

# Karpagam Academy of Higher Education

*(Deemed to be University)*

*(Established Under Section 3 of UGC Act 1956)*



## FACULTY OF ENGINEERING

### Department of Mechanical Engineering

#### (Aerospace Engineering)

**Subject Name / Code :** Industrial Aerodynamics (IAD) / 16BTAR\_E11 / (Credits - 3)

**Name of the Faculty :** R. Suresh Baalaji

**Designation :** Assistant Professor

**Year/Semester :** III / VI

**Branch :** UG / B.Tech - Aerospace Engineering

## **SYLLABUS**

**16BTAR\_E11**

**INDUSTRIAL AERODYNAMICS**

**3 0 0 3 100**

### **OBJECTIVES:**

To familiarize the learner with non-aeronautical uses of aerodynamics such as road vehicle, building aerodynamics and problems of flow induced vibrations

### **UNIT I ATMOSPHERIC BOUNDARY LAYER**

Atmospheric circulation-Local winds-Terrain types-Mean velocity profiles-Power law and logarithm law- wind speeds-Turbulence profiles-Roughness parameters-simulation techniques in wind tunnels

### **UNIT II BLUFF BODY AERODYNAMICS**

Boundary layers and separation-Two dimensional wake and vortex formation-Strouhal and Reynolds numbers-Separation and reattachments-Power requirements and drag coefficients of automobiles-Effects of cut back angle-aerodynamics of trains.

### **UNIT III WIND ENERGY COLLECTORS**

Horizontal and vertical axis machines-energy density of different rotors-Power coefficient- Betz coefficient by momentum theory.

### **UNIT IV BUILDING AERODYNAMICS**

Pressure distribution on low rise buildings-wind forces on buildings-Environmental winds in city blocks-special problems of tall buildings-building codes-ventilation and architectural aerodynamics

### **UNIT V FLOW INDUCED VIBRATIONS**

Vortex shedding, lock & effects of Reynolds number on wake formation in turbulent flows - across wind galloping-wake galloping-along wind galloping of circular cables-oscillation of tall structures and launch vehicles under wind loads-stall flutter.

## TEXT BOOKS

S.No.	Author(s)	Title of the Book	Publisher	Year of Publication
1.	MuyiwaAdaramola	Wind Turbine Technology: Principles and Design	CRC Press, Florida	2014
2.	Charalambos C. Baniotopoulos, Claudio Borri, Theodore Stathopoulos	Environmental Wind Engineering and Design of Wind Energy Structures	Springer Science	2011
3.	Peter Sachs	Wind Forces in Engineering	Pergamon Press	2013

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1.	Tomomichi Nakamura	Flow Induced Vibrations	Butterworth-Heinemann	2013
2.	Scorer R.S	Environmental Aerodynamics	Ellis Harwood Ltd, England	1978
3.	Sovran, M	Aerodynamic drag mechanism of bluff bodies and road vehicles	Plenum Press, N.Y	1978
4.	Calvert N.G	Wind Power Principles	Charles Griffin & Co London	1979

## WEB REFERENCES:

[www.windows2universe.org/earth/Atmosphere/boundary\\_layer.html](http://www.windows2universe.org/earth/Atmosphere/boundary_layer.html)  
[serve.me.nus.edu.sg/fluid/index\\_files/bluffbodyaerodynamics.html](http://serve.me.nus.edu.sg/fluid/index_files/bluffbodyaerodynamics.html)  
[www.sandc.com/solutions/wind-energy.asp](http://www.sandc.com/solutions/wind-energy.asp)  
[www.ifh.kit.edu/english/112.php](http://www.ifh.kit.edu/english/112.php)  
[www.stress.com/servicetier3.php?sid=10&pid=222](http://www.stress.com/servicetier3.php?sid=10&pid=222)

## LESSON PLAN

**Subject Name / Code** : Industrial Aerodynamics (IAD) / 16BTAR\_E11 / (Credits - 3)  
**Name of the Faculty** : R. Suresh Baalaji  
**Designation** : Assistant Professor  
**Year/Semester** : III / VI  
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Sl. No.	No. of Periods	Topics to be Covered	Support Materials
1.	1	Introduction to Industrial Aerodynamics	
<b>UNIT – I : ATMOSPHERIC BOUNDARY LAYER</b>			
1.	1	Fundamentals of Atmospheric Boundary Layer	
2.	1	Atmospheric circulation	
3.	1	Local winds	Environmental Wind Engineering
4.	1	Terrain types	and Design of Wind Energy Structures
5.	1	Mean velocity profiles	
6.	1	Power law and logarithm law	Charalambos C. Baniotopoulos,
7.	1	Wind Speeds - Turbulence profiles	
8.	1	Wind Speeds -Roughness parameters	
9.	1	Simulation Techniques in Wind Tunnels	Lecture Notes - KAHE
10.	1	<b>Tutorial 1:</b> Summary of Unit I and Part A and B questions	
<b>Total No. of Hours Planned for Unit - I</b>			<b>9L + 1T 10 Hours</b>

Sl. No.	No. of Periods	Topics to be Covered	Support Materials
<b>UNIT – II : BLUFF BODY AERODYNAMICS</b>			
11.	1	Basics of Bluff Body Aerodynamics	
12.	1	Boundary layers	Wind Turbine Technology:
13.	1	Boundary separation	Principles and Design
14.	1	Two dimensional wake and vortex formation	



15.	1	Strouhal and Reynolds numbers	Muyiwa Adaramola
16.	1	Separation and reattachments	
17.	1	Power requirements and drag coefficients of automobiles	
18.	1	Effects of cut back angle	
19.	1	Aerodynamics of Trains	Lecture Notes - KAHE
20.	1	<b>Tutorial 2:</b> Summary of Unit II and Part A and B questions	
<b>Total No. of Hours Planned for Unit - II</b>			<b>9L +1T 10 Hours</b>

Sl. No.	No. of Periods	Topics to be Covered	Support Materials
<b>UNIT – III : WIND ENERGY COLLECTORS</b>			
21.	1	Basics of Wind Energy Collectors	
22.	1	Horizontal axis machines	
23.	1	Vertical axis machines-	Wind Forces in Engineering
24.	1	Energy density of different rotors	
25.	1	Power coefficient	Peter Sachs
26.	1	Betz coefficient by momentum theory.	
27.	1	Significance of Renewable Energy source	
28.	1	Growth in wind energy	
29.	1	Component & Mechanism of Wind Turbine	
30.	1	<b>Tutorial 3:</b> Summary of Unit III and Part A and B questions	Lecture Notes - KAHE
<b>Total No. of Hours Planned for Unit - III</b>			<b>9L + 1T 10 Hours</b>

Sl. No.	No. of Periods	Topics to be Covered	Support Materials
<b>UNIT – IV : BUILDING AERODYNAMICS</b>			
31.	1	Introduction Building Aerodynamics	
32.	1	Pressure distribution on low rise buildings	Wind Forces in Engineering
33.	1	Types of wind forces	
34.	1	Wind forces on buildings	Peter Sachs
35.	1	Environmental winds in city blocks	
36.	1	Special Problems of Tall Buildings	
37.	1	Building Codes	
38.	1	Ventilation Aerodynamics	Lecture Notes - KAHE
39.	1	Architectural Aerodynamics	

40.	1	<b>Tutorial 4:</b> Summary of Unit IV and Part A and B questions	
<b>Total No. of Hours Planned for Unit - IV</b>			<b>9L + 1T 10 Hours</b>
<b>Sl. No.</b>	<b>No. of Periods</b>	<b>Topics to be Covered</b>	<b>Support Materials</b>
<b>UNIT – V : FLOW INDUCED VIBRATIONS</b>			
41.	1	Basics of flow induced vibrations	
42.	1	Vortex shedding and lock	Wind Turbine Technology:
43.	1	Effects of Reynolds number on wake formation in turbulent flows	Principles and Design
44.	1	Across wind galloping-.	
45.	1	Wake galloping	Muyiwa Adaramola
46.	1	Along wind galloping of circular cables	
47.	1	Oscillation of tall structures	
48.	1	Oscillation of launch vehicles under wind loads-	
49.	1	Stall flutter	Lecture Notes - KAHE
50.	1	<b>Tutorial 5:</b> Summary of Unit V and Part A and B questions	
<b>Total No. of Hours Planned for Unit - V</b>			<b>9L +1T 10 Hours</b>
1.	1	End Semester Possible Questions Discussion Discussion and Overview of All Five Units	

**TOTAL PERIODS : 45 L + 5T = 50 Hours**

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## WEBSITES

[www.windows2universe.org/earth/Atmosphere/boundary\\_layer.html](http://www.windows2universe.org/earth/Atmosphere/boundary_layer.html)

[serve.me.nus.edu.sg/fluid/index\\_files/bluffbodyaerodynamics.html](http://serve.me.nus.edu.sg/fluid/index_files/bluffbodyaerodynamics.html)

[www.sandc.com/solutions/wind-energy.asp](http://www.sandc.com/solutions/wind-energy.asp)

[www.ifh.kit.edu/english/112.php](http://www.ifh.kit.edu/english/112.php)

[www.stress.com/servicetier3.php?sid=10&pid=222](http://www.stress.com/servicetier3.php?sid=10&pid=222)

## JOURNALS

J [1] – International Journal of Aerodynamics.

J [2] – Journal of Wind Engineering & Industrial Aerodynamics

J [3] – Journal of Aerodynamics.

UNIT	Total No. of Periods Planned	Lecture Periods	Tutorial Periods
I	10	9	1
II	10	9	1
III	10	9	1
IV	10	9	1
V	10	9	1
TOTAL	50	45	05 + 02

### **I. CONTINUOUS INTERNAL ASSESSMENT : 40 Marks**

(Internal Assessment Tests: 30(CIA – I -08 + CIA – II – 08 + Model Exam 14),  
Attendance: 5, Assignment/Seminar: 5)

### **II. END SEMESTER EXAMINATION : 60 Marks**

**TOTAL : 100 Marks**



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**Subject Name:** Industrial Aerodynamics (IAD)

**Year / Semester:** III / VI

**Subject Code:** 16BTAR\_E11

**Programme:** UG / B.Tech. Aerospace

Engg

### **COURSE OBJECTIVE**

This course offers an introduction to industrial aerodynamics and wind engineering with the main characteristics of natural winds. Characteristics of velocity profiles and atmospheric turbulence are described along with the effects of upstream exposure.

Wind speed and turbulence models for inhomogeneous upstream exposures are presented in comparison with atmospheric measurements and wind-tunnel simulations. The basic elements of wind-building interaction in the time-averaged mode for uniform and boundary layer flows are described, external and internal pressures and forces on buildings with emphasis on design significance are discussed. Patterns of air pollutant dispersion influenced by natural winds are presented.

Wind specifications in major international standards and codes together with wind loading provisions and urban air quality measures.

### **LEARNING OUTCOMES**

Upon completion of this course, students will have:

1. Basic understanding of the wind environment in atmosphere and flow structure in the atmospheric boundary layer,
2. Knowledge on wind-tunnel and Computational Fluid Mechanics (CFD) techniques for solving wind engineering and industrial aerodynamics problems,
3. Basic knowledge how to solve problems on wind loading of structures, cross-winds and traffic safety, air pollutant dispersion.
4. Experience in working with international standards and codes.

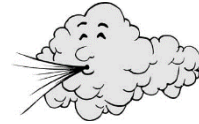


# INDUSTRIAL AERODYNAMICS

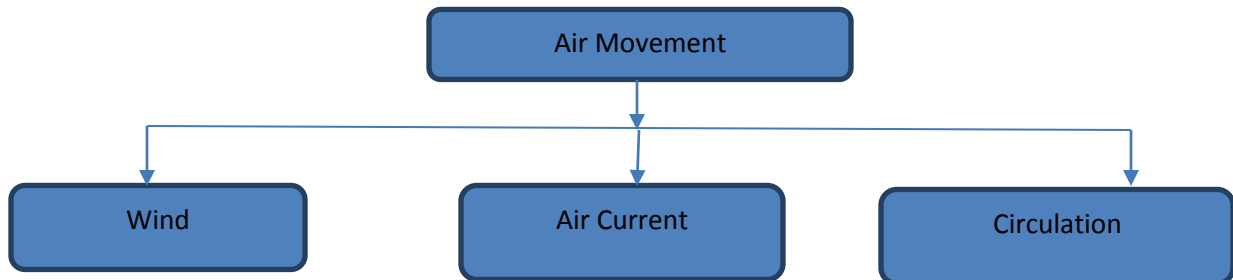


# Unit I

## Wind Energy Collectors



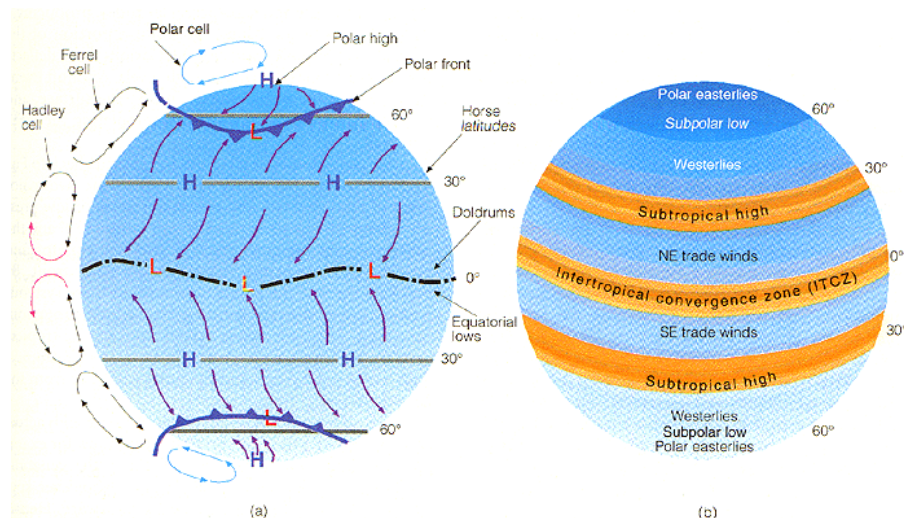
### INTRODUCTION



The horizontal movement of air along the earth's surface is called a *Wind*. The vertical movement of the air is known as an *air current*. Winds and air current together comprise a system of *circulation* in the atmosphere.

