson Education, 2012, ISBN: 81-297-0486-2.
2. Fundamentals of Aerodynamics, Anderson, Jr., J.D., International edition, McGraw Hill, 2001, ISBN: 0-07-118146-6.
3. Kuethe, A.M., and Chow, C., Foundations of Aerodynamics, 5th Edn, Wiley, 1998, ISBN: 0-471-12919-4.
4. Karamcheti, Krishnamurthy, Idea fluid Aerodynamics.

Reference Books:

1. Kuchemann, D., The Aerodynamic Design of Aircraft, Pergamon, 1978.
2. Shevell, R.S., Fundamentals of Flight, Indian reprint, Pearson Education, 2004, ISBN: 81-297-0514-1.
3. McCormick, B.W., Aerodynamics, Aeronautics & Flight Mechanics second edition John Wiley, 1995, ISBN: 0-471-575062.

Outcomes:

- An ability to apply thin airfoil theory to predict aerodynamic characteristics of air foil
- Application of Elementary flows to develop real problems.
- Development of devices to enhance aerodynamic characteristics of aircraft components.

Lesson Plan (2017-2018)

UNIT	TOPIC	No. OF CLASSES
I	Aerodynamics – importance	1
	Types of Flows	1
	ADforce & moment coefficients	1
	Shear and Pressure stress distribution (L,D,N,A)	1
	Types of Drag	1
	dimensional analysis	1
	flow similarity, classification of flows	1
	The continuity equation	1
	momentum equation	1
	energy equation	1
	methods of determination of flow	1
2	Angular velocity, vorticity and circulation	1
	Kelvin's theorem. Irrotational flow. The velocity potential	1
	Stream function for two dimensional incompressible flow	1
	Laplace's equation. Boundary conditions at infinity and at the wall.	1
	Elementary flows and their combinations, non-lifting flow over a circular cylinder, vortex flow	4
	lifting flow over a cylinder. D'Alembert's paradox	1
	Kutta Joukowski theorem and generation of lift. Non-lifting flows over	1
	Theoretical solutions of low speed flow over airfoils - the vortex sheet representation.	1
	The Kutta condition. Kelvin's circulation theorem and the starting vortex. The thin airfoil theory	1
	The aerodynamic centre.	1
	Problems	2
	Revision	1
3	Role of viscosity in fluid flow.	1
	The Navier-Stokes' equation, boundary layer approximation	1
	Boundary layer thicknesses, growth along a flat surface. Laminar boundary layers.	1
	Surface friction drag. Boundary layer separation.	1

	Transition. Turbulent boundary layers,	
	turbulence modelling, eddy viscosity and mixing length concepts. The momentum integral equation	1
	.. Approximate solutions for laminar, turbulent and mixed boundary layers - computational methods.	1 1
	Thermal boundary layer. Reynolds's analogy.	1
4	Downwash and induced drag.	1
	The vortex filament – Biot-Savart's law	1
	Helmholtz's theorems	1
	The starting, bound and trailing vortices	1
	Prandtl's classical lifting line theory for unswept wings– determination of lift,	1
	vortex induced drag.	1
	Elliptical Loading and problems	2
	arbitrary bodies – numerical source panel method. Real flow over a circular cylinder.	1
	Lifting flows over arbitrary bodies – the vortex panel numerical method	1
5	Drag reduction & lift augmentation - Sweep, winglets, Flaps, slats and vortex generators., ,	1
	Airfoil design for high $C_{l\,max}$	1
	Circulation control	1
	Multiple lifting surfaces,	1
	slats and vortex generators	1
	Streamwise vorticity, Secondary flows, Vortex lift strakes	2
	Revision	1

AERODYNAMICS – I (R15)
MODEL PAPER – I
MAXIMUM MARKS: 75

PART A **Marks: 25**

All questions in this section are compulsory
Answer in TWO to FOUR sentences.

1. a. State the applications of Aerodynamics.
   b. Differentiate among Continuum and Free molecular flow.
   c. Define aerodynamic heating. Give the expression for aerodynamic heating rate at the wall.
   d. State the assumptions made in the thin airfoil theory. Give the fundamental equation of thin airfoil theory. What is the aim of thin airfoil theory?
   e. Define adverse pressure gradient. What are the effects of flow separation?
   f. Define laminar boundary layer, critical Reynolds number, and turbulent boundary layer.
   g. Define Vortex filament and state Helmholtz vortex theorem.
   h. Define induced drag and drag polar.
   i. Define the terms critical mach number and drag divergence Mach number
   j. State any three lift augmentation techniques

PART B **Marks: 50**

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

Section I

2. Derive the energy equation by applying the fundamental principle to a suitable flow model.

OR

3. Using neat sketches, explain the flow behavior past stream lined bodies placed in different mach number regimes.

Section II

4. a. Define boundary condition. Explain infinity boundary condition and wall – boundary condition.
   b. Explain Rankine – oval. Derive the equation of Rankine – oval.

OR

5. A stationary circular cylinder is placed in a uniform flow stream of velocity V_∞. Obtain the equation of stream line pattern around the cylinder. Also sketch the pressure distribution over the surface of the cylinder.

Section III

6. Define using neat sketch the viscous drag over a body placed in a uniform free stream. Explain the concept of flow separation and the factors effecting it

OR

7. Obtain the laminar boundary layer thickness and skin friction drag for an incompressible flow over a flat plate at zero angle of attack. (BLASIUS EQUATION)

Section IV

8. a. Derive the fundamental equation of Prandtl’s lifting line theory.

b. Obtain the expressions for coefficients of lift, induced drag, effective angle of attack for an elliptical wing plan-form. Explain the symbols used clearly.

OR

9. Define vortex filament and vortex sheet. Obtain the solution for lifting – flows over 2 – D bodies using vortex panel method. State the advantages of panel method over thin airfoil theory.

Section V

10. Using a neat sketch, explain how lift is augmented by using

a. Flap systems

b. Circulation control wing

OR

11. What is the working principle of Vortex generators? Explain in detail.

AERODYNAMICS – I (R15)
MODEL PAPER – II
MAXIMUM MARKS: 75

PART A **Max Marks: 25**

All questions in this section are compulsory

Answer in TWO to FOUR sentences.

1. a. State Buckingham's pi theorem. What is its significance?

b. Using neat sketches define the aerodynamic forces acting on an airfoil.

c. Define velocity potential and stream function. Obtain the governing equation for in-viscid, incompressible flow in terms of velocity potential and stream function.

d. Define the terms aerodynamic center and center of pressure.

e. Define the terms pressure drag, skin friction drag, parasite drag and profile drag.

f. State the significance of N- S equations.

g. Define wash – in and wash – out conditions.

h. Define the terms aerodynamic twist, downwash and effective angle of attack.

i. State any three lift augmentation and drag reduction techniques used in aircraft designs.

j. State any three drag reduction techniques.

PART B **Marks: 50**

Answer only one question among the two questions in choice.

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

Section I

2. a. Derive Momentum equation in integral form and differential form by applying the physical principle to a suitable flow model. (10 M)

OR

3. Derive the Navier – stokes equation.

Section II

4. A circular cylinder spinning about its own axis is placed in a uniform free – stream of velocity V_∞. Obtain the expression for the lift generated over the cylinder. State all the symbols used clearly.

OR

5. Consider lifting flow over a circular cylinder. The lift coefficient is given by 5. Calculate the peak pressure coefficient, location of stagnation points and the points on the cylinder where the pressure equals free stream static pressure.

Section III

6. Define pressure drag. Explain using neat sketches flow separation and the factors effecting flow separation, and separation control.

OR

7. Define momentum thickness of a boundary layer and derive Von – Karman momentum integral equation.

Section IV

8. Using neat sketches, explain the effect of the presence of down wash on the local airfoil section. How the characteristics of a finite wing are different when compared to the characteristics of airfoil sections?

OR

9. Citing necessary examples, explain the effect the aspect ratio of wings on the performance parameters.

Section V

10. Using neat sketches explain the use of winglets in drag control.

OR

11. Explain the function of leading edge flaps and trailing edge flaps in detail**.**

AERODYNAMICS – I (R15)
MODEL PAPER – III
MAXIMUM MARKS: 75

PART A **Max Marks: 25**

i. All questions in this section are compulsory
ii. Answer in TWO to FOUR sentences.

1. a. Define Reynolds number and Mach number. State their significance.
   b. What are constant – property flows? State any three applications of constant – property flows.
   c. State Kelvin's circulation theorem.
   d. For a thin symmetrical airfoil at an angle of attack of 2^0, calculate the coefficient of lift andcoefficient of moment at the leading edge.
   e. What are the approximations made while solving the incompressible flow over a flat plate using Blasius equation?
   f. Sketch the velocity profile and flow separation over an airfoil in a moving fluid. (**fig 15.2 page 794, J. D. Anderson**)
   g. Give the fundamental equation for Prandtl's lifting line theory.
   h. Define elliptical loading.
   i. Name the primary effects of using a slot (wing gap) on the boundary layer.
   j. What is meant by lift augmentation? State its advantages.

PART B **Marks: 50**

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

Section I

2. Using Buckingham's pi theorem, explain the factors on which the basic parameters of aerodynamics depend on.

OR

3. a. Explain the criterion to be established for the flows to be dynamically similar.

b. Consider an aircraft cruising at a velocity of 245.87m/s at standard altitude of 11582.4 m, where the free stream pressure and temperature are 20712.9 N/m^2 and 216.67 K, respectively. A one – fifth model of the craft is tested in a wind tunnel where the temperature is 238.88 K. Calculate the required pressure and velocity of the test air stream in the wind tunnel such that the aerodynamic coefficients measured for the wind tunnel model are same as for free flight. Assume μ and *a* are proportional to $T^{1/2}$.

Section II

4. a. State Kutta condition.

b. Derive the fundamental equation of thin airfoil theory. Explain the symbols used clearly.

OR

5. a. Define source flow and sink flow. Obtain the expression for velocity potential and stream function for the source flow. Define the strength of the source.

b. Consider a thin flat plate at 5^0, angle of attack. Using the results of thin airfoil theory, calculate the lift coefficient, moment coefficient about the leading edge, moment coefficient about the quarter chord point and the moment coefficient about the trailing edge.

Section III

6. a. Using neat sketch, explain the growth of a boundary layer over a flat plate. Define the terms laminar boundary layer, turbulent boundary layer and transition boundary layer.

b. Define boundary layer thickness, energy thickness and momentum thickness.

OR

7. **Example problems 18.1 and 19.1 of chapters 18 and 19 of J. D. Anderson**

Section IV

8. Consider a rectangular wing with an aspect ratio of 6, an induced drag factor is given by 0.055 and a zero – lift angle of attack of -2^0. At an AoA of 3.4^0, the induced drag coefficient for this wing is 0.01. Calculate the induced drag coefficient for a similar wing (a rectangular wing with the same airfoil section) at the same angle of attack, but with an aspect ration of 10. Assume that the induced factors for the drag and lift slope are equal to each other.

OR

9. .Explain the concept of vortex trunk and vortex theory by Lanchester.

Section V

10. Explain using necessary illustrations, how swept back wings are advantageous in reducing transonic drag rise.

OR

11. State the function of a) Winglets b) Swept wings. Explain the advantages and disadvantages of each.

AERODYNAMICS – I (R15)
MODEL PAPER – IV
MAXIMUM MARKS: 75

PART A **Max Marks: 25**

All questions in this section are compulsory
Answer in TWO to FOUR sentences.

1. a. Using a neat sketch, define transonic flow regime and explain fish tail pattern.
   b. State the criterion for two or more flows to be dynamically similar.

   c. Give the expression for pressure distribution on the surface of circular cylinder placed in a non – lifting flow. Graphically represent it.
   d. Define uniform flow, vortex flow and source flow.
   e. What is the effect of surface roughness on transition point distance from the leading edge?
   f. What is meant by a transport phenomenon? Define viscosity and thermal conduction.
   g. What are the factors on which the lift and induced drag coefficients depend on?
   h. State the significance of elliptical wing plan-form.
   i. Define advance ratio, pitch and solidity of a propeller.
   j. Briefly write about laminar flow control.

PART B **Marks: 50**

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

Section I

2. a. What are the sources of aerodynamic forces and moments? Explain using a neat sketch.

b. Explain the role of lift and drag coefficients in the preliminary design of an aircraft using neat sketches. (**REFER Pg. 45 DESIGN BOX of J. D. Anderson**)

OR

3. a. Derive the continuity equation in integral form and differential form by applying the fundamental principle to the suitable flow model.

b. State the significance of Reynolds number in aerodynamics.

Section II

4. From the fundamental equation of thin airfoil theory, obtain the aerodynamic force and moment coefficients and the position of center of pressure for a cambered airfoil. Explain all the symbols used clearly.

OR

5. Consider a non – lifting flow and lifting flow (of constant circulation) over the circular cylinder of a given radius. For the two cases mentioned, if the free stream velocity is doubled, does the shape of the stream lines change? Explain using necessary equations.

Section III

6. a. Define Viscosity.

b. Explain the role of viscosity in fluid flow and aerodynamics.

c. Define adverse pressure gradient

OR

7. Derive Navier – Stokes equations.

Section IV

8. Define discretisation. State the importance of quarter – chord point and three – quarter chord point in discretisation.

OR

9. Derive the fundamental equation of Prandtl's lifting line theory. Apply it to solve for the aerodynamic parameters of a rectangular swept back wing.

Section V

10. Define stall. Explain the effect of wing – section, wing plan – form and protuberances on the performance of an aircraft.

OR

11. How does the secondary control surfaces operate on an aircraft. Explain in brief.

AERODYNAMICS – I (R15)
MODEL PAPER – V
MAXIMUM MARKS: 75

PART A **Max Marks: 25**

All questions in this section are compulsory
Answer in TWO to FOUR sentences.

1. a. Define with an example, surface forces and body forces acting on an object in fluid flow.

b. Using neat sketches show the various fluid flow models used for analyzing the flow.

c. Define the terms circulation, vorticity and turbulent flows.

d. State Kutta – Joukowski theorem. Brief the importance of friction in generating lift.

e. Give the expressions for energy thickness and momentum thickness of the laminar boundary layer over a flat plate placed at zero angle of attack in a free stream of velocity V_∞.

f. Using a neat sketch show the boundary layer properties. (**Fig. 17.3 Pg. 870, J.D. Anderson**)

g. Using a neat sketch show geometric, effective and induced angles of attack.

h. Define wing tip vortices, horse – shoe vortex and induced drag.

i. State the assumptions made in Rankine – Froude momentum theory of propulsion.

j. What are the factors on which the performance of wing depends on?

PART B **Marks: 50**

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

Section I

2. Explain how drag on a two – dimensional body is measured by applying momentum equation. (**refer Pg. 127 Section 2.6 of J. D. Anderson**)

OR

3. Explain the importance of aerodynamics and applications of the subject in various fields of engineering.

Section II

4. a. The lift on a spinning cylinder in a free stream with a velocity of 30 m/s and at standard sea level conditions is 6 N/m of span. Calculate the circulation round the cylinder.

b. Consider a uniform flow of velocity $V\infty$. Show that it is a possible case of incompressible flow that is irrotational.

OR

5. State the fundamental equation of thin airfoil theory. Obtain the solution for the non – lifting case using singularity distribution method.

Section III

6. Sketch the variation of variation of viscous drag coefficient with the Reynolds number over a circular cylinder and explain.

OR

7. Define critical Reynolds number. State the effect of transition and surface roughness of airfoils on its performance characteristics.

Section IV

8. State the advantages and disadvantages of vortex panel method over thin airfoil theory while solving for the performance parameters of an airfoil in incompressible inviscid flow.

OR

9. Consider a finite wing with an aspect ratio of 6. Assume an elliptical lift distribution. The lift slope for the airfoil section is 0.1/degree. Calculate and compare the lift slopes for (a) straight wing and a (b) swept wing with half – chord sweep of 45^0

Section V

10. a. Using neat sketches, explain how drag is reduced by using variable – twist and variable – camber wings.

    b. Explain power – augmented lift.

OR

11. a. Describe briefly the design philosophies used in conventional high lift airfoil design.

    b. What are the advantages of multiple lifting surfaces and explain about multi lifting surface interference effects.

R15

Code No: R15A2104

MALLA REDDY COLLEGE OF ENGINEERING & TECHNOLOGY

(Autonomous Institution – UGC, Govt. of India)

II B.Tech II Semester supplementary Examinations, November/December 2017

Aerodynamics

(AE)

Roll No										

Time: 3 hours **Max. Marks: 75**

Note: This question paper contains two parts A and B

Part A is compulsory which carriers 25 marks and Answer all questions.

Part B Consists of 5 SECTIONS (One SECTION for each UNIT). Answer FIVE Questions, Choosing ONE Question from each SECTION and each Question carries 10 marks.

PART – A (25 Marks)

1. (a) Distinguish between finite wing and infinite wing. 2M
   (b) List the fundamental aerodynamic variables. 3M
   (c) What is D'Alemberts paradox? 2M
   (d) Prove that the stream lines and equipotential lines are mutually perpendicular. 3M
   (e) What is the Blasius solution for a flow over a flat plate at zero angle of attack? 2M
   (f) Define boundary layer and its properties. 3M
   (g) What are panel methods? 2M
   (h) Define the terms effective angle of attack, down wash and induced drag 3M
   (i) List out the lift augmentation methods. 2M
   (j) Brief the working of vortex generators. 3M

PART – B (50 Marks)

SECTION – I

2. Using neat sketches explain the sources of aerodynamic forces acting on a stationary body placed in the flow. Derive the expression for lift and drag acting on the body.

(OR)

3. Derive the energy equation in the form of a differential equation. 10M

SECTION – II

4. Show that a source flow is a physically possible incompressible flow everywhere except at the origin. Also show that it is irrotational everywhere. 10M

(OR)

5. a. Consider the velocity field given by u = $\frac{y}{(x^2+y^2)}$ and v = $\frac{-x}{(x^2+y^2)}$, calculate the equation of the streamline passing through point (0,4) and calculate the vorticity for the velocity field. 5M

   b. Show that the uniform, and doublet flow fields satisfy the expressions of mass conservation equation (two-dimensional, inviscid flow). 5M

SECTION – III

6. Explain the boundary layer growth over a flat plate with neat sketches. 10M

(OR)

7. a. The airplane is flying at standard sea level conditions at 180 mph. The dimensions of the wing chord = 5ft and span = 30ft. calculate the total friction drag acting on the wing and also find its drag coefficient By representing the wing of an airplane as a flat plate. 5M

   b. Explain about the influence of boundary layer separation due to adverse pressure gradient and sharp bending/turning surface. 5M

SECTION – IV

8. a. Based on the lifting line theory show that the downwash is constant over the span for elliptic lift distribution. 5M

   b. Explain how induced drag is produced by a lifting wing. 5M

(OR)

9. Derive fundamental equation of Prandtl's lifting line theory? And state the assumptions made 10M

SECTION – V

10. What is lift augmentation? Explain in how sweep, winglets and different types of flaps are used in lift augmentation. 10M

(OR)

11. a. Describe briefly the design philosophies used in conventional high lift airfoil design. 5M

    b. What are the advantages of multiple lifting surfaces and explain about multi lifting surface interference effects. 5M

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UNIT – I

Basics of Aerodynamics

Index

Contents:

1. Introduction:

Aerodynamics is a sub-field of fluid dynamics and gas dynamics, and many aspects of aerodynamics theory are common to these fields. The term *aerodynamics* is often used synonymously with gas dynamics, the difference being that "gas dynamics" applies to the study of the motion of all gases, and is not limited to air.

Aerodynamics is primarily concerned with the forces of drag and lift, which are caused by air passing over and around solid bodies. Engineers apply the principles of aerodynamics to the designs of many different things, including buildings, bridges and even soccer balls; however, of primary concern is the aerodynamics of aircraft and automobiles.

Aerodynamics comes into play in the study of flight and the science of building and operating an aircraft, which is called ***Aeronautics.*** Aeronautical engineers use the fundamentals of aerodynamics to design aircraft that fly through the Earth's atmosphere.

(for detailed information: Refer **FUNDAMENTALS OF AERODYNAMICS – JOHN.D.ANDERSON)**

1.1NEED FOR STUDY OF AERODYNAMICS

Aerodynamics is the way objects move through air. The rules of aerodynamics explain how an airplane is able to fly. Anything that moves through air is affected by aerodynamics, from a rocket blasting off, to a kite flying. Since they are surrounded by air, even cars are affected by aerodynamics.

Studying the motion of air around an object allows us to measure the forces of lift, which allows an aircraft to overcome gravity, and drag, which is the resistance an aircraft “feels” as it moves through the air. Everything moving through the air (including airplanes, rockets, and birds) is affected by aerodynamics.

What Are the Four Forces of Flight?

The four forces of flight are lift, weight, thrust and drag. These forces make an object move up and down, and faster or slower. The amount of each force compared to its opposing force determines how an object moves through the air.

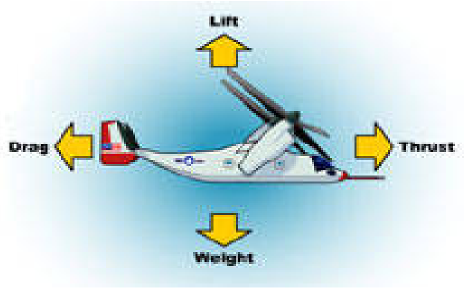


Fig: Four Forces on an Airplane (Ref: NASA)

What Is Weight?

Gravity is a force that pulls everything down to Earth. Weight is the amount of gravity multiplied by the mass of an object. Weight is also the downward force that an aircraft must overcome to fly. A kite has less mass and therefore less weight to overcome than a jumbo jet, but they both need the same thing in order to fly -- lift.

What Is Lift?

Lift is the push that lets something move up. It is the force that is the opposite of weight. Everything that flies must have lift. For an aircraft to move upward, it must have more lift than weight.

A hot air balloon has lift because the hot air inside is lighter than the air around it. Hot air rises and carries the balloon with it.

A helicopter's lift comes from the rotor blades. Their motion through the air moves the helicopter upward.

Lift for an airplane comes from its wings.

How Do an Airplane's Wings Provide Lift?

The shape of an airplane's wings is what makes it possible for the airplane to fly. Airplanes' wings are curved on top and flatter on the bottom. That shape makes air flow over the top faster than under the bottom. As a result, less air pressure is on top of the wing. This lower pressure makes the wing, and the airplane it's attached to, move up. Using curves to affect air pressure is a trick used on many aircraft. Helicopter rotor blades use this curved shape. Lift for kites also comes from a curved shape. Even sailboats use this curved shape. A boat's sail is like a wing. That's what makes the sailboat move.

What Is Drag?

Drag is a force that pulls back on something trying to move. Drag provides resistance, making it hard to move. For example, it is more difficult to walk or run through water than through air. Water causes more drag than air. The shape of an object also affects the amount of drag. Round surfaces usually have less drag than flat ones. Narrow surfaces usually have less drag than wide ones. The more air that hits a surface, the more the drag the air produces.

What Is Thrust?

Thrust is the force that is the opposite of drag. It is the push that moves something forward. For an aircraft to keep moving forward, it must have more thrust than drag. A small airplane might get its thrust from a propeller. A larger airplane might get its thrust from jet engines. A glider does not have thrust. It can only fly until the drag causes it to slow down and land.

For further reference: http://www.encyclopedia.com/science-and-technology/technology/aviation-general/aerodynamics

1.2INTERNAL AND EXTERNAL AERODYNAMICS

Aerodynamics is an applied science with many practical applications in engineering. No matter how elegant an aerodynamic theory may be, or how mathematically complex a numerical solution may be, or how sophisticated an aerodynamic experiment may be, all such efforts are usually aimed at one or more of the following practical objectives:

1. **External Aerodynamics:** ***The prediction of forces and moments on, and heat transfer to, bodies moving through a fluid (usually air).*** For example, we are concerned with the generation of lift, drag, and moments on airfoils, wings, fuselages, engine nacelles, and, most importantly, whole airplane configurations. We want to estimate the wind force on buildings, ships, and other surface vehicles. We are concerned with the hydrodynamic forces on surface ships, submarines, and torpedoes. We need to be able to calculate the aerodynamic heating of flight vehicles ranging from the supersonic transport to a planetary probe entering the atmosphere of Jupiter. These are but a few examples.
2. **Internal Aerodynamics:** ***Determination of flows moving internally through ducts*.** We wish to calculate and measure the flow properties inside rocket and air-breathing jet engines and to calculate the engine thrust. We need to know the flow conditions in the test section of a wind tunnel. We must know how much fluid can flow through pipes under various conditions. A recent, very interesting application of aerodynamics is high-energy chemical and gas-dynamic lasers (see Ref. 1), which are nothing more than specialized wind tunnels that can produce extremely powerful laser beams. Figure 1.5 is a photograph of an early gas-dynamic laser designed in the late 1960s

1.3AERODYNAMICS IN DIFFERENT FIELDS OF ENGINEERING

Aerodynamics is important in a number of applications other than aerospace engineering.