### TYPES OF WINDS

On the earth's surface, certain winds blow constantly in a particular direction throughout the year. These are known as the 'Prevailing Winds'. They are also called the Permanent or the Planetary Winds. Certain winds blow in one direction in one season and in the opposite direction in another. They are known as Periodic Winds. Then, there are Local Winds in different parts of the world.



## 1. Planetary Winds:

There are three main planetary winds that constantly blow in the same direction all around the world. They are also called prevailing or permanent winds.

### 1. Trade Winds:

Blow from the subtropical high pressure belt towards the Equator. They are called the north-east trades in the northern hemisphere and south-east trades in the southern hemisphere.

### 2. Westerly winds:

Blow from the same subtropical high pressure belts, towards 60° S and 60° N latitude. They are called the sought Westerly wind sin the northern hemisphere and North Westerly winds in the southern hemispheres.

### 3. Polar Winds

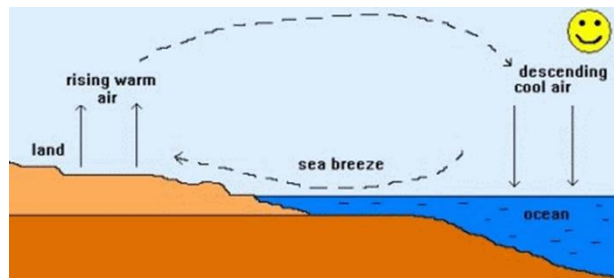
Blow from the polar high pressure to the sub polar low pressure area. In the northern hemisphere, their direction is from the north-east. In the southern hemisphere, they blow from the south-east.

## 2. Periodic Winds

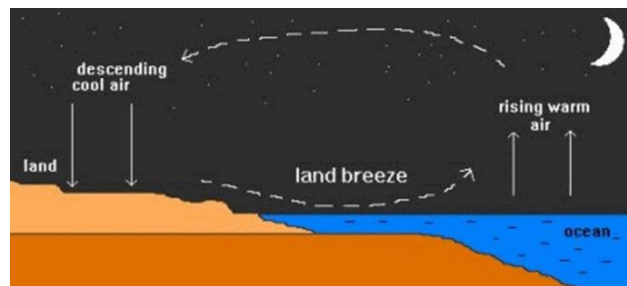
These winds are known to blow for a certain time in a certain direction - it may be for a part of a day or a particular season of the year.

### Example 1: Land and Sea breeze

During the day, near an ocean, sea or lake, the land heats up faster than the water. The air above the land also gets heated. As warm air rises, it draws cooler air from over the water to blow towards the land, creating a sea breeze.



At night, the opposite conditions prevail. The land loses heat rapidly while the sea is still warm. The air resting over the land is cold while the air resting over the sea is warm and rises creating a low pressure area. A land breeze thus blows in from the high



pressure over the land towards the water. These land and sea breezes maintain air circulation in the coastal areas and have a moderating effect on the temperatures.

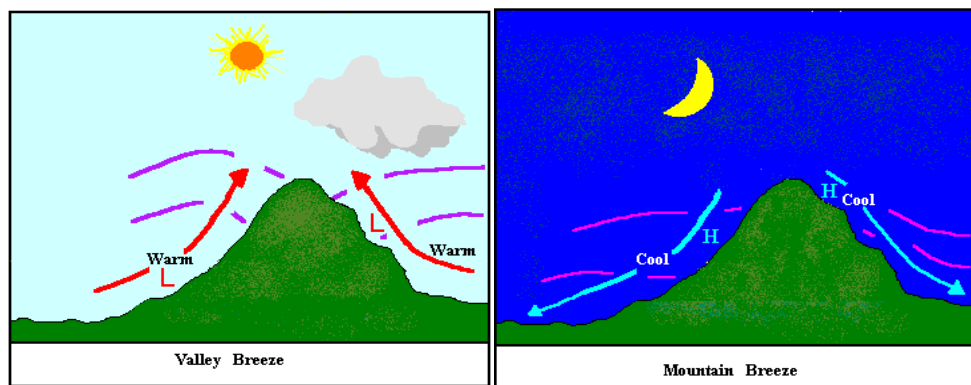
### Example 2: Monsoons

They are land and sea breezes on a large scale. The word 'monsoon' comes from the Arabic word 'mausim' meaning weather. They change or reverse their directions according to the seasons. Strong contrasts in temperature between summer and winter because great differences in pressure conditions over the interior parts of the big continents like Asia. Hence winds blow onshore from a sea to the land in summer and from land to the sea in winter. The onshore winds bring moisture and heavy rainfall while the offshore winds are relatively dry. Although the monsoons are associated with south-east USA, Australia, parts of South America and East Africa they are most effective over south-east Asia and India blows from June to September while the winter monsoons prevails from October to December.



### Example 3: Mountain and Valley Breezes (tertiary circulation)

During the day, the valley heats up, so the warm less dense air flows up the mountain, creating a *valley breeze*.



At night, the mountain will cool off faster than the valley, so the cool mountain air descends because it is more dense, creating a *mountain breeze*.

## **3. Local Winds**

On the earth's surface, some local variations of temperature on the land may cause changes in air pressure. As a result local winds blow. They blow in a particular season and are



known by the local names in that region. For instance, the hot dry, dusty winds that blow in the month of May and June over the northern plains in India are called Loo.

Some other examples of local winds that bring unusual changes in the temperature of the places are the warm Chinooks that devour the snow on the leeward side of the Rocky mountains of North America, the Foehn in the Swiss Alps and the hot, sand laden Siocco that blows over Southern Europe from the Sahara and causes 'blood rain' which is actually desert sand and dust that falls with the rain.

There are still other types of winds that are irregular and keep changing their direction and blow in an area for a very short time, such as tornadoes, typhoons and cyclones.

## **CAUSES OF VARIATION OF WINDS**

The movement and the speed of wind are affected by three main factors

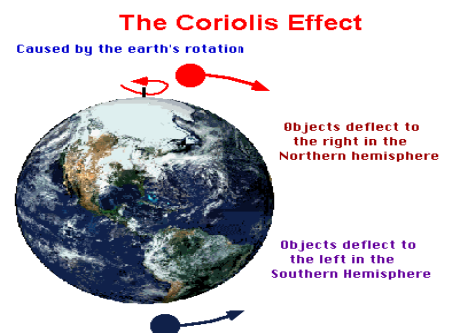
### **1. Pressure Gradient Force**

- The change in pressure measured across a given distance is called a "pressure gradient".
- The pressure gradient results in a net force that is directed from high to low pressure. The magnitude of the force depends on
  - 1) How great the pressure difference is between the high pressure area and low pressure area
  - 2) how far apart the two pressure areas are from each other. A large difference in pressure combined with pressure areas that are close to each other will cause a huge pressure gradient which produces a strong wind.

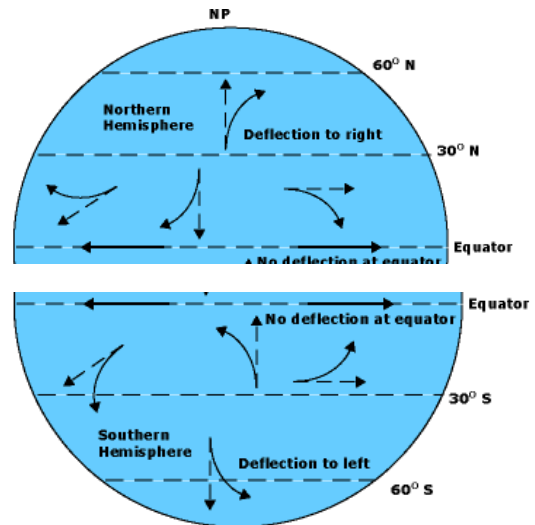
### **2. Coriolis Effect**

*The Coriolis Effect* (also called the Coriolis force) is defined as the apparent deflection of objects (such as airplanes, wind, missiles, and ocean currents) moving in a straight path relative to the earth's surface.

If the Earth did not rotate upon its axis, winds would follow the direction of the pressure gradient. But the rotation produces another force other than the pressure force. It is called the '*Coriolis force*'.



- Causes air to move in a curved path
- It is caused by the Earth spinning on its axis
- The Earth spins fastest at the equator, and slowest near the poles
- As air moves from the equator to the pole, it will travel east faster than the land beneath it causing the air to follow a curved path
- So the Coriolis effect causes wind flowing from high pressure to low pressure to curve as the wind moves



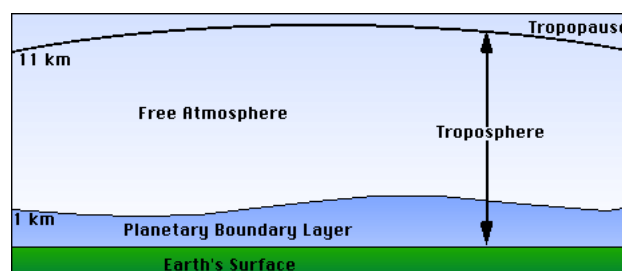
- In the *Northern Hemisphere*, the Coriolis effect causes things to curve to the *Right*
- In the *Southern Hemisphere*, the Coriolis effect causes things to curve to the *Left*

### 3. Friction

The surface of the Earth exerts a frictional drag on the air blowing just above it. This friction can act to change the wind's direction and slow it down -- keeping it from blowing as fast as the wind aloft. Actually, the difference in terrain conditions directly affects how much friction is exerted. For example, a calm ocean surface is pretty smooth, so the wind blowing over it does not move up, down, and around any features. By contrast, hills and forests force the wind to slow down and/or change direction much more.

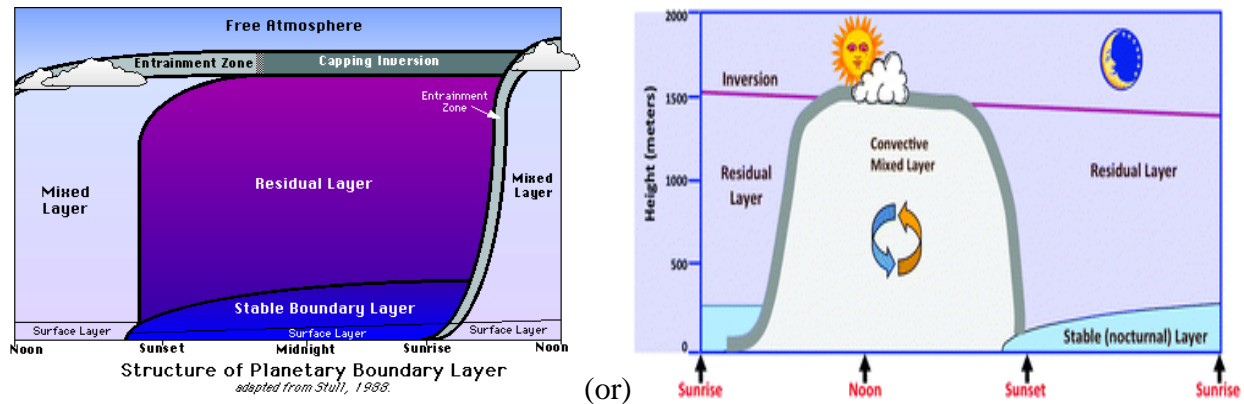
## ATMOSPHERIC BOUNDARY LAYER

The planetary boundary layer (PBL), also known as the atmospheric boundary layer (ABL), is the lowest part of the atmosphere and its behavior is directly influenced by its contact with a planetary surface. Above the PBL is the "free atmosphere" where the wind is approximately geostrophic (parallel to the isobars) while within the PBL the wind is affected by surface drag. The free atmosphere is usually non-turbulent.



## Structure of the Planetary Boundary Layer

The PBL can be subdivided into four separate component layers: the surface layer, the mixed layer, the stable layer, and the residual layer. We will discuss each of these in turn.



### *1. Mixed Layer(or) Convective Boundary Layer (CBL)*

During the daytime, surface heating leads to convective motion in the PBL. Heat transfer from the surface forms rising warm air. Radiative cooling from clouds forms sinking cooler air. Convective motion also leads to significant turbulence which mixes the air within this layer. Because of the convective motion and significant mixing of air, this sub-layer is called the convective layer or mixed layer. Above the mixed layer is a stable layer which prevents the continued upward motion of thermals. This stable layer also restricts turbulence, preventing frictional influences from reaching above the PBL. This stable layer is called the entrainment zone, because it is here where air from above the PBL entrains into the mixed layer. During the day, the mixed layer reaches heights over 1 km and make up the entire layer of the PBL above the surface layer. However, the mixed layer vanishes with the sun as the thermally driven convection ceases.

### *2. Stable Layer(or) Nocturnal Boundary Layer (NBL)*

After sunset, convective motion dramatically decreases. However, the earth's surface still affects the air, and a stable boundary layer forms (also called the nocturnal boundary layer). This boundary layer is characterized by light winds and weaker, more sporadic turbulence than in the mixed layer. The height of the PBL, therefore, decreases significantly during the night. Though the height of the nocturnal layer varies, it is usually less than half that of the mixed layer. Unlike

the mixed layer, the stable boundary layer does not have a well-defined top. Instead, it slowly merges with the residual layer.

### *3. Residual Layer*

As turbulence and the mixed layer decay with sunset, the air maintains many of the state variables that the well-mixed air had. This layer is called the residual layer (because its properties are residuals of the mixed layer) and forms above the stable boundary layer. While the nocturnal boundary layer has a very stable profile, the residual layer tends to have more of a neutral profile. The residual layer does not have contact with the earth's surface, and so is not influenced by turbulent stresses like the stable boundary layer below it. The residual layer is bounded above by a capping inversion, which approximates the height of the daytime height of the mixed layer. This inversion simply prevents entrainment from aloft.

Because the residual layer is not influenced directly by the earth's surface (i.e. no turbulent stresses) it is not considered a boundary layer. However, we include it in our discussion for descriptive purposes. Only the mixed layer and stable layer are true boundary layers.

### *4. Mixing Height (or) Gradient Height (or) Height of the PBL*

Because turbulent fluxes vary based on surface heating and other factors, the height of the PBL also varies. At night, the height of the PBL decreases dramatically as the stable layer forms. The height of the PBL is called the mixing height, because it is the height up to which the air is well-mixed. The mixing height is very important to air quality experts when determining air pollution dispersion. We will cover this more in the Focus on Air Quality section. Meanwhile, we'll look at some of the factors which influence the PBL.