- It is a significant factor in any type of **vehicle design**, including automobiles.
- It is important in the prediction of forces and moments acting on **sailing vessels**.
- It is used in the **design of mechanical components** such as hard drive heads.
- **Structural engineers** also use aerodynamics, and particularly aero-elasticity, to calculate wind loads in the design of large buildings and bridges.
- **Urban aerodynamics** seeks to help town planners and designers improve comfort in outdoor spaces, create urban microclimates and reduce the effects of urban pollution.
- The field of **environmental aerodynamics** describes the ways atmospheric circulation and flight mechanics affect ecosystems.
- The aerodynamics of **internal passages** is important in heating/ventilation, gas piping, and in automotive engines where detailed flow patterns strongly affect the performance of the engine.

- People who do **wind turbine design** use aerodynamics.
- A few aerodynamic equations are used as part of **numerical weather prediction**.

2. REVIEW OF FLUID MECHANICS

Fluid dynamics is "the branch of applied science that is concerned with the movement of liquids and gases,". Fluid dynamics is one of two branches of fluid mechanics, which is the study of fluids and how forces affect them. (The other branch is fluid statics, which deals with fluids at rest.)
The movement of liquids and gases is generally referred to as "flow," a concept that describes how fluids behave and how they interact with their surrounding environment — for example, water moving through a channel or pipe, or over a surface. Flow can be either steady or unsteady."If all properties of a flow are independent of time, then the flow is steady; otherwise, it is unsteady." *(Reference: "Lectures in Elementary Fluid Dynamics" (University of Kentucky, 2009) J. M. McDonough)*. An example of steady flow would be water flowing through a pipe at a constant rate. On the other hand, a flood or water pouring from an old-fashioned hand pump are examples of unsteady flow.

The gas most commonly encountered in everyday life is air; therefore, scientists have paid much attention to its flow conditions. Wind causes air to move around buildings and other structures, and it can also be made to move by pumps and fans.

One area of particular interest is the movement of objects through the atmosphere. This branch of fluid dynamics is called aerodynamics, which is "the dynamics of bodies moving relative to gases, especially the interaction of moving objects with the atmosphere," according to the American Heritage Dictionary. Problems in this field involve reducing drag on automobile bodies, designing more efficient aircraft and wind turbines, and studying how birds and insects fly.

For further information refer: https://www.livescience.com/47446-fluid-dynamics.html

2.1Types of flows

Aerodynamic flows are categorized and visualized under various broad headings and the subject deals with the physical phenomenon of each flow.

2.1.1 Continuum and Free Molecular Flow

- The concept of continuum is a kind of idealization of the continuous description of matter where the properties of the matter are considered as continuous functions of space variables. Although any matter is composed of several molecules, the concept of continuum assumes a continuous distribution of mass within the matter or system with no empty space, instead of the actual conglomeration of separate molecules.

- Describing a fluid flow quantitatively makes it necessary to assume that flow variables (pressure, velocity etc.) and fluid properties vary continuously from one point to another. Mathematical description of flow on this basis has proved to be reliable and treatment of fluid medium as a continuum has firmly become established. For example density at a point is normally define

$$\boldsymbol{\rho = \lim_{\Delta V \to 0} \left[\frac{m}{\Delta V}\right]}$$

Here ΔV is the volume of the fluid element and m is the mass

- If ΔV is very large ρ is affected by the in homogeneities in the fluid medium. Considering another extreme if ΔV is very small, random movement of atoms (or molecules) would change their number at different times. In the continuum approximation point density is defined at the smallest magnitude of ΔV, before statistical fluctuations become significant. This is called continuum limit and is denoted by ΔV_c.

$$\boldsymbol{\rho = \lim_{\Delta V \to \Delta V_C} \left[\frac{m}{\Delta V}\right]}$$

- One of the factors considered important in determining the validity of continuum model is molecular density. It is the distance between the molecules which is characterised by **mean free path (λ)**.
- It is calculated by finding statistical average distance the molecules travel between two successive collisions. *If the mean free path is very small as compared with some characteristic length in the flow domain (i.e., the molecular density is very high) then the gas can be treated as a* ***continuous medium****. If the mean free path is large in comparison to some characteristic length, the gas cannot be considered continuous and it should be analysed by the* ***molecular theory****.*

A dimensionless parameter known as **Knudsen number**,

$$\boldsymbol{K_n = \frac{\lambda}{L}}$$

where λ is the mean free path and L is the characteristic length. It describes the degree of departure from continuum. *Usually when $K_n > 0.01$, the concept of continuum does not hold good.*

Beyond this critical range of Knudsen number, the flows are known as

- Slip flow or continuum flow **($0.01 < K_n < 0.1$),**
- Transition flow **($0.1 < K_n < 10$)** and
- free-molecule flow **($K_n > 10$)**.

However, for the flow regimes considered in this course, K_n is always less than 0.01 and it is usual to say that the fluid is a continuum. Other factor which checks the validity of continuum is the elapsed time between collisions. The time should be small enough so that the random statistical description of molecular activity holds good.

In continuum approach, fluid properties such as density, viscosity, thermal conductivity, temperature, etc. can be expressed as continuous functions of space and time.

For the calculations in Classical Aerodynamics, we always assume the flow to be continuous.

2.1.2 Classification of flows with respect to Mach number

As an aircraft moves through the air, the air molecules near the aircraft are disturbed and move around the aircraft. If the aircraft passes at a low speed, typically less than 250 mph, the density of the air remains constant. But for higher speeds, some of the energy of the aircraft goes into compressing the air and locally changing the density of the air. This compressibility effect alters the amount of resulting force on the aircraft. The effect becomes more important as speed increases. Near and beyond the speed of sound, about 330 m/s or 760 mph, small disturbances in the flow are transmitted to other locations isentropically or with constant entropy. But a sharp disturbance generates a shock wave that affects both the lift and drag of an aircraft.

The ratio of the speed of the aircraft to the speed of sound in the gas determines the magnitude of many of the compressibility effects. Because of the importance of this speed ratio, aerodynamicists have designated it with a special parameter called the **Mach number** in honor of **Ernst Mach**, a late 19th century physicist who studied gas dynamics. The Mach number **M** allows us to define flight regimes in which compressibility effects vary.

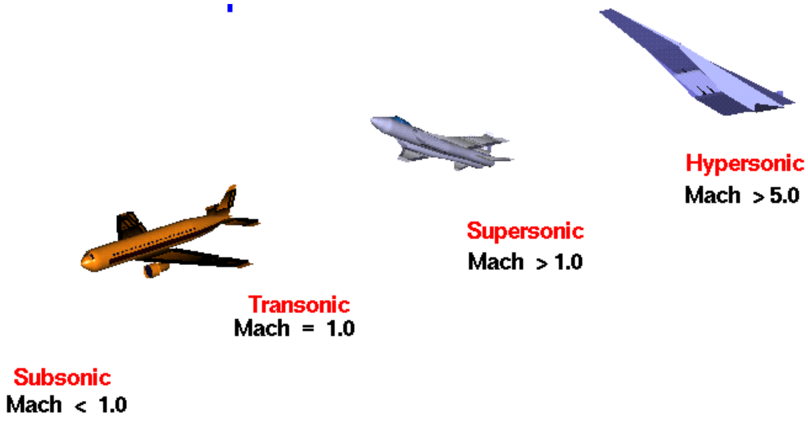


Fig: Aircraft Designs in Different Flow regimes (Courtesy: NASA)

*Various **flow regimes** are classified based on the definition of Mach number:*

Subsonic Flow (M_∞<1): When the fluid velocity is lower than the acoustic speed **(M<1**) then the fluid flow is called as subsonic. However Mach number of the flow changes while passing over an object or through a duct. Hence for simplicity, flow is considered as subsonic if Mach number is in the range of 0-0.8. All small amplitude disturbances travel with acoustic speed and speed of the flow in the subsonic regime is less than acoustic speed hence presence of the disturbance is felt by the whole fluid domain. Therefore subsonic flow is pre-warned or prepared to face the disturbance.

Fig: Subsonic flow over an airfoil

Transonic flow (0.8< M_∞<1.2): When the flow Mach number is in the range 0.8-1.2 it is called transonic flow. Highly unstable and mixed subsonic and supersonic flows are the main features of this regime.

Fig: Transonic flow with M_∞ <1

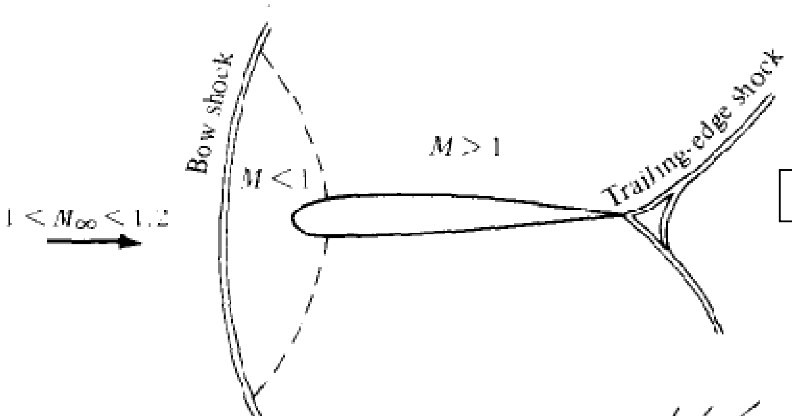


Fig: Transonic flow with M_∞ >1

Sonic flow (M_∞=1): When flow Mach number is 1 it is called sonic flow.

Supersonic Flow (M_∞>1 everywhere): When the flow Mach number is more than one *everywhere in the domain* then it is called as supersonic flow. This flow is not pre-warned since the fluid speed is more than the speed of sound.

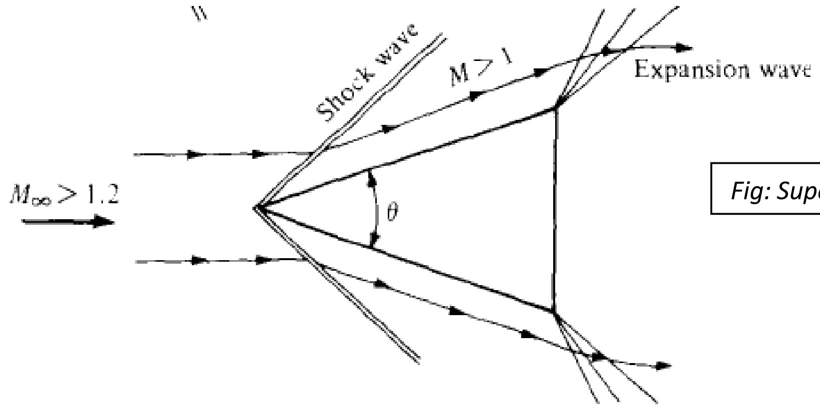


Fig: Supersonic flow with M∞ >1.2

Hypersonic Flow (M>5): As per the thumb rule, when the flow Mach number is more than 5 then it is called as hypersonic flows. This is not the fixed definition for hypersonic flow since hypersonic flow is defined by certain characteristics of flow.

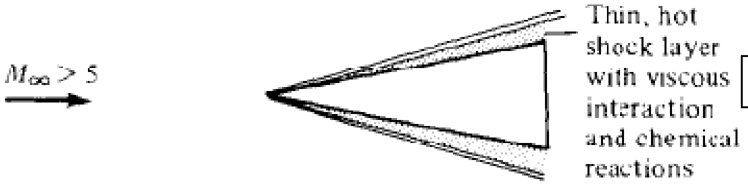


Fig: Hypersonic flow with M∞ >1.2

M∞ = Free stream Mach Number

***For further reading Refer: John.D.Anderson "Fundamentals of Aerodynamics"*

2.1.3 Compressible and incompressible flow (Bernoulli'sPrinciple)

- In order to know, if it is necessary to take into account the compressibility of gases in fluid flow problems, we need to consider whether the change in pressure brought about by the fluid motion causes large change in volume or density.

  Using Bernoulli's equation

$p + (1/2)\rho V^2$= constant *(V* being the velocity of flow), change in pressure, *Δp,* in a flow field, is of the order of $(1/2)\rho V^2$ (dynamic head).

Invoking this relationship into

$$E = \lim_{\delta\rho \to 0} \left(\frac{\Delta p}{\Delta \rho / \rho} \right) = \rho \frac{dp}{d\rho}$$

we get ,

$$\frac{\Delta \rho}{\rho} \approx \frac{1}{2} \frac{\rho V^2}{E} \qquad (2.12)$$

So if Δρ/ρ is very small, the flow of gases can be treated as incompressible with a good degree of approximation.

According to Laplace's equation, the velocity of sound is given by

$$a = \sqrt{\frac{E}{\rho}}$$

Hence

$$\frac{\Delta\rho}{\rho} \sim \frac{1}{2}\frac{V^2}{a^2} \sim \frac{1}{2}Ma^2$$

where, M_a is the ratio of the velocity of flow to the acoustic velocity in the flowing medium at the condition and is known as **Mach number**. So we can conclude that the compressibility of gas in a flow can be neglected if Δρ/ρ is considerably smaller than unity, i.e. $(1/2)M_a^2 << 1$.

- In other words, if the flow velocity is small as compared to the local acoustic velocity, compressibility of gases can be neglected. ***Considering a maximum relative change in density of 5 per cent as the criterion of an incompressible flow, the upper limit of Mach number becomes approximately 0.33***. *In the case of air at standard pressure and temperature, the acoustic velocity is about 335.28 m/s.*
- *Hence a Mach number of 0.33 corresponds to a velocity of about 110 m/s. Therefore flow of air up to a velocity of 110 m/s under standard condition can be considered as incompressible flow.*

2.2 Forces acting on a body moving in a fluid

In some cases, fluid forces have little effect on an object’s motion (e.g., shotput). In other cases, fluid forces are significant - badminton, baseball, swimming, cycling, etc.

Three major fluid forces of interest:

- Buoyancy – The forces
- Drag
- Lift

***For more definitions/explanations refer: JD Anderson, ‘Fundamentals of Aerodynamics’*

***https://www.asu.edu/courses/kin335/documents/Fluid%20mechanics.pdf*

2.3Boundary Layer concepts

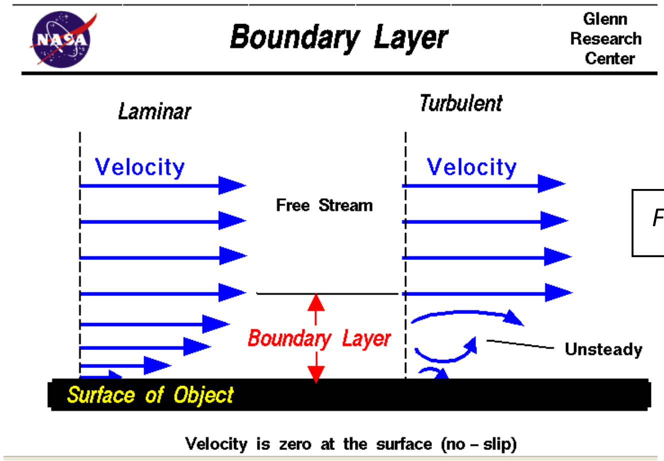


Fig: Concept of Boundary Layer (Courtesy: NASA)

The concept of boundary layer was first introduced by a German engineer, Prandtl in 1904. According to Prandtl theory, when a real fluid flows past a stationary solid boundary, the flow will be divided into two regions.

i) A thin layer adjoining the solid boundary where the viscous force and rotation cannot be neglected.

ii) An outer region where the viscous force is very small and can be neglected. The flow behaviour is similar to the upstream flow.

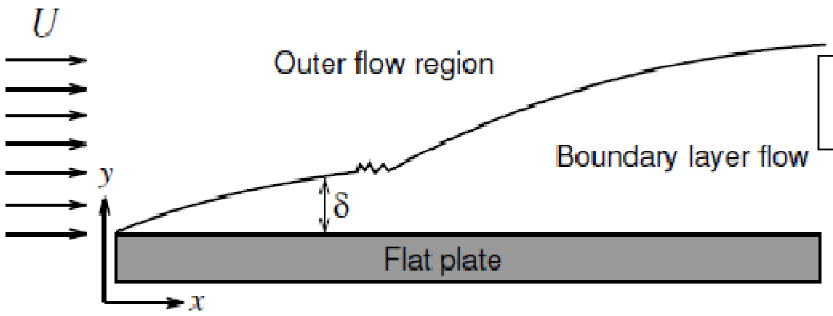


Fig: Boundary Layer growth over a Flat Plate

In a boundary layer the character of the flow thus changes from creeping near the boundary to ideal far from it. The most interesting and also most difficult physics characteristically takes place in such transition regions. Boundary layers serve to insulate bodies from the ideal flow that surrounds them. They have a "life of their own" and may separate from the solid walls and wander into regions containing only fluid. Detached layers may again split up, creating complicated unsteady patterns of whirls and eddies. Advanced understanding of fluid mechanics begins with the understanding of boundary layers.

Consider a nearly ideal flow with velocity U along a solid wall at rest as in above figure. The Reynolds number is as usual calculated as $Re \approx UL/v$ where L is a typical length scale for significant changes in the flow, determined by the geometry of bodies and containers. The no-slip condition requires the velocity to vary from zero right at the wall to U in the flow at large.

Under many — but not all— circumstances, this transition will for Re À 1 take place in a thin boundary layer of thickness δ << L.

Close to the wall, the velocity field is tiny because of the no-slip condition. The flow pattern will in this region always be laminar, in fact creeping, with the parallel (streamwise) velocity rising linearly from zero. The laminar flow may extend all the way to the edge of the boundary layer, or the flow may at sufficiently high Reynolds number become turbulent.

3. SOURCES OF AERODYNAMIC FORCES

Four of the most frequently used words in aerodynamics: "pressure," "density," "temperature," and "flow velocity."

The ***pressure p*** is the limiting form of the force per unit area, where the area of interest has shrunk to nearly zero at the point B. Pressure is a *point property* and can have a different value from one point to another in the fluid.

Where *dA->0*

***Density**,* defined as the mass per unit volume. it is a *point property* that can vary from point to point in the fluid.

Where *dv->0*

Temperature takes on an important role in high-speed aerodynamics. The temperature *T* of a gas is directly proportional to the average kinetic energy of the molecules of the fluid.

In fact, if KE is the mean molecular kinetic energy, then temperature is given by KE = 3/2 *kT,* where *k* is the Boltzmann constant. Hence, we can qualitatively visualize a high,-temperature gas as one in which the molecules and atoms are randomly rattling about at high speeds, whereas in a low-temperature gas, the random motion of the molecules is relatively slow. Temperature is also a *point property*, which can vary from point to point in the gas.

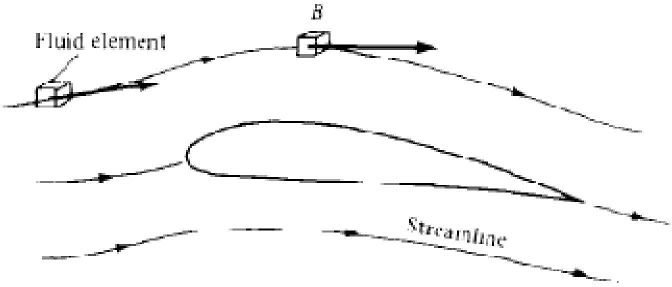


Fig: Flow velocity along the Streamlines at Point B in the flow

Flow velocity can now be defined as follows: The velocity of a flowing gas at any fixed point *B* in space is the velocity of an infinitesimally small fluid element as it sweeps through *B.* The flow velocity **V** has both magnitude and direction; hence, it is a vector quantity.
A moving fluid element traces out a fixed path in space. As long as the flow is steady, i.e., as long as it does not fluctuate with time, this path is called a *streamline* of the flow. Drawing the streamlines of the flow field is an important way of visualizing the motion of the gas.

3.1Pressure and Shear stress distribution

The basic sources of aerodynamic forces on a body moving in a fluid or flow over a stationary body are

1. Pressure distribution(**p=p(s)**) over the body surface – Normal to the surface
2. Shear stress distribution(**τ=τ(s)**) over the body surface – tangential to the surface

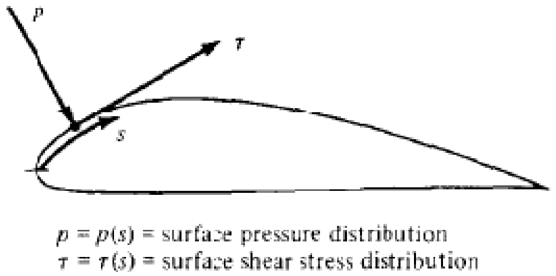


Fig:Pressure(P) and shear stress(τ) over the surface

3.2 Airfoil Nomenclature

It is a fact of common experience that a body in motion through a fluid experiences a resultant force which, in most cases is mainly a resistance to the motion. A class of body exists, However for which the component of the resultant force normal to the direction to the motion is many time greater than the component resisting the motion, and the possibility of the flight of an airplane depends on the use of the body of this class for wing structure.

***<u>Mechanism for generation of lift:</u>* Airfoil is such an aerodynamic shape that when it moves through air, the air is split and passes above and below the wing.** The wing's upper surface is shaped so the air rushing over the top speeds up and stretches out. This decreases the air pressure above the wing. The air flowing below the wing moves in a comparatively straighter line, so its speed and air pressure remains the same.
Since high air pressure always moves toward low air pressure, the air below the wing pushes upward toward the air above the wing. The wing is in the middle, and the whole wing is "lifted." The faster an airplane moves, the more lift there is. And when the force of lift is greater than the force of gravity, the airplane is able to fly.
*An **airfoil** is a body of such a shape that when it is placed in an airstreams, it produces an aerodynamic force. Airfoil is the cross sections of wings; propeller blades, windmill blades, compressor and turbine blades in a jet engine, and hydrofoils are examples of airfoils.*

Airfoil Basic Geometry: The leading edge is the point at the front of the airfoil that has maximum curvature. The trailing edge is defined similarly as the point of maximum curvature at the rear of the airfoil. The chord line is a straight line connecting the leading and trailing edges of the airfoil. The chord length, or simply chord is the length of the chord line and is the characteristic dimension of the airfoil section.