## **EFFECT OF TERRAIN ON GRADIENT HEIGHT**

For winds near ground surface, frictional effects play a significant role. Ground obstruction retard the movement of air close to the ground surface, causing a reduction in wind speed.

At some height above ground, the movement of air is no longer affected by ground obstruction. This height is called gradient height ( $Z_G$ ) which is a function of ground roughness.

The unobstructed wind speed is called gradient wind speed ( $V_{zg}$ ) and it is considered to be constant above gradient height.

### Wind Profile

Wind profile is the variation of mean wind speed with height above ground. It is usually represented by power law or logarithmic law.

#### *1. Power law*

The Power law, which is used by some engineers to represent variation of wind speed with height, is an empirical equation, which for the case of *mean speeds* takes the form of

$$\frac{V_z}{V_{zg}} = \left[ \frac{Z}{Z_g} \right]^\alpha$$

Where,

$V_z, V_{zg}$  = the wind speeds at height  $Z, Z_g$  respectively, and

$\alpha$  = the power law exponent.

( $Z_g$  and  $\alpha$  are functions of ground roughness)

#### *2. Logarithmic law*

The Logarithmic law is used by both engineers and meteorologists. It is based on physics of the boundary layer and it is valid in the bottom 20 to 30% of the boundary layer.

$$\text{Mean wind speed } \bar{V}_z = 2.5 \times U^* \times \ln \frac{z}{z_o}$$

Where,

$z_o$  = Roughness length – see typical values in Table 1

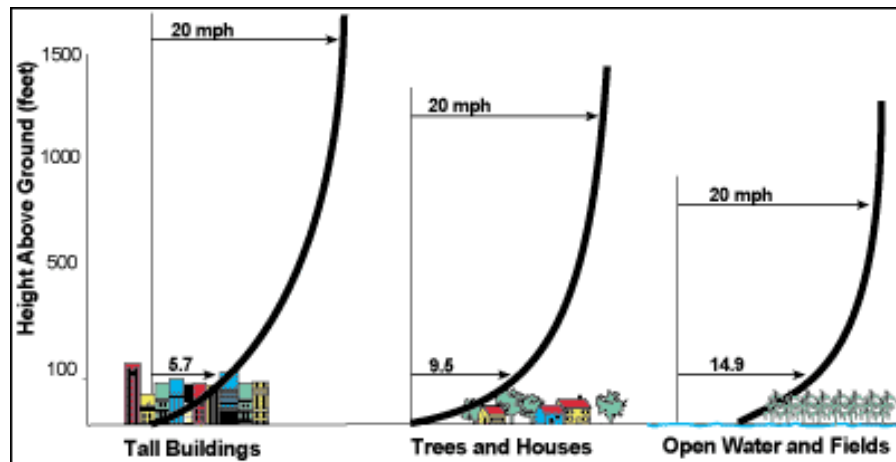
$$U^* = \text{Friction velocity} = \sqrt{\frac{\tau_o}{\rho}}$$

$\tau_o$  = Shear stress at the ground surface

$\rho$  = Air density

*Table 1: Typical values of parameters in wind profiles based on effect of terrain type*

<b>Terrain category</b>	<b>Terrain description</b>	<b>Gradient height <math>Z_g</math> (m)</b>	<b>Roughness length <math>Z_o</math> (m)</b>	<b>Mean speed exponent <math>\alpha</math></b>
1	Open sea, ice, tundra, desert	250	0.001	0.11
2	Open country with low scrub or scattered trees	300	0.03	0.15
3	Suburban areas, small towns, well wooded areas	400	0.3	0.25
4	Numerous tall buildings. City centers, well developed industrial areas	500	3	0.36



*Figure: Variation of wind speed with height for different terrain types*

The turbulence created is higher in rougher terrain than in smoother terrain. Turbulence decreases with increasing height above ground.

#### *Turbulence Intensity*

The most commonly used parameter to define turbulence in time domain is turbulence intensity. It is a measure of the relative amplitude of the fluctuations compared to the mean component of wind. It is expressed as:

$$T_u = \frac{\sigma}{V_z}$$

Where,

$T_u$  = The turbulence intensity.

$\sigma$  = The root mean square of wind speed, and

$V_z$  = The mean wind speed.

Turbulence intensity decreases with height since the mean wind speed increases and the fluctuation of wind decreases.

## **WIND ENERGY**

Wind energy is produced by the movement of air (wind) and converted into power for human use. Wind has been used as a source of energy for more than a thousand years, but was replaced by fossil fuels for much of the 20th century. Today, wind is making a comeback as a source of electricity and power.

## **WIND ENERGY CONVERSION SYSTEM**

An apparatus for converting the kinetic energy available in the wind to mechanical energy that can be used to power machinery (grain mills, water pumps, etc) and/or to operate an electrical generator.

### **Windmills**

Windmills convert wind energy directly into mechanical energy for such tasks as milling grain or pumping water, which is usually the purpose of windmills you see on farms.

#### *Windmill Mechanism*

The spinning vanes of a windmill turn a camshaft, which is connected by gears and rods to the machinery that does the work. All power is directed into the work

### **Wind Turbines**

A wind turbine converts wind energy into electricity, which can then be used to power electrical equipment, stored in batteries or transmitted over power lines.

## *Wind Turbine Mechanism*

The blades turn, convert the energy of wind into rotational energy, a form of mechanical energy, and this energy is in turn converted into electrical energy. A wind turbine has essentially the same parts as a simple electric motor, but it works in reverse: A motor uses electrical current to produce motion; a wind turbine uses motion to create electrical current.

## *Wind Farms*

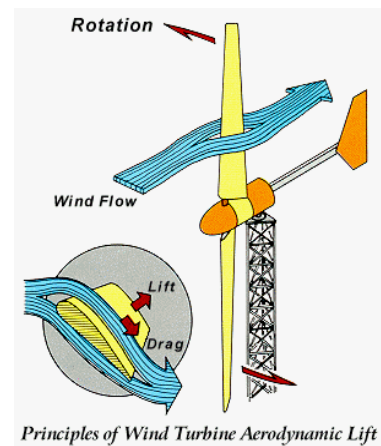
In order to generate a large amount of electricity, wind turbines are often constructed in large groups called wind farms. Wind farms are made up of hundreds of turbines, spaced out over hundreds of acres.

*The two main categories of wind turbines are*

1. Vertical axis wind turbines and
2. Horizontal axis wind turbines.

## **HORIZONTAL AXIS MACHINES**

A wind turbine in which the axis of the rotor's rotation is parallel to the wind stream and the ground. All grid-connected commercial wind turbines today are built with a propeller-type rotor on a horizontal axis. Horizontal-axis wind turbines (HAWT) have the main rotor shaft and electrical generator at the top of a tower, and may be pointed into or out of the wind. Small turbines are pointed by a simple wind vane, while large turbines generally use a wind sensor coupled with a servo motor. Most have a gearbox, which turns the slow rotation of the blades into a quicker rotation that is more suitable to drive an electrical generator.



HAWTs can be subdivided into upwind wind turbines and downwind wind turbines. Compare with vertical-axis wind turbine.



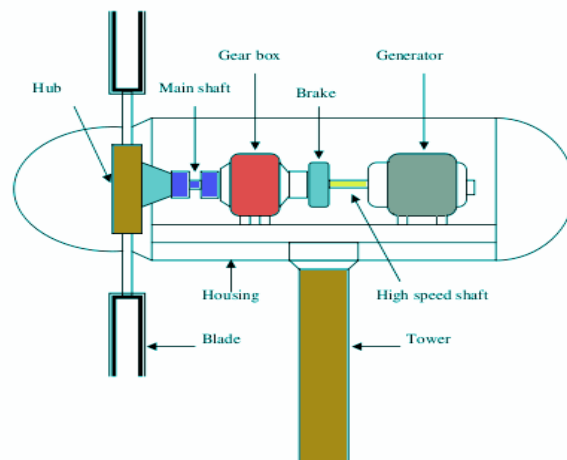
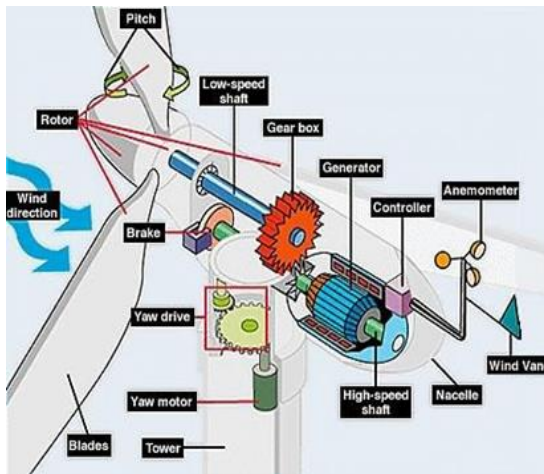
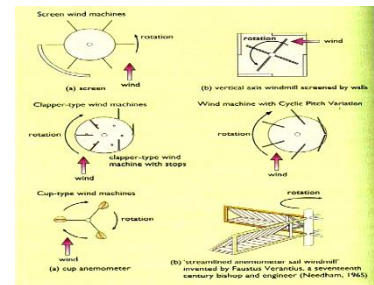
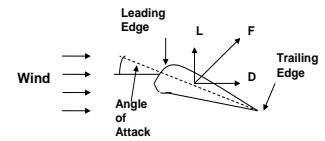
## Parts of the wind turbine

### *1. Blades*

Most wind turbines have three blades. Very small turbines may use two blades for ease of construction and installation. Vibration intensity decreases with larger numbers of blades. Noise and wear are generally lower, and efficiency higher, with three instead of two blades.

Also, the cost of the turbine usually increases with the number of blades. Based on blade style classified as

- The lifting style wind turbine blade. These are the most efficiently designed, especially for capturing energy of strong, fast winds.
- The drag style wind turbine blade, most popularly used for water mills, as seen in the old Dutch windmills. The blades are flattened plates which catch the wind. These are poorly designed for capturing the energy of heightened winds.

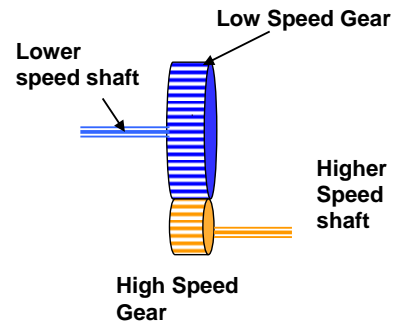


### *2. Rotor*

The rotor is designed aerodynamically to capture the maximum surface area of wind in order to spin the most ergonomically. The blades are lightweight, durable and corrosion-resistant material. The best materials are composites of fiberglass and reinforced plastic.

### 3. Gear box

A gear box magnifies or amplifies the energy output of the rotor. The gear box is situated directly between the rotor and the generator. A rotor rotates the generator (which is protected by a nacelle), as directed by the tail vane.



### 4. Generator

The generator produces electricity from the rotation of the rotor. Generators come in various sizes, relative to the output you wish to generate. The nacelle is the housing or enclosure that seals and protects the generator and gear box from the elements. It is easily removed for maintenance.

### 5. Yaw Mechanism

Yaw mechanism turns the rotor into the upwind direction as the wind direction changes. Electric motors and gear boxes are used to keep the turbine yawed against wind. This can be also used as controlling mechanism during high wind speeds.

### 6. Anemometers

Wind speed is the most important factor for determining the power content in the wind. The power content in the wind is directly proportional to cube of the wind velocity. Measuring wind speed is important for site selection. The device which is used for measuring wind speed is called anemometer. These are usually located on top of the nacelle.

#### Advantages

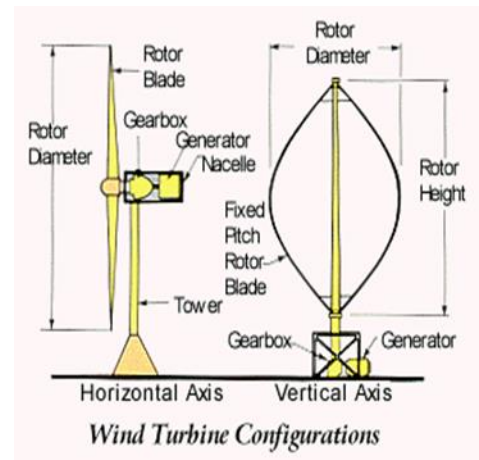
- Higher wind speeds
- Great efficiency

#### Disadvantages

- Angle of turbine is relevant
- Difficult access to generator for repairs

## VERTICAL AXIS MACHINES

A type of wind turbine in which the axis of rotation is perpendicular to the wind stream and the ground. A vertical-axis wind turbine's (VAWTs) main rotor shaft is set vertically and the main components are located at the base of the turbine. VAWTs work somewhat like a classical water wheel in which water arrives at a right angle (perpendicular) to the rotational axis (shaft) of the water wheel. Vertical-axis wind turbines fall into two major categories: Darrieus turbines (Lift Device) and Savonius turbines (Drag Device). Neither type is in wide use today.



The basic theoretical advantages of a vertical axis machine are:

- The generator, gearbox etc. may be placed on the ground, and a tower is not essential for the machine
- A yaw mechanism isn't needed to turn the rotor against the wind

The basic disadvantages are:

- Wind speeds are very low close to ground level, so although a tower isn't essential, the wind speeds will be very low on the lower part of the rotor
- The overall efficiency of the vertical axis machines is not impressive
- The machine is not self-starting, i.e. a Darrieus machine needs a "push" before it will start. This is only a minor inconvenience for a grid-connected turbine, however, since the generator may be used as a motor drawing current from the grid to start the machine
- The machine may need guy wires to hold it up, but guy wires are impractical in heavily farmed areas
- Replacing the main bearing for the rotor necessitates removing the rotor on both a horizontal and a vertical axis machine. In the case of the latter, it means tearing the whole machine down.