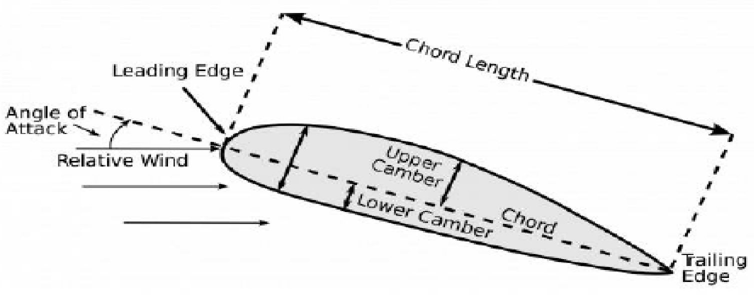
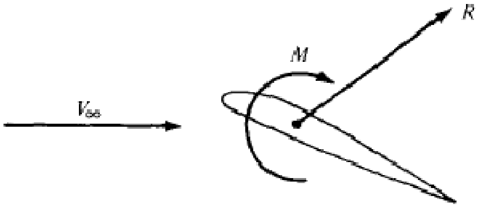
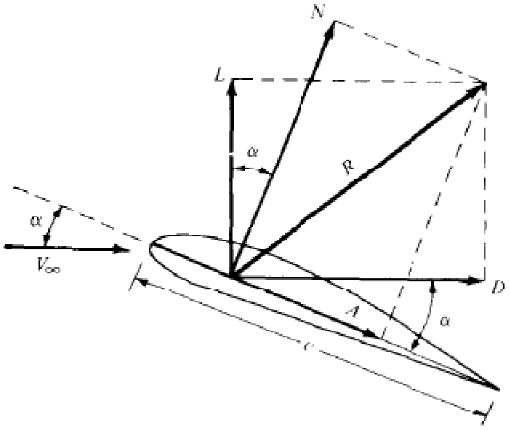


Fig: Basic Geometry of a Airfoil

3.3 Expressions for N, A, L, D (Detailed notes given in the class – derivation)

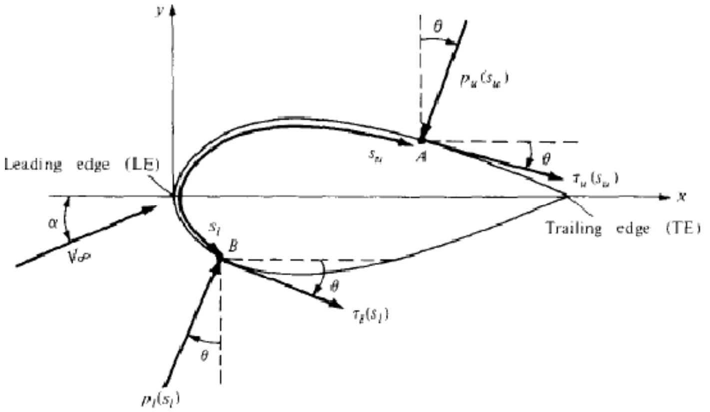


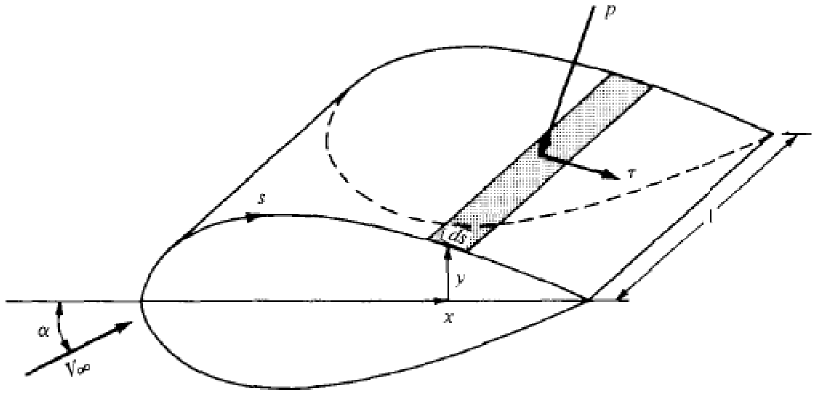


$$L = N\cos\alpha - A\sin\alpha$$

$$D = N\sin\alpha + A\cos\alpha$$

where α – Angle of attack





$$N' = -\int_{\mathrm{LE}}^{\mathrm{TE}} (p_u \cos\theta + \tau_u \sin\theta)\, ds_u + \int_{\mathrm{LE}}^{\mathrm{TE}} (p_l \cos\theta - \tau_l \sin\theta)\, ds_l$$

$$A' = \int_{\mathrm{LE}}^{\mathrm{TE}} (-p_u \sin\theta + \tau_u \cos\theta)\, ds_u + \int_{\mathrm{LE}}^{\mathrm{TE}} (p_l \sin\theta + \tau_l \cos\theta)\, ds_l$$

$$M'_{\mathrm{LE}} = \int_{\mathrm{LE}}^{\mathrm{TE}} [(p_u \cos\theta + \tau_u \sin\theta)x - (p_u \sin\theta - \tau_u \cos\theta)y]\, ds_u$$

$$+ \int_{\mathrm{LE}}^{\mathrm{TE}} [(-p_l \cos\theta + \tau_l \sin\theta)x + (p_l \sin\theta + \tau_l \cos\theta)y]\, ds_l$$

3.4 Aerodynamic Coefficients (Detailed notes given in the class – Derivation)

Dynamic Pressure: q_∞: **Dynamic pressure** is the kinetic energy per unit volume of a fluid particle.

$$q_\infty = \frac{1}{2\rho_\infty V_\infty^2}$$

For a3-D body (Such as a wing of definite span ‘b’), the force and moment coefficients are given by,

Lift coeffiecient:

Drag Coefficient:

Normal Force coefficient:

Axial Force coefficient:

Moment Coefficient:

Where,

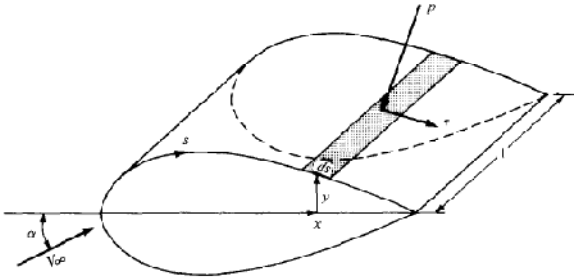
S – Wetted Area of the wing

l – Length/distance

c – Chord of the airfoil

In general, we use a 2-D body such as an airfoil (cross – section of the wing and infinite span length) for estimating the forces and moments on an aircraft which are given per unit span

The coefficient of force for a 2-D body is given by, [the wetted area S is given by, S = c(1)]



Lift coeffiecient:

Drag Coefficient:

Moment Coefficient:

Where,

S – Wetted Area of the wing

l – Length/distance

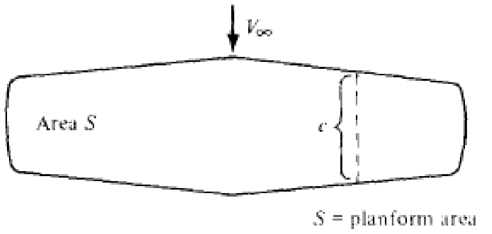
c – Chord of the airfoil

There are two additional coefficients given by,

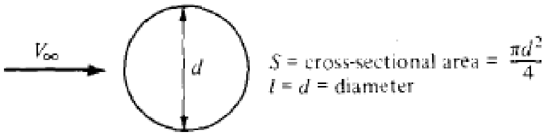
Pressure coefficient:

Skin Friction coefficient: $c_f = \frac{\tau}{q_\infty}$

Where, p_∞ = Free Stream Pressure



(a)



(b)

3.5 Types of Drag

Drag

Drag is one of the four aerodynamic forces that act on a plane. For more information on aerodynamic forces click here. Drag is a restrictive force which opposes the motion of an aircraft. There are various types of drag depending upon their sources.

Types of drag

- Parasite drag
- Form drag or pressure drag
- Skin friction drag
- Profile drag
- Interference drag
- Lift induced drag
- Wave drag

A Detailed explanation of each type of drag is given below

Parasite drag

Parasite drag is a drag produced due to the motion of an object through a fluid. With respect to aviation, the object is an aircraft and the fluid is the atmospheric air. Parasite drag occurs due to air molecules. Parasite drag is classified as form drag or pressure drag, skin friction drag and interference drag.

Form drag or pressure drag

Form drag is produced due to the shape of the object moving through the fluid. It depends on the cross section of an object. An object with a larger cross section and blunt shape will have a larger form drag whereas an object with a smaller cross section area and a sharper shape will have a lesser form drag.

It can be reduced using smaller cross section area for making wings and by using aerodynamic shape for an aerofoil.

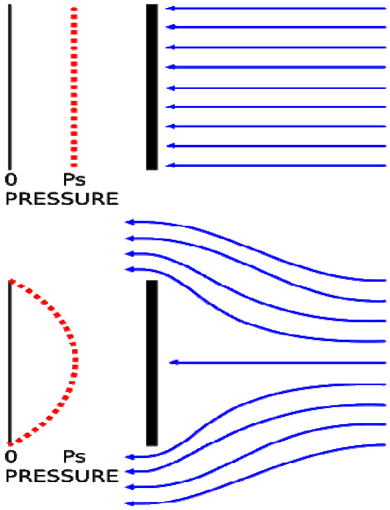


Fig:Pressure Drag

Skin friction drag

Skin friction drag is a drag produced due to friction between an object (aircraft) & fluid (atmospheric air). The rough surface will have high skin friction drag and conversely a smooth surface will have less skin friction drag.

Making the aircraft skin smooth will reduce skin friction.

Profile drag

Profile drag is a sum of the form drag & skin friction drag.

Interference drag

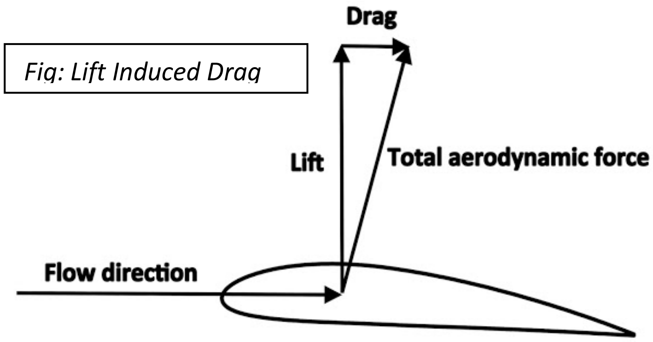
Interference drag is produced due to the interference of two or more airflows having different speeds. And this drag is produced by the interference of different aircraft parts, that is, due to a mixture of airflow around wing and the airflow around the fuselage.

This can be reduced by keeping the angle between these two below 90 degrees

Lift Induced drag

Lift is another aerodynamic force. It is a force which keeps an aircraft in the air and its magnitude is equal to the weight of the aircraft during stable flight. The direction of lift is perpendicular to the oncoming airflow towards the aircraft. Lift induced drag, as the name suggests, is a drag produced due to lift. At slower speed & higher angle of attack, aircraft will have more lift. But as the angle of attack increases, the air pushes the aircraft in the backward direction. This backward push is

Fig: Lift Induced Drag



the induced drag. Technically speaking change in a vector direction of lift of the aircraft results in the formation of this type of drag.

Other types of induced drag are due to a mixture of airflow above and below the wing. The air flow mixes at the tips of the aircraft. We know that speed of airflow above the wing is higher than the speed of an airflow below the wing. Want to know the reason.

At the wing tips, these two air flows with variable speed, get mixed with each other which produces vortices at wing tips. The Reason for production of vortices is that high-pressure airflow gets pulled toward low-pressure airflow.

It is reduced Using winglet or shark-lets at wing tips.

Wave drag

Wave drag is generally produced at transonic speed (speed almost equals to speed of sound) & Supersonic speed (speed greater than speed of sound). Due to high speed of airflow, shock waves are produced. Shockwaves are nothing but the disturbance in the air. This disturbance increases drag of the aircraft known as wave drag.

Drag Curve

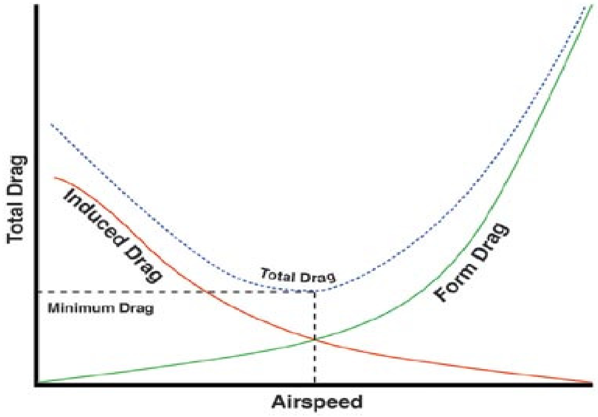


Fig: Drag curve shows the variation of different types of drag with respect to airspeed.

4. DERIVATION OF LIFT, DRAG AND PITCHING MOMENT COEFFICIENTS

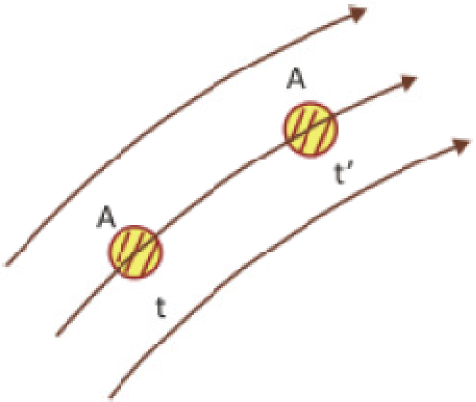
4.1 Problems on above

5. FLUID FLOW MODELS – EULERIAN AND LAGRANGIAN APPROACH

There are two approaches to describe the motion of a fluid and its associated properties. 1. Lagrangian approach 2. Eulerian approach

Lagrangian approach:

Identify (or label) a material of the fluid; track (or follow) it as it moves, and monitor change in its properties. The properties may be velocity, temperature, density, mass, or concentration, etc in the flow field.



Refer the above-figure.

The 'material' or 'particle' of the fluid 'A' at time t has moved to some other location at time t'. Its property, say temperature, is recorded, as the material moves in the flow-field: Note that the recorded temperatures are associated with the same fluid particle, but at different locations and at different times.

t_1 -> T_1

t_2 -> T_2

t_3 -> T_3…..

Think of a temperature sensor attached to a balloon, both having negligible mass and floating in the atmosphere and recording the atmosphere-temperature or the temperature of the flow-field.

In such case, the following temperature-data are recorded by the sensor: The time change of the temperature in such a measurement is denoted as which is called material derivative or substantial derivative.

Location	**Time**	**Temperature**
X_1 , Y_1, Z_1	t_1	T_1
X_2 , Y_2, Z_2	t_2	T_2
X_3 , Y_3, Z_3	t_3	T_3

It reflects time change in the temperature (or any other properties) of the labeled /marked/tagged fluid particles as observed by an observer moving with the fluid.

Lagrangian approach is also called "particle based approach".

Eulerian approach (a field approach)

]

Identify (or label) a certain fixed location in the flow field and follow change in its property, as different materials pass through that location. In such case, the following property, say temperature is recorded by the sensor **:**

t_1 -> T_1
t_2 -> T_2
t_n -> T_n.....

Note that the recorded temperatures are associated with the fixed location in the flow-fluid, having different fluid elements at different times.

The time- change of the temperature in such a measurement is denoted as $\left.\frac{\partial T}{\partial t}\right]_{(x,y,z)}$ which is called the partial derivative of the temperature with respect to time. Note that the suffix (x,y,z) implies that the observer records the change in the property at the fixed location (x,y,z). is also called the local rate of change of that property (temperature in this case).

Based on the above, the following 4 approaches can be deduced for Mathematical modeling

1. Control volume fixed in space
2. Control volume moving in space
3. Infinetisimal small Control volume fixed in space
4. Infinetisimal small control volume moving in space

For further more reading refer Fundamentals of Aerodynamics by John.D. Anderson

6. FUNDAMENTAL PRINCIPLES GOVERNING THE FLUID FLOW

There are three fundamental principles governing the fluid flow. Viz:

1. Principle of conservation of Mass -- Mathematical model for the same is C**ontinuity Equation**
2. Principle of conservation of Energy -- Mathematical model for the same is **Energy Equation**
3. Principle of conservation of Momentum -- Mathematical model for the same is **Momentum Equation**

7. MATHEMATICAL EQUATIONS DERIVED FROM THE FUNDAMENTAL PRINCIPLES – GOVERNING EQUATIONS

7.1 Continuity Equation (integral and differential forms)

Here, the control volume is fixed in space, with the flow moving through it . the volume V and control surface S are now constant with time, and the mass of fluid contained within the control volume can change as a function of time (due to unsteady fluctuations of the flow field).

Consider a given area A arbitrarily oriented in a flow field as shown in the figure 7.1. In this figure we are looking at an edge view of area A.

Let A be small enough such that the flow velocity V is uniform across A. Consider the fluid elements with velocity V that pass through A. In time *dt* after crossing A, they have moved a distance V*dt* and have swept out the shaded volume shown in figure 7.1 . This volume is equal to the base area A times the height of the cylinder $V_n dt$, where V_n is the component of velocity normal to A i.e.,

$$\text{Volume} = (V_n\, dt)A$$

The mass inside the shaded volume is therefore

$$\text{Mass} = \rho(V_n\, dt)A \qquad \text{...} (7.1)$$

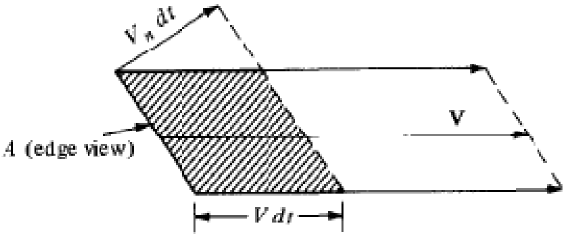
This is the mass that has swept past A in time *dt*. By definition, the mass flow through A is the mass crossing A per second (e.g., kilograms per second, slugs per second).

Let ? denote mass flow. From equation (7.1)

$$\dot{m} = \frac{\rho(V_n\, dt)A}{dt}$$

Or

$$\boxed{\dot{m} = \rho V_n A} \qquad \text{...} (7.2)$$



sketch for discussion of mass flow through area A in a flow field.

Equation (7.2) Demonstrates that mass flow through A is given by the Product

$$\boxed{\text{Area} \times \text{density} \times \text{component of flow velocity } \textit{normal} \text{ to the area}}$$

A related concept is that of *mass flux*, defined as the mass flow *per unit area*.

$$\boxed{\text{Mass flux} = \frac{\dot{m}}{A} = \rho V_n}$$ ………………………………………………. (7.3)

Typical units of mass flux are kg/(s.m^2) and slug/(s.ft^2).

The concepts of mass flow and mass flux are important. Note from equation (7.3) the mass flux across a surface is equal to the product of density times the component of velocity perpendicular to the surface.

In a more general sense, if V is the magnitude of velocity in an arbitrary direction, the product ρV is physically the mass flux (mass flow per unit area) across an area oriented perpendicular to the direction of V.

We are now ready to apply our first physical principle to a finite control volume fixed in space.

Physical Principle: Mass can neither be created nor destroyed.

Consider a flow field wherein all properties vary with spatial location and time e.g. *ρ=ρ(x,y,z,t).* In this flow field, consider the fixed finite control volume shown in below figure. At a point on the control surface, the flow velocit **V** and the vector elemental surface area is **dS.** Also d*V* is an elemental volume inside the control volume. Applied to this control volume, the above physical principle means

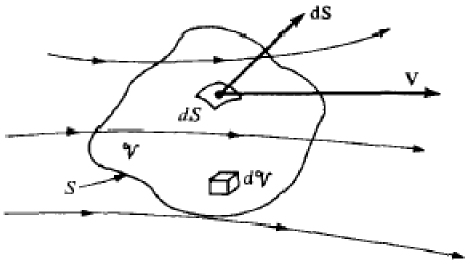
$$\begin{matrix}\text{Net mass flow } \textit{out} \text{ of control} \\ \text{volume through surface } S\end{matrix} = \begin{matrix}\text{time rate of decrease of} \\ \text{mass inside control volume } \mathcal{V}\end{matrix}$$ ………………………(7.4a)

Or $B=C$ …………………………………………………………………………………………(7.4b)

Where B and C are just convenient symbols for the left and right sides, respectively, of equation (7.4a). first let us obtain an expression for B in terms of the quantities shown in figure 7.2 below. From equation (7.2), the elemental mass flow across the area *dS* is

$$\rho V_n \, dS = \rho \mathbf{V} \cdot \mathbf{dS}$$

Examining the figure 7.2, note that by convention, **dS** always point in a direction out of the control Volume. Hence, when V also point out of the control volume(as shown in figure 7.2), the product *ρ**V. dS*** is posititve.



7.2 Finite Control volume fixed in space

Moreover, when V points out of the control volume, the mass flow is physically leaving the control volume; i.e., it is an *outflow*. Hence, a positive *ρ**V. dS*** denotes an outflow. In turn, when V points into the control volume, *ρ**V. dS*** is *negative .* moreover, when V points inward, the mass flow is physically entering the control volume; i.e., it is an inflow. Hence , a negative ρV. dS denotes an *inflow.* The net mass flow out of the entire control surface S is the Summation over S of the elemental mass flow, in the limit, this becomes a surface integral, which is physically the left side of equations(7.4a&b); i.e.,

$$B = \oiint_S \rho \mathbf{V} \cdot \mathbf{dS}$$

…………………………………………………….(7.5)

Now consider the right side of equations (7.4a&b). the mass contained within the elemental volume d*V* is

$$\rho \, d\mathcal{V}$$

Hence, the total mass inside the control volume is

$$\iiint_{\mathcal{V}} \rho \, d\mathcal{V}$$

The time rate of increase of mass inside *V* is then

$$\frac{\partial}{\partial t} \iiint_{\mathcal{V}} \rho \, d\mathcal{V}$$

In turn, the time rate of decrease of mass inside *V* is the negative of the above; i.e.,

$$-\frac{\partial}{\partial t}\oiiint_{\mathcal{V}} \rho \, d\mathcal{V} = C$$

………………………………………………………………………………..…(7.6)

Thus, substituting equations (7.5) and (7.6) into (7.4 b), we have

$$\oiint_{S} \rho \mathbf{V} \cdot \mathbf{dS} = -\frac{\partial}{\partial t}\oiiint_{\mathcal{V}} \rho \, d\mathcal{V}$$

Or

$$\boxed{\frac{\partial}{\partial t}\oiiint_{\mathcal{V}} \rho \, d\mathcal{V} + \oiint_{S} \rho \mathbf{V} \cdot \mathbf{dS} = 0}$$

……………………………………………………. (7.7)

The above equation is called the *Continuity equation*. It is one of the most fundamental equations of *fluid dynamics.* It expresses the continuity equation in integral form.

However, equations (7.7) is fixed in space, the limits of integration are also fixed. Hence the time derivative can be placed inside the volume integral and equation (7.7) can be written as

$$\oiiint_{\mathcal{V}} \frac{\partial \rho}{\partial t} d\mathcal{V} + \oiint_{S} \rho \mathbf{V} \cdot \mathbf{dS} = 0$$

………………………………………… (7.8)

Applying the divergence theorem, we can express the right-hand term of equation (7.8) as

$$\oiint_{S} (\rho \mathbf{V}) \cdot \mathbf{dS} = \oiiint_{\mathcal{V}} \nabla \cdot (\rho \mathbf{V}) \, d\mathcal{V}$$

…………………………………………… (7.9)

Substituting Equation (7.9) into (7.8), we obtain

$$\oiiint_{\mathcal{V}} \frac{\partial \rho}{\partial t} d\mathcal{V} + \oiiint_{\mathcal{V}} \nabla \cdot (\rho \mathbf{V}) \, d\mathcal{V} = 0$$

Or

$$\oiiint_{\mathcal{V}} \left[\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{V})\right] d\mathcal{V} = 0$$

…………………………………………………… (7.10)

However, the finite control volume is arbitrarily drawn in space, there is no reason to expect cancellation of one region by the other. Hence, the only way for the integral in equation

(7.10) to be zero for an arbitrarily control volume is for the integrand to be zero at all points within the control volume. Thus, from equation (7.10), we have

$$\boxed{\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{V}) = 0}$$

………………………………………………………….………(7.11)

Equation (7.11) is the continuity equation in the form of a partial differential equation. This equation relates the flow field variables at a point in the flow, as opposed to the equation (7.7), which deal with a finite space.

It is important to emphasize the difference between unsteady and steady flows. In an unsteady flow, the flow-field variables are a function of both spatial location and time, e.g,

$$\rho = \rho(x, y, z, t)$$

This means that if you lock your eyes on one fixed point in space, the density at that point will change with time. Such unsteady fluctuations can be caused by time-varying boundaries. Equations (7.7) and (7.10) hold for such unsteady flows. On the other hand, the vast majority of practical aerodynamic problems involve steady flow. Here, the flow-field variables are a function of spatial location only, e.g.

$$\rho - \rho(x, y, z)$$

The density at that point will be a fixed value, invariant with time. For steady flow $\partial/\partial t = 0$, and hence Equations (7.7) and (7.10) reduce to

$$\boxed{\oiint_S \rho \mathbf{V} \cdot \mathbf{dS} = 0}$$

……………………………………………………………….. (7.12)

And

$$\boxed{\nabla \cdot (\rho \mathbf{V}) = 0}$$

………………………………………………………………………….(7.13)

7.3 Momentum Equation (integral and differential forms)

Newton's Second law is frequently written as

$$\mathbf{F} = m\mathbf{a}$$ …………………………………………………………………… (7.14)

Where F is the force exerted on a body of mass m and a is the acceleration, however a more general form of equation (7.14) is

$$\mathbf{F} = \frac{d}{dt}(m\mathbf{V})$$ ………………………………………………………………………… (7.15)

Equation (7.15) represents the second fundamental principle upon which theoretical fluid dynamics is based.