## **POWER COEFFICIENT, BETZ COEFFICIENT BY MOMENTUM THEORY**

### **Introduction**

#### **Available Wind Energy**

The kinetic energy of a stream of air:

$$E = \frac{1}{2}mV^2$$

#### **Available Wind Power**

Power is the *energy per unit time* and expressed

$$P = dE/dt$$

$$P = \frac{1}{2}\rho_a A_T V^3$$

#### **Power Co-efficient**

The efficiency is the ratio of actual power developed by wind turbine rotor to the available wind power. It is also defined as power coefficient and expressed as

$$C_p = \frac{P_r}{\frac{1}{2}\rho_a A_T V^3}$$

The power coefficient or the power picked up by the wind turbine rotor is influenced by many factors:

- profile of the rotor blade
- number of blades
- blade arrangement

#### **Torque Co-efficient**

The thrust force developed by the rotor is

$$F = \frac{1}{2}\rho_a A_T V^2$$

The rotor torque is

$$T = \frac{1}{2}\rho_a A_T V^2 R$$

The torque developed by the rotor shaft is less than the maximum theoretical torque and given in terms of *coefficient of torque*

$$C_T = \frac{T_r}{\frac{1}{2} \rho_a A_r V^2}$$

### Tip Speed Ratio

$$V_{rw} = \frac{\omega R}{V} = \frac{2\pi NR}{V}$$

Where,

R = radius of the rotor

$\omega$  = Angular velocity

N = Rotor rotational speed, rpm

Also, it can be shown that power coefficient and torque coefficient is related by relative speed:

$$\frac{C_P}{C_T} = V_{rw} = \frac{\omega R}{V}$$

### Solidity

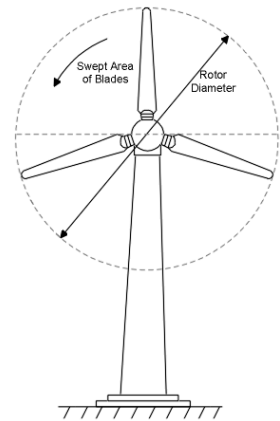
Solidity is the ratio of total rotor plan form area to total swept area.

$$\text{Solidity} = 3a/A$$

### Betz' Limit

All wind power cannot be captured by rotor or air would be completely still behind rotor and not allow more wind to pass through. Betz' law States the theoretical limit for the conversion of wind energy in wind turbine. According to this law maximum possible wind turbine efficiency is less than 59.3 %

$$C_{p,\max} = \frac{16}{27} = .5926$$



## BETZ COEFFICIENT BY MOMENTUM THEORY

This analysis uses the following assumptions:

- Homogenous, incompressible, steady state fluid flow
- No frictional drag
- An infinite number of blades
- Uniform thrust over the disk or rotor area
- A nonrotating wake
- The static pressure far upstream and far downstream of the rotor is equal to the undisturbed ambient static pressure

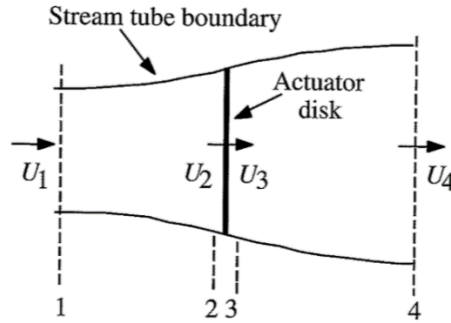


Figure: Actuator model of a wind turbine:  $U$ =Mean air velocity; 1,2,3,4, indicate locations

Applying the conservation of linear momentum to the control volume enclosing the whole system, one can find the net force on the contents of the control volume. That force is equal and opposite to the thrust,  $T$ , which is the force of the wind on the wind turbine. From the conservation of linear momentum for a one-dimensional, incompressible, time-invariant flow, the thrust is equal and opposite to the change in momentum of air stream:

$$T = U_1 (\rho A U)_1 - U_4 (\rho A U)_4 \quad (3.2.1)$$

where  $\rho$  is the air density,  $A$  is the cross sectional area,  $U$  is the air velocity and the subscripts indicate values at numbered cross sections in Figure 3.1.

For steady state flow,  $(\rho A U)_1 = (\rho A U)_4 = \dot{m}$ , where  $\dot{m}$  is the mass flow rate. Therefore:

$$T = \dot{m}(U_1 - U_4) \quad (3.2.2)$$

The thrust is positive so the velocity behind the rotor,  $U_4$ , is less than the free stream velocity,  $U_1$ . No work is done on either side of the turbine rotor. Thus the Bernoulli function can be used in the two control volumes on either side of the actuator disk. In the stream tube upstream of the disk:

$$p_1 + \frac{1}{2} \rho U_1^2 = p_2 + \frac{1}{2} \rho U_2^2 \quad (3.2.3)$$

In the stream tube downstream of the disk:

$$p_3 + \frac{1}{2} \rho U_3^2 = p_4 + \frac{1}{2} \rho U_4^2 \quad (3.2.4)$$

where it is assumed that the far upstream and far downstream pressures are equal ( $p_1 = p_4$ ) and that the velocity across the disk remains the same ( $U_2 = U_3$ ).

The thrust can also be expressed as the net sum of the forces on each side of the actuator disc:

$$T = A_2 (p_2 - p_3) \quad (3.2.5)$$

If one solves for ( $p_2 - p_3$ ) using Equations 3.2.3 and 3.2.4 and substitutes that into Equation 3.2.5, one obtains:

$$T = \frac{1}{2} \rho A_2 (U_1^2 - U_4^2) \quad (3.2.6)$$

Equating the thrust values from Equations 3.2.2 and 3.2.6 and recognizing that the mass flow rate is  $A_2 U_2$ , one obtains:

$$U_2 = \frac{U_1 + U_4}{2} \quad (3.2.7)$$

Thus, the wind velocity at the rotor plane, using this simple model, is the average of the upstream and downstream wind speeds.

If one defines the axial induction factor,  $a$ , as the fractional decrease in wind velocity between the free stream and the rotor plane, then

$$a = \frac{U_1 - U_2}{U_1} \quad (3.2.8)$$

$$U_2 = U_1(1 - a) \quad (3.2.9)$$

and

$$U_4 = U_1(1 - 2a) \quad (3.2.10)$$

The quantity,  $U_1 a$ , is often referred to as the induced velocity at the rotor, in which case velocity of the wind at the rotor is a combination of the free stream velocity and the induced wind velocity. As the axial induction factor increases from 0, the wind speed behind the rotor slows more and more. If  $a = 1/2$ , the wind has slowed to zero velocity behind the rotor and the simple theory is no longer applicable.

The power out,  $P$ , is equal to the thrust times the velocity at the disk:

$$P = \frac{1}{2} \rho A_2 (U_1^2 - U_4^2) V_2 = \frac{1}{2} \rho A_2 U_2 (U_1 + U_4)(U_1 - U_4) \quad (3.2.11)$$

Substituting for  $U_2$  and  $U_4$  from Equations 3.2.9 and 3.2.10 gives

$$P = \frac{1}{2} \rho A U^3 4a(1 - a)^2 \quad (3.2.12)$$

where the control volume area at the rotor,  $A_2$ , is replaced with  $A$ , the rotor area, and the free stream velocity  $U_1$  is replaced by  $U$ .

Wind turbine rotor performance is usually characterized by its power coefficient,  $C_P$ :

$$C_P = \frac{P}{\frac{1}{2} \rho U^3 A} = \frac{\text{Rotor power}}{\text{Power in the wind}} \quad (3.2.13)$$

The non-dimensional power coefficient represents the fraction of the power in the wind that is extracted by the rotor. From Equation 3.2.12, the power coefficient is:

$$C_P = 4a(1 - a)^2 \quad (3.2.14)$$

The maximum  $C_P$  is determined by taking the derivative of the power coefficient (Equation 3.2.14) with respect to  $a$  and setting it equal to zero, yielding  $a = 1/3$ . Thus:

$$C_{P,\max} = 16/27 = 0.5926 \quad (3.2.15)$$



when  $a = 1/3$ . For this case, the flow through the disk corresponds to a stream tube with an upstream cross-sectional area of  $2/3$  the disk area that expands to twice the disk area downstream. This result indicates that, if an ideal rotor were designed and operated such that the wind speed at the rotor were  $2/3$  of the free stream wind speed, then it would be operating at the point of maximum power production. Furthermore, given the basic laws of physics, this is the maximum power possible.

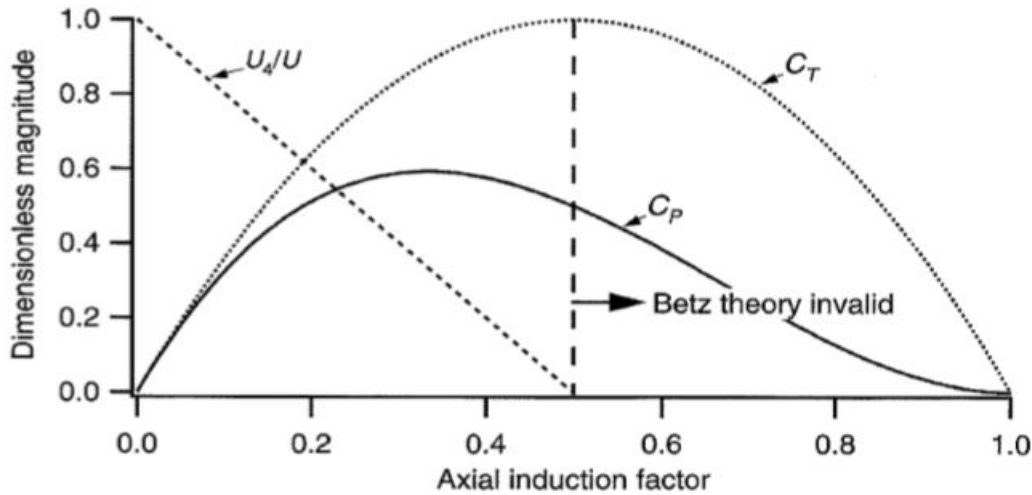
From Equations 3.2.6, 3.2.9 and 3.2.10, the axial thrust on the disk is:

$$T = \frac{1}{2} \rho A U_1^2 [4a(1-a)] \quad (3.2.16)$$

Similarly to the power, the thrust on a wind turbine can be characterized by a non-dimensional thrust coefficient:

$$C_T = \frac{T}{\frac{1}{2} \rho U^2 A} = \frac{\text{Thrust force}}{\text{Dynamic force}} \quad (3.2.17)$$

From Equation 3.2.16, the thrust coefficient for an ideal wind turbine is equal to  $4a(1-a)$ .  $C_T$  has a maximum of 1.0 when  $a = 0.5$  and the downstream velocity is zero. At maximum power output ( $a = 1/3$ ),  $C_T$  has a value of  $8/9$ . A graph of the power and thrust coefficients for an ideal Betz turbine and the non-dimensionalized downstream wind speed are illustrated in Figure 3.2.



**Figure 3.2** Operating parameters for a Betz turbine;  $U$ , velocity of undisturbed air;  $U_4$ , air velocity behind the rotor;  $C_p$ , power coefficient;  $C_T$ , thrust coefficient

As mentioned above, this idealized model is not valid for axial induction factors greater than 0.5. In practice (Wilson et al., 1976), as the axial induction factor approaches and exceeds 0.5, complicated flow patterns that are not represented in this simple model result in thrust coefficients that can go as high as 2.0. The details of wind turbine operation at these high axial induction factors appear in Section 3.7.

The Betz limit,  $C_{p,max} = 16/27$ , is the maximum theoretically possible rotor power coefficient. In practice three effects lead to a decrease in the maximum achievable power coefficient:

- Rotation of the wake behind the rotor
- Finite number of blades and associated tip losses
- Non-zero aerodynamic drag

Note that the overall turbine efficiency is a function of both the rotor power coefficient and the mechanical (including electrical) efficiency of the wind turbine:

$$\eta_{overall} = \frac{P_{out}}{\frac{1}{2} \rho A U^3} = \eta_{mech} C_p \quad (3.2.18)$$

Thus:

$$P_{out} = \frac{1}{2} \rho A U^3 (\eta_{mech} C_p) \quad (3.2.19)$$

\*\*\*\*\*

## Unit II

# Ground Vehicle Aerodynamics



**Ground Vehicle aerodynamics** is the study of the aerodynamics of road vehicles. Its main goals are reducing drag and wind noise, minimizing noise emission, and preventing undesired lift forces and other causes of aerodynamic instability at high speeds. For some classes of racing vehicles, it may also be important to produce downforce to improve traction and thus cornering abilities.

### Comparison with Aircraft Aerodynamics

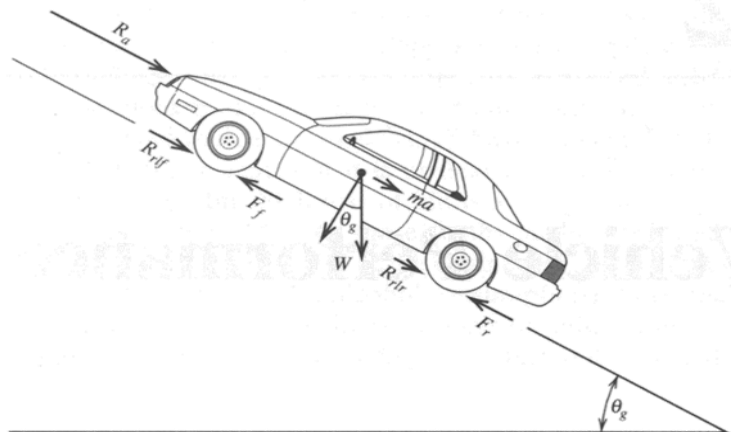
Ground Vehicle aerodynamics differs from aircraft aerodynamics in several ways. First, the characteristic shape of a road vehicle is much less streamlined compared to an aircraft. Second, the vehicle operates very close to the ground, rather than in free air. Third, the operating speeds are lower (and aerodynamic drag varies as the square of speed). Fourth, a ground vehicle has fewer degrees of freedom than an aircraft, and its motion is less affected by aerodynamic forces. Fifth, passenger and commercial ground vehicles have very specific design constraints such as their intended purpose, high safety standards (requiring, for example, more 'dead' structural space to act as crumple zones), and certain regulations.

### VEHICLE POWER REQUIREMENTS

Resistance forces acting on a ground vehicle are

1. Aerodynamic
2. Rolling
3. Grade

$$F = ma + R_a + R_{rl} + R_g$$



### Aerodynamic Resistance ( $R_a$ )

Composed of:

1. Turbulent air flow around vehicle body (85%)
2. Friction of air over vehicle body (12%)
3. Vehicle component resistance, from radiators and air vents (3%)

$$R_a = \frac{\rho}{2} C_D A_f V^2$$

Where,

$C_D$  = drag coefficient

$\rho$  = Density of air 1.225 kg/m<sup>3</sup>

$V$  = flow velocity

$A_f$  = characteristic frontal area of the body

### Rolling Resistance ( $R_{rl}$ )

Composed primarily of

1. Resistance from tire deformation (~90%)
2. Tire penetration and surface compression (~ 4%)
3. Tire slippage and air circulation around wheel (~ 6%)

$$R_{rl} = C_R \cdot m \cdot g$$

Where,

$C_R$  = coefficient of rolling resistance

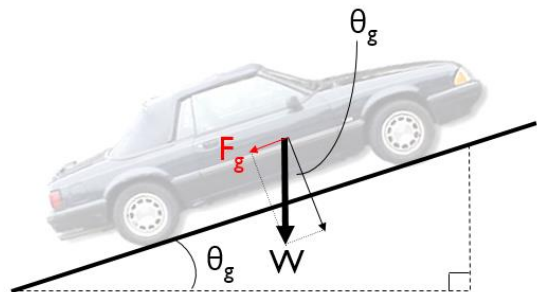
$m$  = mass of vehicle [kg]

$g$  = 9.81 m/s<sup>2</sup>

### Grade Resistance $R_g$

Composed of

- Gravitational force acting on the vehicle



$$R_g = W \sin \theta_g$$

The coefficients of rolling resistance and drag are determined from experiment. A typical value for the coefficient of rolling resistance is 0.015. The drag coefficient for cars varies, a value of 0.3 is commonly used.

The power output requirement can be determined from the drag force given above and the vehicle velocity.

$$P = F.V$$

### **DRAG COEFFICIENTS OF AUTOMOBILES**

- The drag coefficient expresses the drag of an object in a moving fluid.
- Reducing the drag coefficient in an automobile improves the performance of the vehicle as it pertains to speed and fuel efficiency.

Drag force can be expressed as:

$$F_d = c_d . (1/2) . \rho . v^2 . A$$

Where,

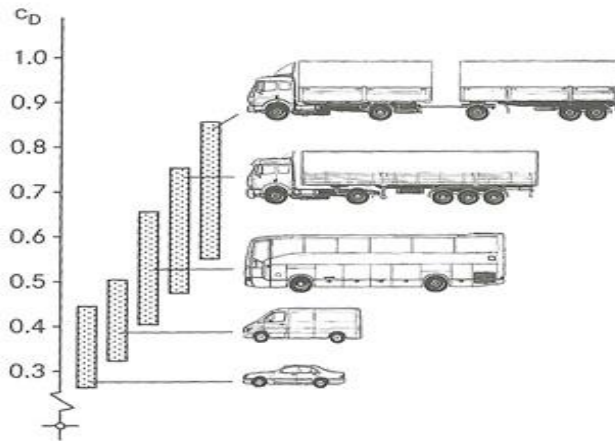
$F_d$  = drag force (N)

$c_d$  = drag coefficient

$\rho$  = Density of fluid  $1.2 \text{ kg/m}^3$

$v$  = flow velocity

$A$  = characteristic frontal area of the body



### **Vehicle aerodynamics includes three interacting flow fields:**

- flow past vehicle body
- flow past vehicle components (wheels, heat exchanger, brakes, windshield),
- flow in passenger compartment

### **AERODYNAMICS OF CAR**

A body in motion is affected by aerodynamic forces. The aerodynamic force acts externally on the body of a vehicle. The component of the resultant aerodynamic force which opposes the forward motion is called the aerodynamic drag. The aerodynamic drag affects the performance of a car in both speed and fuel economy as it is the power required to overcome the opposing force. The other component, directed vertically, is called the aerodynamic lift. It reduces the frictional forces between the tyres and the road thus changing dramatically the

handling characteristics of the vehicle. The aerodynamic force is the net result of all the changing distributed pressures which airstreams exert on the car surface. Therefore aerodynamic studies are very important as far as the car stability is concerned.

The main concerns of automotive aerodynamics are reducing drag, reducing wind noise, and preventing undesired lift forces at high speeds. For some classes of vehicles, it may also be important to produce desirable downwards aerodynamic forces, to improve cornering.

As the years passed the studies on aerodynamic effects on cars increased and the designs were being developed to accommodate for the increasing needs and for economic reasons. The wheels developed to be designed within the body, lowering as a result the aerodynamic drag and produce a more gentle flow. The tail was for many years long and oddly shaped to maintain attached streamline. The automobiles became developed even more with smooth bodies, integrated fenders and headlamps enclosed in the body. The designers had achieved a shape of a car that differed from the traditional horse-drawn carriages. They had certainly succeeded in building cars with low drag coefficient.

Road conditions have limited the width of automobiles. It is said this width was established by the width needed for two horses running comfortably side by side drawing a carriage. Length is not as much of a restriction but long bodies were not efficient enough for traffic use.

### Aerodynamic drag

In order to explain the Aerodynamic drag the two forces - the frontal pressure and the rear vacuum – have to be analyzed.

Frontal pressure is caused by the air attempting to flow around the front of the car. As millions of air molecules approach the front part of the car, they begin to compress, and in doing so raise the air pressure in front of the car. At the same time, the air molecules traveling along the sides of the car are at atmospheric pressure, a lower pressure compared to the molecules at the front of the car. The compressed molecules of air naturally seek a way out of the high pressure zone in front of the car, and they find it around the sides, top and bottom of the car.

Rear vacuum or wake is caused by the "hole" left in the air as the car passes through it. This empty area is a result of the air molecules not being able to fill the hole as quickly as the car can make it. The air molecules attempt to fill in to this area, but the car is always one step ahead. As a result, a continuous vacuum in the rear of the car sucks in the opposite direction of the motion of the car. This inability to fill the hole left by the car is technically called Flow detachment.

Flow detachment applies only to the "rear vacuum" portion of the drag equation, and it is really about giving the air molecules time to follow the contours of a car's bodywork, and to fill the hole left by the vehicle, it's tyres, it's suspension and protrusions (i.e. mirrors, roll bars).

The flow attachment is very important because the drag created by the vacuum far exceeds that created by frontal pressure, and this can be attributed to the turbulence created by the detachment. That is why in the early years of automotive industry the cars used to be designed with long tail. This was done as to maintain the streamlines created by the flow, attached.

Turbulence generally affects the "rear vacuum" portion of the drag equation, but if we look at a protrusion from the race car such as a mirror, we see a compounding effect. For instance, the air flow detaches from the flat side of the mirror, which of course faces toward the back of the car. The turbulence created by this detachment can then affect the air flow to parts of the car which lie behind the mirror. Intake ducts, for instance, function best when the air entering them flows smoothly. Therefore, the entire length of the car really needs to be optimized to provide the least amount of turbulence at high speed.

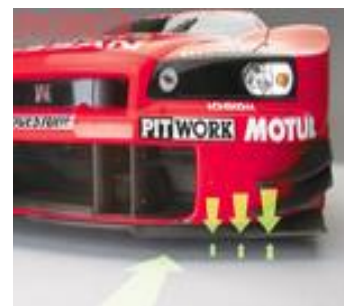
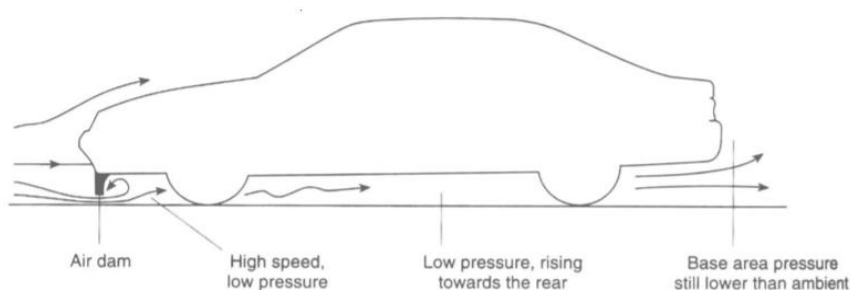
### Drag Coefficient

The shape of a car, as the aerodynamic theory above suggests, is largely responsible for how much drag the car has. Ideally, the car body should:

- Have a small grill, to minimize frontal pressure.
- Have minimal ground clearance below the grill, to minimize air flow under the car. In combination to this, a raked underside with the rear of the car raised can create down force.
- Have a steeply raked windshield to avoid pressure build up in front.
- Have a "Fastback" style rear window and deck, to permit the air flow to stay attached.
- Have a converging "Tail" to keep the air flow attached.

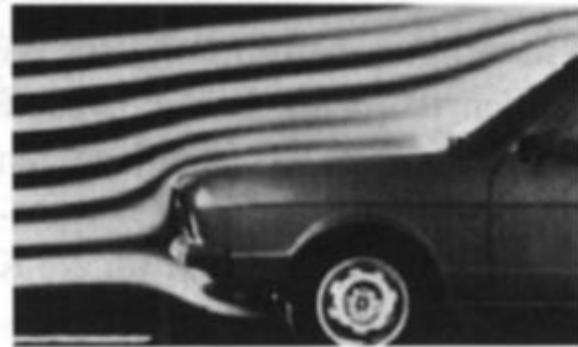
### **Air dams (also called front spoiler):**

- ❖ An air dam is a panel that reduces ground clearance at the front of the car below the bumper
- ❖ The smaller gap forces flow to locally accelerate under the air dam reducing pressure under the car and creating downforce
- ❖ Lower air volume flow to underbody reduces drag due to underbody roughness



### Splitter:

The splitter is a horizontal lip that brought the airflow to stagnation above the surface, causing an area of high pressure. Below the splitter the air is accelerated, causing the pressure to drop. This, combines with the high pressure over the splitter creates downforce.

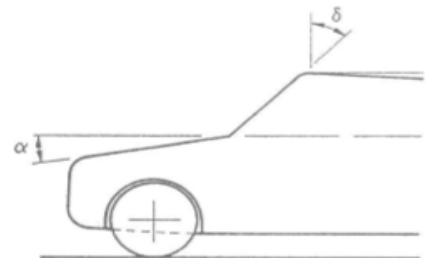


### Reduction of forebodydrag:

- ❖ The most significant drag reduction can be achieved by rounding up the vertical and upper horizontal leading edges on the front face.
- ❖ Relatively small amendments can result considerable drag reduction.
- ❖ The drag reduction of front spoiler is large if its use is combined with rounded leading edges.

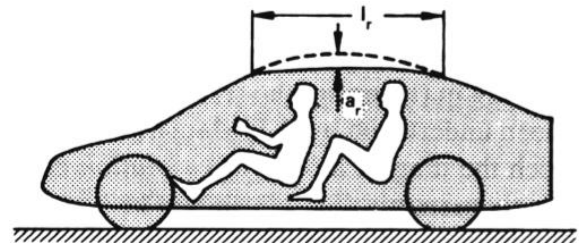
### Hood and Windshield Angle of Inclination:

- ❖ The hood angle ( $\alpha$ ) determines the pressure gradient and plays a role in maintaining attached flow
- ❖ The windshield angle,  $\delta$  (rake) plays a stronger role by controlling point of attachment of flow to roof



### Roofline Shape:

- ❖ Curved (cambered) roofline helps maintain attached flow over the rear of the car



### Scoops:

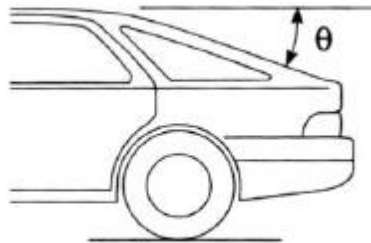
- ❖ Engine cooling
- ❖ Increases flow rate of air



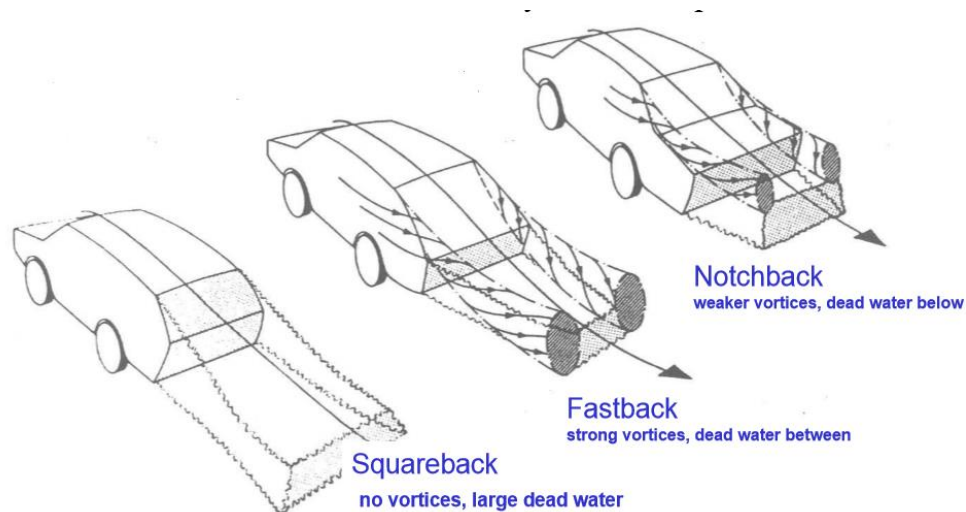


### EFFECT OF CUT BACK ANGLE (*Back Light Angle Or Rear Wind Shield Angle*):

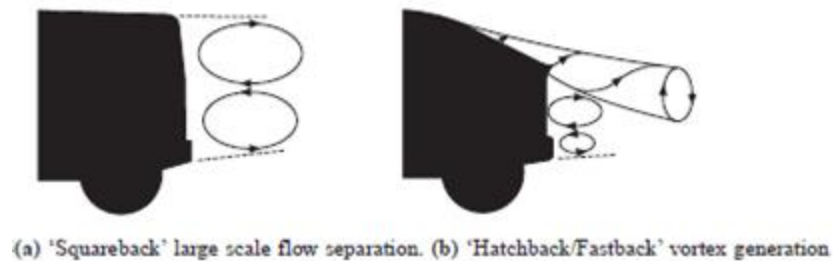
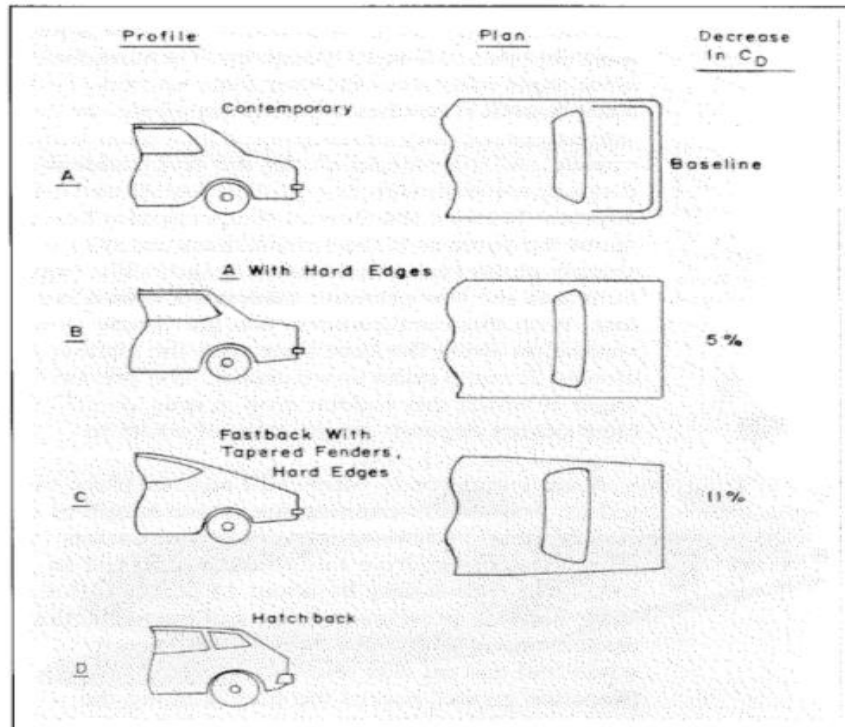
The rear window angle with horizontal is called the “cut back angle” or “back light angle”.