Physical principle Force = time rate of change of momentum

We will apply this principle to the model of a finite control volume fixed in space as sketched in figure 7.2.

Let us concentrate on the left side of equation (7.15), i.e., obtain an expression for F, which is the force exerted on the fluid as it flows through the control volume. This force comes from two sources:

1. *Body forces:* gravity, electromagnetic forces, or any other forces which "act at a distance" on the fluid inside *V.*
2. *Surface Forces:* Pressure and shear stress acting on the control surface *S.*

Let f represent the net body force per unit mass exerted on the fluid inside *V.* The body force on the elemental volume d*V* in figure 7.2 is therefore

$$\rho\mathbf{f}\,d\mathcal{V}$$

And the total body force exerted on the fluid in the control volume is the summation of the above over the volume *V:*

$$\text{Body force} = \iiint_{\mathcal{V}} \rho\mathbf{f}\,d\mathcal{V}$$ ……………………………………………………………………… (7.16)

The elemental surface due to pressure acting on the element of area dS is

$$-p\,\mathbf{dS}$$

Where the negative sign indicates that the force is in the direction opposite of dS. That is, the control surface is experiencing a pressure force which is directed into the control volume and which is due to the pressure from the surroundings, and examination of figure 7.2 shows that such an inward-directed force is in the direction opposite of dS. The complete pressure force is the summation of the elemental forces over the entire control surface:

$$\text{Pressure force} = -\oiint_S p\,\mathbf{dS}$$ …………………………………………………………………. (7.17)

In a viscous flow, the shear and normal viscous stresses also exert a surface force. Let us simply recognize this effect by letting $\mathbf{F}_{\text{viscous}}$ denote the total viscous force exerted on the control surface. The total force experienced by the fluid as it is sweeping through the fixed control volume is given by the sum of equations (7.16) and (7.17) and $\mathbf{F}_{\text{viscous}}$:

$$\mathbf{F} = \oiiint_{\mathcal{V}} \rho \mathbf{f}\, d\mathcal{V} - \oiint_S p\,\mathbf{dS} + \mathbf{F}_{\text{viscous}}$$ ………………………………………………. (7.18)

The time rate of change of momentum of the fluid as it sweeps through the fixed control volume is the sum of two terms:

$$\begin{matrix}\text{Net flow of momentum } \mathit{out} \\ \text{of control volume across surface } S\end{matrix} = \mathbf{G}$$ ………………………………………. (7.19a)

And

$$\begin{matrix}\text{Time rate of change of momentum due to} \\ \text{unsteady fluctuations of flow properties inside } \mathcal{V}\end{matrix} = \mathbf{H}$$ …………………….. (7.19b)

Consider the term denoted by G in equation (7.19a). The flow has a certain momentum as it enters the control volume in figure 7.2, and in general it has a different momentum as it leaves the control volume. The net flow of momentum out of the control volume across the surface S is simply this outflow minus the inflow of momentum across the control surface. This change in momentum is denoted by G, as noted above. To obtain an expression for G, recall the mass flow across the elemental area dS is $(\rho \mathbf{V} \cdot \mathbf{dS})$;

Hence, the flow of momentum per second across dS is

$$(\rho \mathbf{V} \cdot \mathbf{dS})\mathbf{V}$$

The net flow of momentum out of the control volume through S is the summation of the above elemental contributions, namely,

$$\mathbf{G} = \oiint_S (\rho \mathbf{V} \cdot \mathbf{dS})\mathbf{V}$$ ……………………………………………………….. (7.20)

If G has a positive value , there is more momentum flowing out of control volume per second than flowing in; conversely, if G has a negative value, there is more momentum flowing into the control volume per second than flowing put.

The momentum of the fluid in the elemental volume d*V* shown in figure 7.2 is

$$(\rho\, d\mathcal{V})\mathbf{V}$$

The momentum contained at any instant inside the control volume is therefore

$$\oiiint_{\mathcal{V}} \rho \mathbf{V}\, d\mathcal{V}$$

And its time rate of change due to unsteady flow fluctuations is

$$\mathbf{H} = \frac{\partial}{\partial t}\oiiint_{\mathcal{V}} \rho \mathbf{V}\, d\mathcal{V}$$ ……………………………………………………….. (7.21)

The total rate of change of momentum of the fluid is

$$\frac{d}{dt}(m\mathbf{V}) = \mathbf{G} + \mathbf{H} = \oiint_S (\rho \mathbf{V} \cdot \mathbf{dS})\mathbf{V} + \frac{\partial}{\partial t}\oiiint_{\mathcal{V}} \rho \mathbf{V}\, d\mathcal{V}$$ ……………………… (7.22)

From Newton's second law,

$$\frac{d}{dt}(m\mathbf{V}) = \mathbf{F}$$

$$\boxed{\frac{\partial}{\partial t}\oiiint_{\mathcal{V}} \rho \mathbf{V}\, d\mathcal{V} + \oiint_S (\rho \mathbf{V} \cdot \mathbf{dS})\mathbf{V} = -\oiint_S p\, \mathbf{dS} + \oiiint_{\mathcal{V}} \rho \mathbf{f}\, d\mathcal{V} + \mathbf{F}_{\text{viscous}}}$$ …………(7.23)

Equation (7.23) is the momentum equation in integral form.

WE now proceed to a partial differential equation which relates flow-field properties at a point in space.

Apply gradient theorem, to the first term on the right side of equation (7.23)

$$-\oiint_S p\,\mathbf{dS} = -\iiint_{\mathcal{V}} \nabla p\, d\mathcal{V}$$ ……………………………………………………………………. (7.24)

Hence, equation (7.23) can be written as

$$\iiint_{\mathcal{V}} \frac{\partial(\rho\mathbf{V})}{\partial t} d\mathcal{V} + \oiint_S (\rho\mathbf{V}\cdot\mathbf{dS})\mathbf{V} = -\iiint_{\mathcal{V}} \nabla p\, d\mathcal{V} + \iiint_{\mathcal{V}} \rho\mathbf{f}\, d\mathcal{V} + \mathbf{F}_{\text{viscous}}$$ ………. (7.25)

Using cartesian coordinates, where

$$\mathbf{V} = u\mathbf{i} + v\mathbf{j} + w\mathbf{k}$$

The x component of equation (7.25) is

$$\iiint_{\mathcal{V}} \frac{\partial(\rho u)}{\partial t} d\mathcal{V} + \oiint_S (\rho\mathbf{V}\cdot\mathbf{dS})u = -\iiint_{\mathcal{V}} \frac{\partial p}{\partial x} d\mathcal{V} + \iiint_{\mathcal{V}} \rho f_x\, d\mathcal{V} + (F_x)_{\text{viscous}}$$ ……… (7.26)

$$\oiint_S (\rho\mathbf{V}\cdot\mathbf{dS})u = \oiint_S (\rho u\mathbf{V})\cdot\mathbf{dS} = \iiint_{\mathcal{V}} \nabla\cdot(\rho u\mathbf{V})\, d\mathcal{V}$$ ……………………………… (7.27)

Substituting equation (7.17) into equation (7.16), we have

$$\iiint_{\mathcal{V}} \left[\frac{\partial(\rho u)}{\partial t} + \nabla\cdot(\rho u\mathbf{V}) + \frac{\partial p}{\partial x} - \rho f_x - (\mathcal{F}_x)_{\text{viscous}}\right] d\mathcal{V} = 0$$ ………………………. (7.28)

The integrand in equation (7.28) is identically zero at all points in the flow; hence,

$$\boxed{\frac{\partial(\rho u)}{\partial t} + \nabla\cdot(\rho u\mathbf{V}) = -\frac{\partial p}{\partial x} + \rho f_x + (\mathcal{F}_x)_{\text{viscous}}}$$ ……………………………………………… (7.29a)

Similarly writing y and z components

$$\boxed{\frac{\partial(\rho v)}{\partial t} + \nabla\cdot(\rho v\mathbf{V}) = -\frac{\partial p}{\partial y} + \rho f_y + (\mathcal{F}_y)_{\text{viscous}}}$$ ………………………………………………… (7.29b)

$$\boxed{\frac{\partial(\rho w)}{\partial t} + \nabla \cdot (\rho w \mathbf{V}) = -\frac{\partial p}{\partial z} + \rho f_z + (\mathcal{F}_z)_{\text{viscous}}}$$ ………………………………………………(7.29c)

Equations (7.29 a to c) apply ti the unsteady, three- dimensional flow of any fluid, compressible or incompressible, viscous or inviscid. Specialized to a steady, inviscid flow with no body forces. These equations become

$$\boxed{\oiint_S (\rho \mathbf{V} \cdot \mathbf{dS})\mathbf{V} = -\oiint_S p\, \mathbf{dS}}$$ ………………………………………………………..(7.30)

And

$$\boxed{\begin{aligned} \nabla \cdot (\rho u \mathbf{V}) &= -\frac{\partial p}{\partial x} \\ \nabla \cdot (\rho v \mathbf{V}) &= -\frac{\partial p}{\partial y} \\ \nabla \cdot (\rho w \mathbf{V}) &= -\frac{\partial p}{\partial z} \end{aligned}}$$ ……………………………………………………………………………..(7.31)

The momentum equations for an inviscid flow are called the *Euler equations*. The momentum equations for a viscous flow are called the *Navier-strokes equations.*

7.4 Energy Equation (integral and differential forms)

For an incompressible flow, where ρ is constant, the primary flow-field variables are P and V.

Physical principle Energy can be neither created nor destroyed; it can only change in form.

Consider a fixed amount of matter contained within a closed boundary. This matter defines the system. Because the molecules and atoms within the system are constantly in motion, the system contains a certain amount of energy. For simplicity, let the system contain a unit mass; in turn denote the internal energy per unit mass by e.

The region outside the system defines the surroundings. Let an incremental amount of heat δq be added to the system from the surroundings. Also let δw is the work done on the system by the surroundings.

Both heat and work are forms of energy, and when added to the system, they change the amount of internal energy in the system. Denote this change of internal energy by de. From our physical principle that energy is conserved, we have for the system

$$\delta q + \delta w = de \qquad \text{……………………………………………………………………………… (7.32)}$$

Equation (7.32) is a statement of the first law of thermodynamics.

Let us apply the first law of fluid flowing through the fixed control volume shown in figure 7.2

B_1 = rate of heat added to fluid inside control volume from surroundings
B_2 = rate of work done on fluid inside control volume
B_3 = rate of change of energy of fluid as it flows through control volume

From the first law,

$$B_1 + B_2 = B_3 \qquad \text{……………………………………………………………………………(7.33)}$$

First, consider the rate of heat transferred to or from the fluid. This can be visualised as volumetric heating of the fluid inside the control volume due to absorption of radiation originating outside the system or the local emission of radiation by the fluid itself. Let this volumetric rate of heat addition per unit mass be denoted by $\dot{q}$ for the figure 7.2 the mass contained within an elemental volume is $\rho\, d\mathcal{V}$;hence the rate of heat addition to this mass is

$\dot{q}(\rho\, d\mathcal{V})$. Summing over the complete control volume,

We obtain

$$\text{Rate of volumetric heating} = \oiiint_{\mathcal{V}} \dot{q}\rho\, d\mathcal{V} \qquad \text{………………………………………… (7.34)}$$

Let us denote the rate of heat addition to the control volume due to viscous effects. Therefore in equation 7.33, the total rate of heat addition is given by equation (7.34) plus $\dot{Q}_{\text{viscous}}$:

$$B_1 = \oiiint_{\mathcal{V}} \dot{q}\rho\, d\mathcal{V} + \dot{Q}_{\text{viscous}} \qquad \text{…………………………………………………………………(7.35)}$$

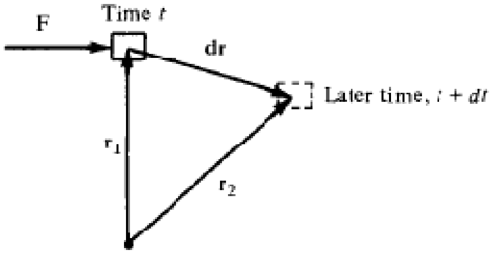


Figure 7.3: schematic for the rate of doing work by a force F exerted on a moving body

Before considering the rate of work done on the fluid inside the control volume, consider a simpler case of solid object in motion, with a force F being exerted on the object as shown in figure 7.3. the position of the object is measure from a fixed origin by the radius vector r. in moving from r1 to r2 over an interval of time dt.

$$\text{Rate of doing work on moving body} = \mathbf{F} \cdot \mathbf{V}$$

$$\begin{array}{r}\text{Rate of work done on fluid inside} \\ \mathcal{V} \text{ due to pressure force on } S\end{array} = -\oiint_S (p\, \mathbf{dS}) \cdot \mathbf{V} \qquad \text{...(7.36)}$$

In addition consider an elemental volume dV inside the control volume as shown in 7.2. recalling that f is the body force per unit mass. The rate of work done on the elemental volume due to the body is $(\rho \mathbf{f}\, d\mathcal{V}) \cdot \mathbf{V}$.