- ✓ The angle of inclination affects the trailing vortex location and strength
- ✓ The nature of the counter rotating vortex structure is controlled primarily by the cut back angle.
- ✓ Vortices expend energy gives Drag. So the amount of drag force creation is controlled by the cut back angle.



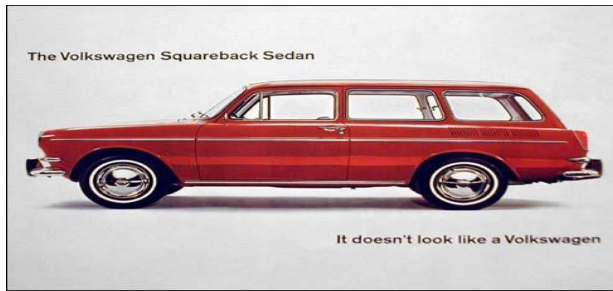
The airflow over the rear surfaces of the vehicle is more complex and the solutions required to minimize drag for practical shapes are less intuitive. The inclination of the screen may be sufficient to cause the flow to separate from the rear window although in many cases the separation is followed by flow re-attachment along the boot lid.



The first occurs for 'squareback' shapes and is characterized by a large, low pressure wake. Here the airflow is unable to follow the body surface around the sharp, rear corners. The drag that is associated with such flows depends upon the cross-sectional area at the tail, the pressure acting upon the body surface and, to a lesser extent, upon energy that is absorbed by the creation of eddies.

A very different flow structure arises if the rear surface slopes more gently as is the case for hatchback, fastback and most notchback shapes. The centreline pressure distribution that the surface air pressure over the rear of the car is significantly lower than that of the surroundings. Along the sides of the car the body curvature is much less and the pressures recorded here differ little from the ambient conditions.

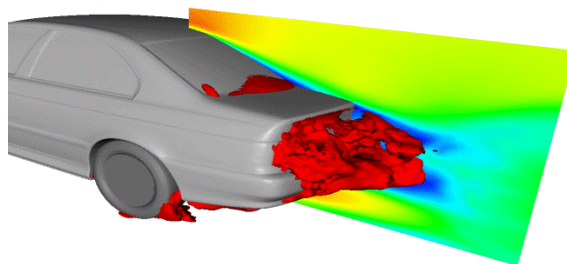
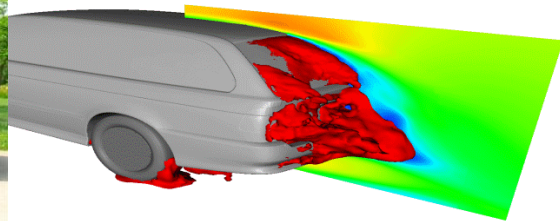
## SQUARE BACK



## HATCH BACK



## NOTCH BACK



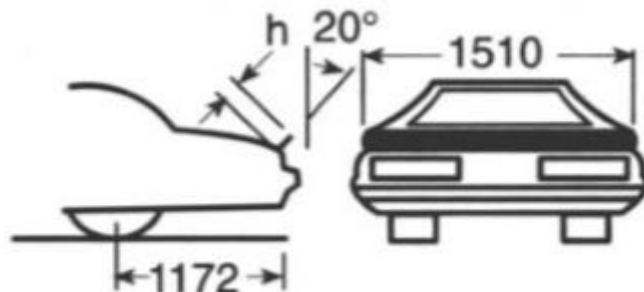
The low pressure over the upper surface draws the relatively higher pressure air along the sides of the car upwards and leads to the creation of intense, conical vortices at the 'C' pillars. These vortices increase the likelihood of the upper surface flow remaining attached to the surface even at backlight angles of over 30 degrees. Air is thus drawn down over the rear of the car resulting in a reacting force that has components in both the lift and the drag directions. The backlight angle has been shown to be absolutely critical for vehicles of this type. demonstrates the change in the drag coefficient of a typical vehicle with changing backlight angle. As the angle increases from zero (typical squareback) towards 15 degrees there is initially a slight drag reduction as the effective base area is reduced. Further increase in backlight angle reverses this trend as the drag inducing influence of the upper surface pressures and trailing vortex creation

increase. As  $30^\circ$  is approached the drag is observed to increase particularly rapidly as these effects become stronger until at approximately  $30^\circ$  the drag dramatically drops to a much lower value.

This sudden drop corresponds to the backlight angle at which the upper surface flow is no longer able to remain attached around the increasingly sharp top, rear corner and the flow reverts to a structure more akin to that of the initial squareback. In the light of the reasonably good aerodynamic performance of the squareback shape it is not surprising that many recent, small hatchback designs have adopted the square profiles that maximize interior space with little aerodynamic penalty.

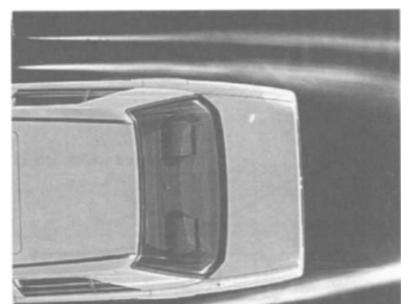
### Rear Spoilers:

- ❖ Rear spoiler act in a similar way than front, they spoils the airflow tumbling over the rear edge of the car that causes a recirculation bubbles, this vortex doesn't allow a good underfloor flow increasing lift and instability.
- ❖ Can be free standing device or "deck strip"
- ❖ Causes increase in pressure just forward of the spoiler



### Boat-Tailing (Tapering the rear end)

- ❖ Tapering of rear part results in reduction of the size of rear separation bubble and increase of pressure

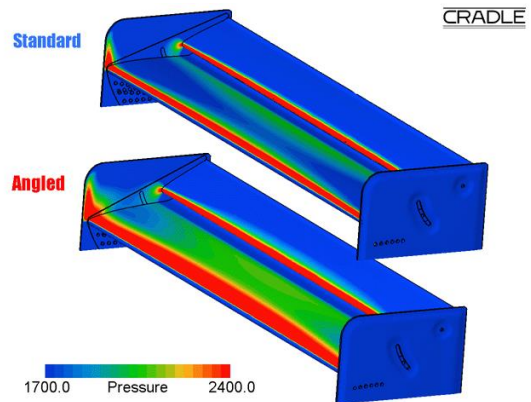


## Aerodynamics of Race Car

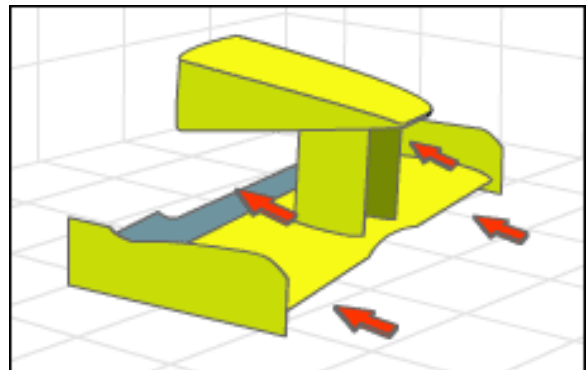
### Front and rear wings:

The main focus in race cars is on the down force and drag. The relationship between drag and down force is especially important. Aerodynamic improvements in wings are directed at generating down force on the race car with a minimum of drag. Down force is necessary for maintaining speed through the corners.

A track with low speed corners requires a car setup with a high down force package. A high down force package is necessary to maintain speeds in the corners. This setup includes large front and rear wings. The front wings have additional flaps which are adjustable. The rear wing is made up of more than one section that maximizes down force.

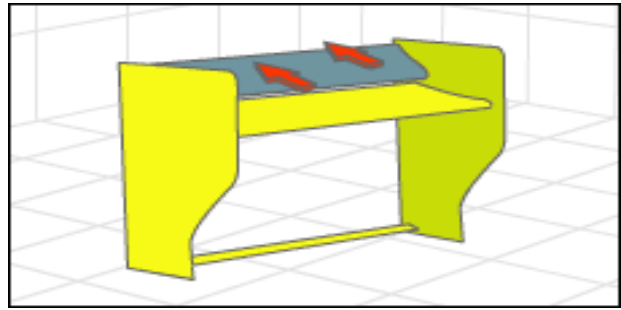


- The front wing is important because it is the first part of the car that makes contact with the air.
- It affects the airflow in the full length of the car and even tiny changes can have huge effects on the overall performance.
- Front wing is one of the elements that is used for down force because it creates high pressure area on top and hence large amount of down force.



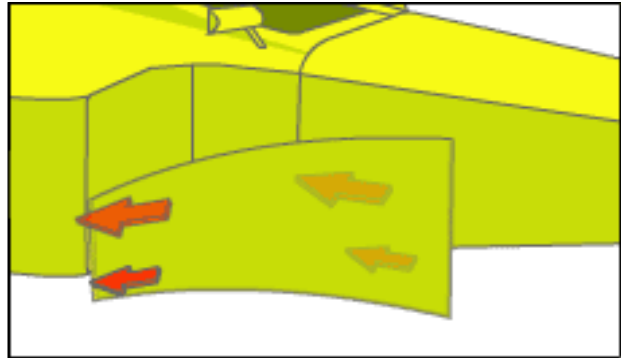


- The rear wing helps glue the rear wheels to the track, but it also can hugely increase drag (air resistance against the body of the car).



### **Barge Boards:**

Barge boards, or turning vanes, smooth out and separate the air that has been disrupted by the front wheels. They separate the flow into two parts - one is directed into the side pods to cool the engine; the other is diverted outside to reduce drag.



### **Wheels:**

- ❖ Open-wheeled race cars have a very complicated aerodynamics due to the large exposed wheels
- ❖ The flow behind wheels is completely separated



### **Diffusers:**

- ❖ The diffusers help to drive the low-pressure from beneath the car. The most common one is the upswept duct at the rear and below the bumper. The other type is located directly behind the splitter leading into the front wheel wells. Aerodynamically, both of these diffusers achieve the same thing i.e. minimising pressure under the car.



## AERODYNAMICS OF TRAIN

Table 1  
Aerodynamic problems and their related matters

	Aerodynamic problems	Related matters
1	Aerodynamic drag of train	Maximum speed, energy consumption
2	Aerodynamic characteristics of train due to cross-winds	Safety in strong cross-winds
3	Aerodynamic force due to passing-by of two trains	Running stability, Quality of comfort for passengers
4	Winds induced by train	Safety for passengers on platforms, Safety for maintenance workers
5	Pressure variations in tunnels	Quality of comfort for passengers, (Ear discomfort) Airtightness of vehicle, Stress upon vehicle, Ventilating system of vehicle
6	Micro-pressure waves radiating from tunnel exit	Environmental problems near tunnel exit
7	Ventilation and heat transfer in underground station and tunnel	Quality of comfort for passengers, Prevention of disaster (fire)
8	Aerodynamic noise	Environmental problems

### Aerodynamic drag of train

The aerodynamic characteristics of train are quite different from those of airplane. There are many characteristic features in the aerodynamics of the high-speed railway train, in the points that the train length is, in general, very long, compared with the equivalent diameter of it, the train runs close to adjacent structures, passes through a confined tunnel, and intersecting with each other, the train runs along a fixed railway track, always interacting with ground, and the train can be influenced by cross-winds. Thus, the aerodynamics, which has been applied to airplane, may not be of help for a detailed understanding of the HST aerodynamics.

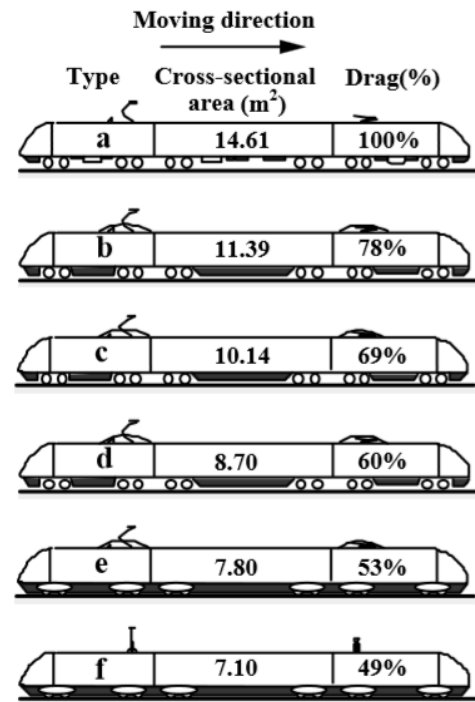


Fig. . Aerodynamic drag on ICE (the hatching area is the device to smooth the structures underneath train).

In general, a desirable train system should be aerodynamically stable and have low aerodynamic forces. These aerodynamic characteristics are closely associated with the aerodynamic drag of the running train. The aerodynamic drag on the traveling train is largely divided into mechanical and aerodynamic ones. Of both, the aerodynamic drag can influence the

energy consumption of train. Thus, detailed understanding on the aerodynamic drag and its precise evaluation are of practical importance. It has been well known that the aerodynamic drag is proportional to the square of speed, while the mechanical drag is proportional to the speed. Compared with the mechanical drag, the portion of the aerodynamic drag becomes larger as the train speed increases. Thus, reduction of the aerodynamic drag on high-speed railway train is one of the essential issues for the development of the desirable train system. In the open air without any cross-wind effects, the total drag on the traveling train can be expressed by a sum of the aerodynamic and mechanical ones:

$$D = D_M + D_A = (a + bV)W + cV^2$$

Where,  $D_A$  and  $D_M$  are the aerodynamic and mechanical drags, respectively,

$a, b$  and  $c$  are the constants to be determined by the experiment,

$V$  the train speed and

$W$  the train weight.

In Eq., the mechanical drag, being proportional to the train weight, includes the sliding drag between rails and train wheels, and the rotating drag of the wheels. The measurement of the total drag on train and its precise prediction are not straightforward.

### Cross-wind effects

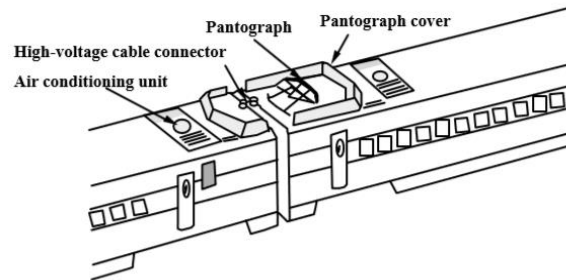
The cross-wind effects on the traveling train can closely be associated with the traveling safety. The cross-winds can be more seriously influence when the train runs over a bridge. Heavier vehicles could improve the crosswind stability but on the contrary issues like lower energy consumption demand lighter vehicles, which at the same time would lead to benefits regarding track deterioration and track maintenance. Since the aerodynamic forces are most critical on the leading vehicle of a train, the weight change from a locomotive -as the leading and heaviest vehicle of a loco-train - to a vehicle of a multiple unit increases the demands on crosswind stability of trains. In addition, unsteady crosswind like various gusts is becoming a major concern.





## Aerodynamic noise due to train

For the assessment of aerodynamic noises produced by a traveling train in the open air, it can be often convenient to classify the noise sources. In addition to the aerodynamic noises due to the flows around the traveling train, there are many different noises which are



caused by train wheels, structures around track, pantograph system, etc. In order to reduce these noises, it is required to know how extent is each contribution to the noises. In general, aerodynamic noises are strongly dependent on the train speed  $U$ , being approximately proportional to  $U^6$ - $U^8$ : Thus, the noise alleviation is of more practical importance when the train speed increases.

It can be found that the aerodynamic noises due to the traveling train are largely generated by the fore-body of the train, the connection part between trains, and the pantograph system.

The fore-body of a train is one of the noise sources. In usual, there are a lot of roughness on the fore-body surface. The aerodynamic noises are strongly dependent on the detailed configuration of the surface roughness and the entire shape of train fore-body as well. These geometrical configurations are associated with the wind speed along them and separation.

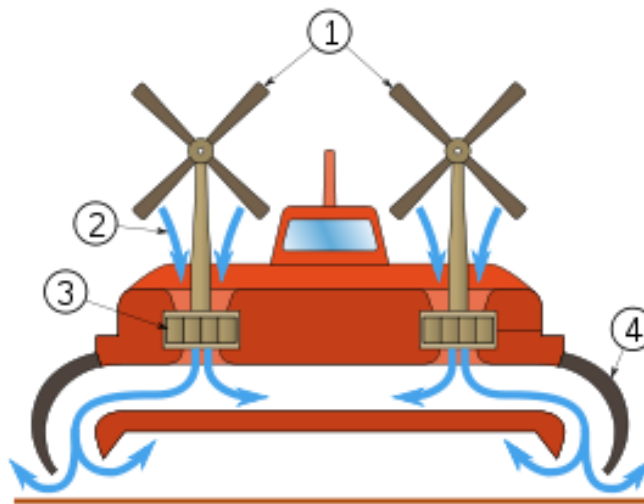
In practice, the pantograph system is composed of many bars with small diameters, which can play a musical instrument to create the aerodynamic noises. The pantograph system creates a number of vortices behind it. A pantograph cover can be used to reduce the aerodynamics noises generated by the pantograph system.

## AERODYNAMICS OF HOVERCRAFT

A **hovercraft**, also known as an **air-cushion vehicle** or **ACV**, is a craft capable of travelling over land, water, mud or ice and other surfaces.



Hovercraft use blowers to produce a large volume of air below the hull that is slightly above atmospheric pressure. The pressure difference between the higher pressure air below the hull and lower pressure ambient air above it produces lift, which causes the hull to float above the running surface. For stability reasons, the air is typically blown through slots or holes around the outside of a disk or oval shaped platform, giving most hovercraft a characteristic rounded-rectangle shape. Typically this cushion is contained within a flexible "skirt", which allows the vehicle to travel over small obstructions without damage.

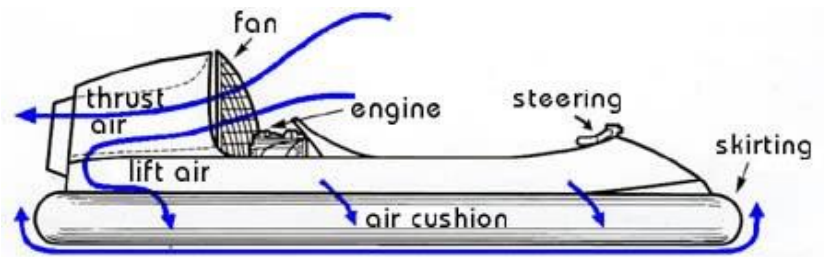


1. Propellers, 2. Air, 3. Fan, 4. Flexible skirt

### **Aerodynamics:**

Hovercraft float on a cushion of air that has been forced under the craft by a fan. This causes the craft to rise or lift. The amount of lift can range from 6" to 108" (152mm to 2,743mm) depending on the size of the hovercraft. The amount of total weight that a hovercraft can raise is equal to cushion pressure multiplied by the area of the hovercraft. To make the craft function more efficiently, it is necessary to limit the cushion air from escaping, so the air is contained by the use of what is called a hovercraft skirt. Fashioned from fabric, which allows a deep cushion

or clearance of obstacles, hovercraft skirts vary in style ranging from bags to cells (jupes) to separate fingered sections called segments.



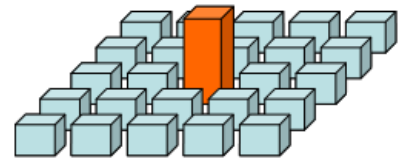
Once "lifted" or "on cushion", thrust must be created to move the hovercraft forward. With many craft, this is generated by a separate engine from the one used to create the lift, but with some, the same engine is used for both. As the diagram above indicates, the fan-generated air stream is split so that part of the air is directed under the hull for lift, while most of it is used for thrust.

Now that the hovercraft has lift and thrust, it must be steered safely. This is achieved through the use of a system of rudders behind the fan, controlled by handlebars up front. Steering can also be controlled by the use of body weight displacement ... a skill which is achieved after practice.

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# Unit III

## Building Aerodynamics

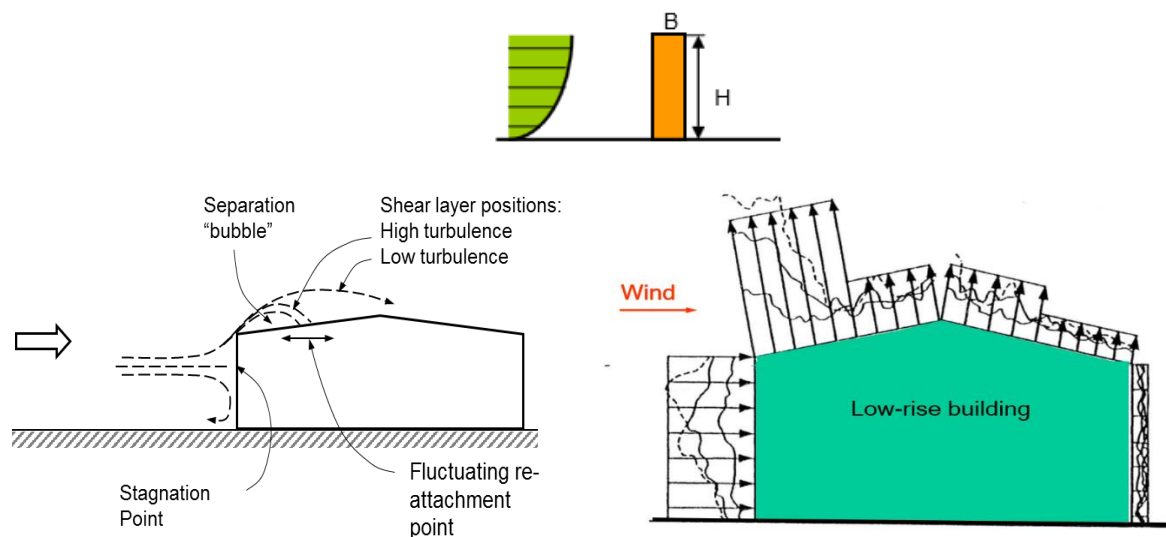


### LOW RISE BUILDINGS

- ❖ Low rise building is defined as an enclosed structure less than 50 feet (15 m) in height.
- ❖ Usually immersed with in atmospheric boundary layer [Where turbulent intensity is high, interference and shelter effects are important but different to quantify]
- ❖ Non engineered and lack of maintenance
- ❖ Wind loads on roof are important
- ❖ Internal pressure are important – especially for dominant openings
- ❖ Resonant effects are negligible
- ❖ Must sustain most damages in severe wind storms

### PRESSURE DISTRIBUTION ON LOW RISE BUILDINGS

Majority of the houses that are constructed all over the world are low-rise buildings. These buildings are constructed in different types of terrain and topography with various planforms. Measurements of the static pressure on low-rise building models in boundary layer wind tunnels provide vital information that can be used to design houses which are safer and more resistant to adverse weather conditions such as cyclones and hurricanes.



The values of static pressure are converted to non-dimensional pressure coefficient,  $C_p$ , which is defined as

$$C_p = \frac{P - P_\infty}{0.5\rho U_\infty^2}$$

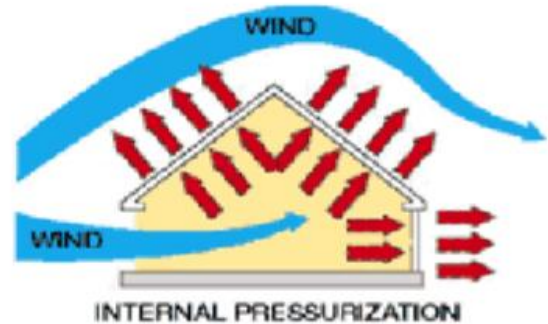
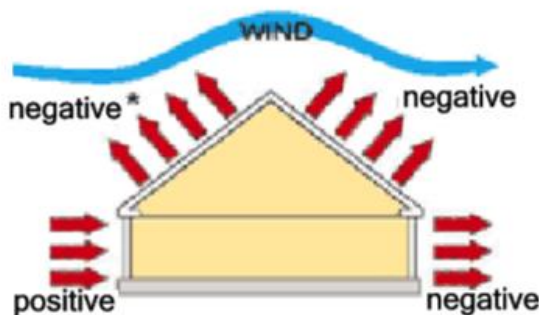
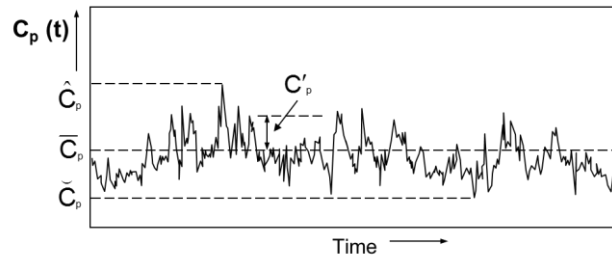
Where,

$P$  is the pressure at a given location

$P_\infty$  is the free-stream static pressure

$U_\infty$  is the free-stream velocity and

$\rho$  is the air density.



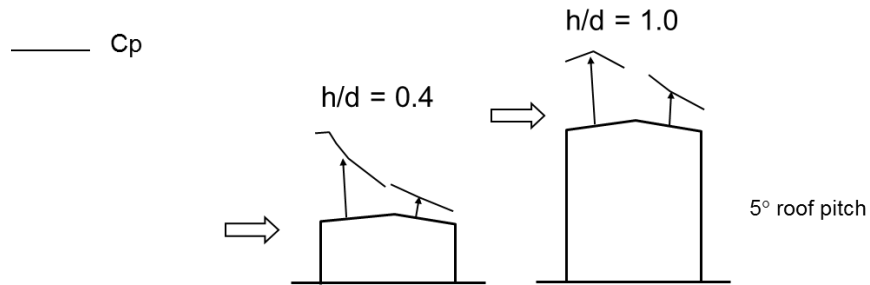
The intensity of internal pressure is directly related to the size of dominant openings and their location with respect to the direction of wind angle of attack.

- Peak positive internal pressure occurs when a dominant opening of the building faces the incoming wind flow.
- Peak negative internal pressure occurs when a dominant opening of the building are in parallel to the incoming wind flow.
- Dominant openings resulted in an increase internal pressure. For example, the opening of the window together with ceiling hatch led to 45% increase on the net wind load on the windward side of the gable roof and 20 % increase for hip roofs. This reinforces the need for keeping doors and windows covered with shutters during strong storms.

The point pressure measurements are processed with the help of a contour plotting to obtain surface contour plots on an entire surface of the building. The average values of  $C_p$  are estimated on all the faces of the gabled roof building models.