Summing over the complete control volume, we obtain

$$\begin{array}{r}\text{Rate of work done on fluid} \\ \text{inside } \mathcal{V} \text{ due to body forces}\end{array} = \iiint_{\mathcal{V}} (\rho \mathbf{f}\, d\mathcal{V}) \cdot \mathbf{V} \qquad \text{..(7.37)}$$

The total rate of work done on the fluid inside the control volume is the sum of equations (7.36) & (7.37) and $\dot{W}_{\text{viscous}}$:

$$B_2 = -\oiint_S p\mathbf{V} \cdot \mathbf{dS} + \iiint_{\mathcal{V}} \rho(\mathbf{f} \cdot \mathbf{V})\, d\mathcal{V} + \dot{W}_{\text{viscous}} \qquad \text{... (7.38)}$$

The elemental flow of total energy across dS is $(\rho \mathbf{V} \cdot \mathbf{dS})(e + V^2/2)$.

We obtain

$$\text{Net rate of flow of total energy across control surface} = \oiint_S (\rho \mathbf{V} \cdot \mathbf{dS}) \left(e + \frac{V^2}{2} \right)$$

………………………………………(7.39)

The total energy inside the complete control volume at any instant in time is

$$\oiiint_{\mathcal{V}} \rho \left(e + \frac{V^2}{2} \right) d\mathcal{V}$$

Therefore,

$$\begin{aligned}&\text{Time rate of change of total energy}\\ &\text{inside } \mathcal{V} \text{ due to transient variations} = \frac{\partial}{\partial t} \oiiint_{\mathcal{V}} \rho \left(e + \frac{V^2}{2} \right) d\mathcal{V}\\ &\text{of flow-field variables}\end{aligned}$$

………………………………… (7.40)

In turn B3 is the sum of equations (7.39) & (7.40):

$$B_3 = \frac{\partial}{\partial t} \oiiint_{\mathcal{V}} \rho \left(e + \frac{V^2}{2} \right) d\mathcal{V} + \oiint_S (\rho \mathbf{V} \cdot \mathbf{dS}) \left(e + \frac{V^2}{2} \right)$$

……………………………………………(7.41)

Combining the equation (7.33)(7.35)(7.39)&(7.41)

$$\boxed{\begin{aligned}\oiiint_{\mathcal{V}} \dot{q} \rho \, d\mathcal{V} + \dot{Q}_{\text{viscous}} - \oiint_S p \mathbf{V} \cdot \mathbf{dS} + \oiiint_{\mathcal{V}} \rho (\mathbf{f} \cdot \mathbf{V}) \, d\mathcal{V} + \dot{W}_{\text{viscous}}\\ = \frac{\partial}{\partial t} \oiiint_{\mathcal{V}} \rho \left(e + \frac{V^2}{2} \right) d\mathcal{V} + \oiint_S \rho \left(e + \frac{V^2}{2} \right) \mathbf{V} \cdot \mathbf{dS}\end{aligned}}$$

……………(7.42)

The above equation represents the energy equation in integral form.

Applying the divergence theorem to the surface integrals in above equation collecting all terms inside the same volume integral, and setting the integrand equal to zero, we obtain

$$\boxed{\begin{aligned}\frac{\partial}{\partial t} \left[\rho \left(e + \frac{V^2}{2} \right) \right] + \nabla \cdot \left[\rho \left(e + \frac{V^2}{2} \right) \mathbf{V} \right] = \rho \dot{q} - \nabla \cdot (p \mathbf{V}) + \rho (\mathbf{f} \cdot \mathbf{V})\\ + \dot{Q}'_{\text{viscous}} + \dot{W}'_{\text{viscous}}\end{aligned}}$$

……………….(7.43)

If the flow is steady, inviscid, adiabatic, without body forces the equation (7.42) & (7.43) reduces to

$$\boxed{\oint\!\!\!\!\!\!\oint_S \rho\left(e+\frac{V^2}{2}\right)\mathbf{V}\cdot\mathbf{dS} = -\oint\!\!\!\!\!\!\oint_S p\mathbf{V}\cdot\mathbf{dS}}$$

…………………………………………………………………(7.44)

and

$$\boxed{\nabla\cdot\left[\rho\left(e+\frac{V^2}{2}\right)\mathbf{V}\right] = -\nabla\cdot(p\mathbf{V})}$$

……………………………………………………………(7.55)

If the gas is calorically perfect, then

$$e = c_v T$$

……………………………………………………………………………………………………….(7.56)

The system can be completed by using the perfect gas equation of state

$$p = \rho R T$$

……………………………………………………………………………………………………(7.57)

https://www.experimentalaircraft.info/flight-planning/aircraft-stall-effect-1.php

Summary:

- Importance of Aerodynamics
- Aerodynamic forces and moments
- Governing equations of fluid flow

Objectives

1. Total pressure at a point is defined as the pressure when the flow is brought to rest
   a) adiabatically b) isentropically c) isothermally d) isobarically
2. Lift is defined as________________
   a. The force that holds the palne back
   b. The force that moves the plane forward
   c. The downward force of the plane

   d. The upward force on the plane

3. What is the noise you hear after a high speed plane flies by
   a. Supersonic flight
   b. Aerodynamics
   c. The sound barrier
   d. A sonic boom

4. What is the interaction of the moving object with the atmosphere?
   a. Supersonic flight
   b. Aerodynamics
   c. The sound barrier
   d. A sonic boom

5. What are the objectives of aerodynamics?
6. What are the sources of aerodynamic forces?
7. What are the conditions for the flows to be dynamically similar?
8. What is the difference between continuum and free molecular flow?
9. What is the difference between viscous and inviscid flow?
10. How are the flows classified with respect to mach number?
11. Define point property.
12. Define free stream velocity.
13. Define reynold’s number, Mach number and Knudsen number.
14. What is boundary layer?
15. What are the fundamental principles of fluid flow?

II B.TECH II SEMESTER

DEPARTMENT OF AERONAUTICAL ENGINEERING

SUBJECT: **AERODYNAMICS-I**

TOPIC: BASIC AERODYNAMICS (**UNIT I**)

ASSIGNMENT **I**

SUBJECTIVE

I. SHORT ANSWER QUESTIONS

1. State the applications of Aerodynamics.
2. Differentiate among internal aerodynamics and external aerodynamics.
3. What are constant – property flows? State any three applications of constant property flows.
4. State the fundamental principles of aerodynamics.
5. Define Reynolds number and Mach number. Explain their significance in fluid flows.
6. State Buckingham's pi theorem. What are its advantages?
7. How aerodynamic flows are described basing on Mach number? Show using neat sketches, the flow over a stream lined body.
8. Using a neat sketch, explain the sources of aerodynamic forces and moments.
9. Define normal force and axial force.
10. Define continuum and free molecular flows.

II. LONG ANSWER QUESTIONS

1. Explain the term 'applied aerodynamics.' How do the aerodynamic coefficients vary form theory to practice. Explain using neat sketches [Refer page 71, J.D. Anderson]
2. Explain using neat sketches, how the aerodynamic flows are described with respect to Mach number. How do flow properties change in different flows?
3. a. Derive Continuity equation in integral and differential form applying the fundamental principle to a control volume fixed in space.
   b. What are the basic fluid flow models used to study aerodynamic flows.
4. Derive energy equation in integral form applying the fundamental principle to a control volume fixed in space.
5. Derive momentum equation in integral and differential form applying the fundamental principle to a control volume fixed in space.
6. Define viscosity and using neat sketches explain the concept of boundary layer. [pg 64, Anderson]
7. Define substantial derivative. [refer pg 142, Anderson]
8. Derive the differential form of momentum equation applicable for compressible and viscous flows. [Navier – Stokes equations]. [refer Bertin Chapter 2 Section 2.3]

III. PROBLEMS

1. Consider two different flows over geometrically similar airfoil shapes, one airfoil being twice the size of the other. The flow over the smaller airfoil has free stream properties given by T_∞ = 200 K, ρ_∞=1.23 kg/m^3, and V_∞ = 100 m/s. The flow over the larger airfoil is described by T_∞ = 800 K, ρ_∞=1.739 kg/m^3, and V_∞ = 200 m/s. Assume both μ and a are proportional to $T^{1/2}$. Are the flows dynamically similar?
2. Consider a body of arbitrary shape. If the pressure distribution over the surface of the body is constant, prove that the resultant pressure force on the body is zero. [Chapter 2 of Anderson]

OBJECTIVE **ROLL NUMBER** _______________

Refer Text books by **BERTIN, ANDERSON, CLANCY**

1. Pressure is defined as _________________________________.

2. Define point property____. What are point properties?

3. The tugging action on the surface is due to ____

4. Define ‘Lift’.____

5. The sources of aerodynamic forces and moments are __________________ and ________________ distributions integrated over the body.

6. The coefficient of lift is given by __________________________________

7. The pressure coefficient is given by ________________________________

8. The parameter that is commonly used to identify the low – density (free molecular flow) is ______________________ number and is defined as ____.

9. Continuum flow starts to break down when the Knudsen number is roughly of the order of _______.

10. Viscosity is a ________________________ property. [Transport/point].

11. Coefficient of viscosity is a function of ______________________, ________________ and ________________.

12. The speed at which a disturbance of infinitesimal proportions propagates through a fluid that is at rest is known as ___________________.

13. Static medium is defined as ____________________________

14. The forces which act directly on the mass of the fluid element are known as ___________________

15. Stokes Hypothesis is given by _________________________

16. Flow work is the work done by ___________________ forces on the surroundings as the fluid moves through the space.

17. Viscous work is the work done by ___________________ forces on the surroundings as the fluid moves through the space.

18. Shaft work is the work done by ___________________ forces on the surroundings as the fluid moves through the space.

19. Dynamic pressure is defined as the difference between ______________________ and _________________.

20. ______________ and _____________ pressures vary through out the flow field.

21. The fluid properties are described as functions of spatial coordinates and time is __________________ approach. [Eulerian/Lagrangian].

22. The analysis is made for a tagged fluid particle that moves through the flow region is _________________ approach.

23. The criterion for the flow similarity to be establishes is

1. ____
2. ____

24. The hydrostatic equation is given by ______________________________

25. For free – molecular flow the mean – free path is ____________________ than the characteristic diameter.

26. The flow in which the viscous interactions and/or chemically reacting effects dominate the flow is called ______________________.

27. Mass flow rate is given by _______________________________________[no symbols]

28. The Euler's equations in differential form are given by __________________ , _______________________, ________________.

29. Reynolds number is defined as _______________________

30. A streamline is defined as ____ and mathematically given by __________________________________.

LAST DATE FOR SUBMISSION: 10/1/2018

Weblinks:

https://www.physicsforums.com/threads/objective-question-related-to-aerodynamics.182006/

https://www.experimentalaircraft.info/flight-planning/aircraft-stall-effect-1.php

https://www.scribd.com/doc/137701633/Questions-and-Answers-in-Aerodynamics

http://nptel.ac.in/courses/103104043/Lecture_pdf/Lecture9.pdf