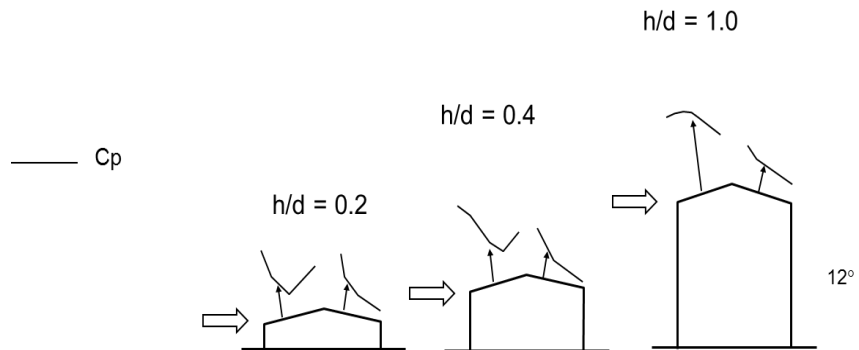
### Mean pressure coefficients on pitched roofs

#### 5° roof pitch:



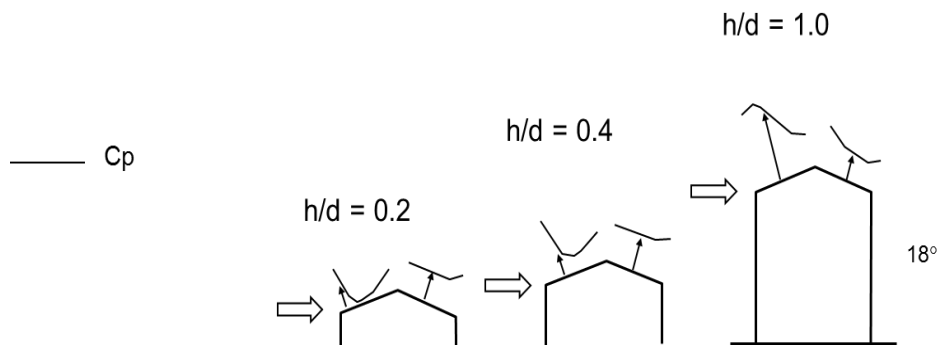
No separation at ridge. Higher negative pressures for greater  $h/d$ .

#### 12° roof pitch:



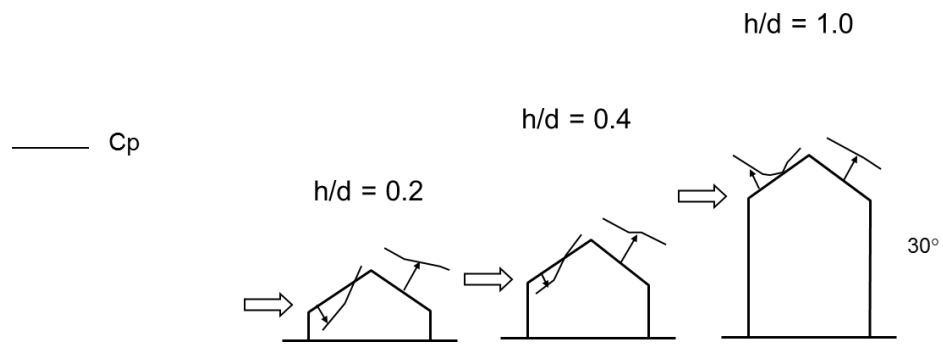
Second separation at ridge. Higher negative pressures for greater  $h/d$ .

#### 18° roof pitch:



Pressure on windward face is less negative at lower  $h/d$

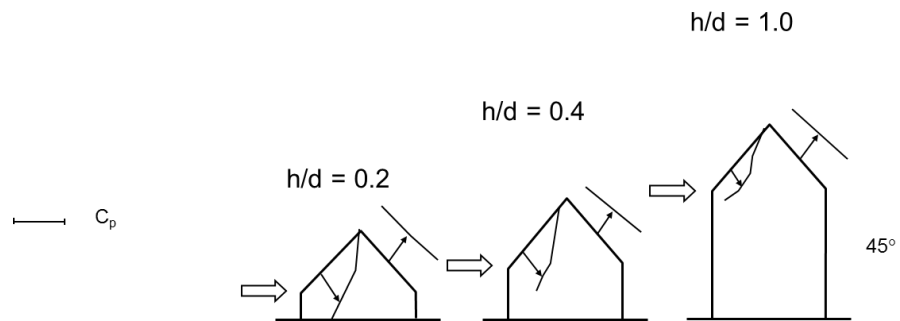
### 30° roof pitch:



Positive pressure on upwind face of roof for lower  $h/d$ .

Uniform negative pressure on downwind roof.

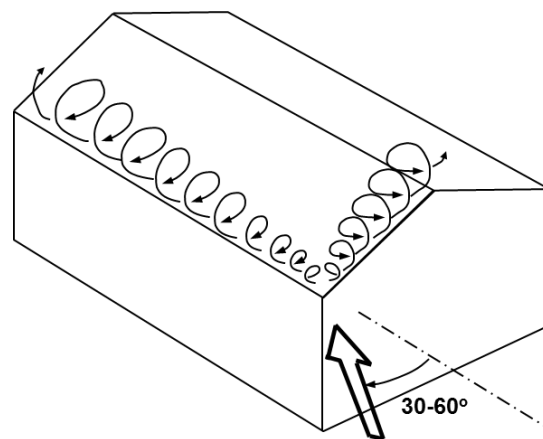
### 45° roof pitch:



High positive pressure on upwind face of roof at all  $h/d$ .

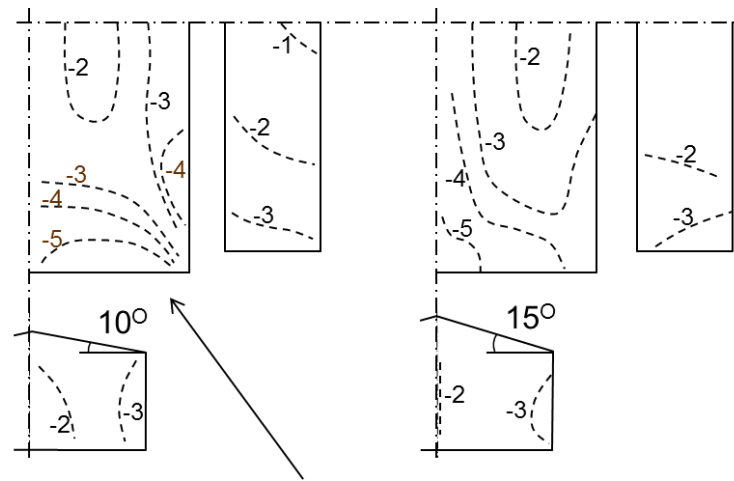
Uniform negative pressure on downwind roof.

### Fluctuating and peak pressures at corners of roofs

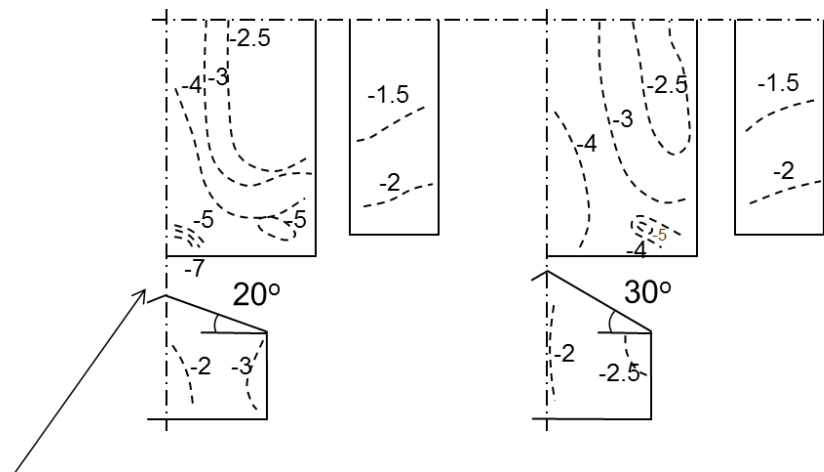


Formation of conical vortices

**The variation of the minimum pressure coefficient over the roof of different building models with the roof pitch angle for any wind direction**



Contours converge towards corner of roof (effect of conical vortices)



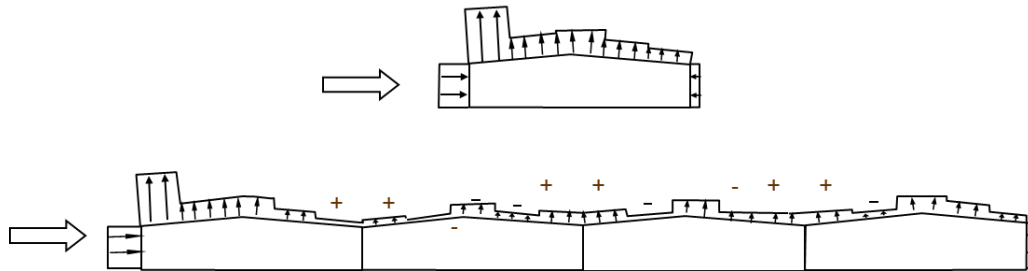
Gable end has highest minimum pressure coefficients

Looking at the windward and the leeward portions of the roof, the peak suction over the leeward side is higher compared to that over the windward side with the difference between the two increasing with an increase in the roof pitch. It is clear from this figure that the worst suction reduces continuously when the roof pitch is increased. Interesting observations are made for the 45° pitch building models. The minimum  $C_p$  value is positive for both the gabled and the hip



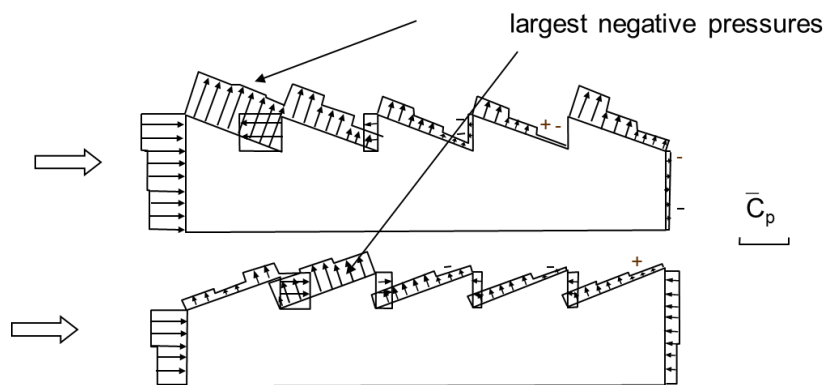
roof models. It is also interesting to note that there is a slight increase in the suction on the leeward side for the gabled roof compared to the 30° case.

### Multi-span buildings



*Note: Pitches less than 10 degrees are 'aerodynamically flat'*

Saw-tooth roofs - magnitude of negative pressures reduces downwind:



## **WIND FORCES ON BUILDINGS**

Forces are classified as static and dynamic. Static loads are independent from time but dynamic loads are function of time. Usually, wind loads are dynamic loads. The design of buildings must account for wind loads, and these are affected by wind shear. For engineering purposes, a power law wind speed profile may be defined as follows:

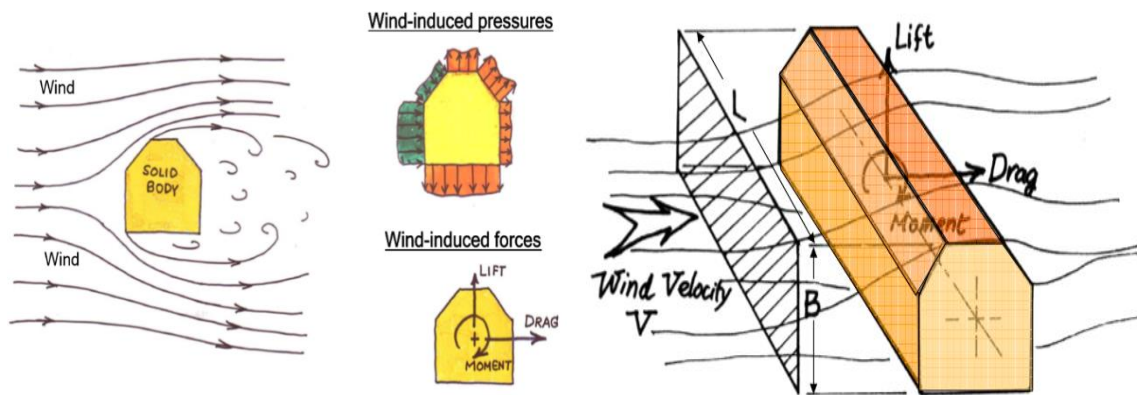
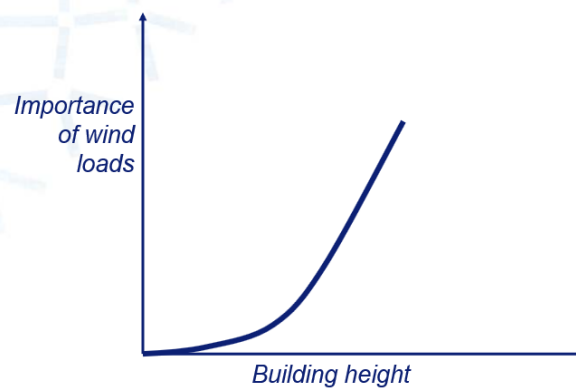
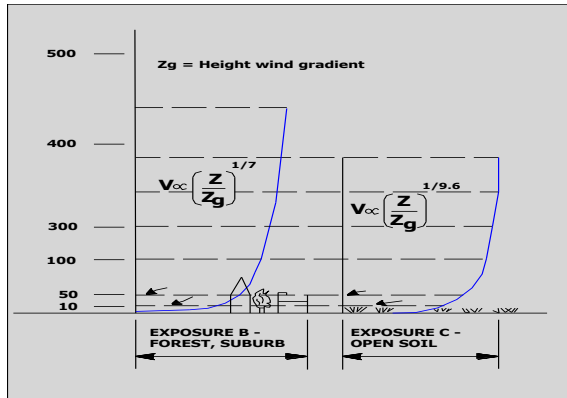
$$v_z = v_g \cdot \left( \frac{z}{z_g} \right)^{\frac{1}{\alpha}}, 0 < z < z_g$$

Where,

$V_z$  = speed of the wind at height;

$V_g$  = gradient wind at gradient height

$\alpha$  = exponential coefficient

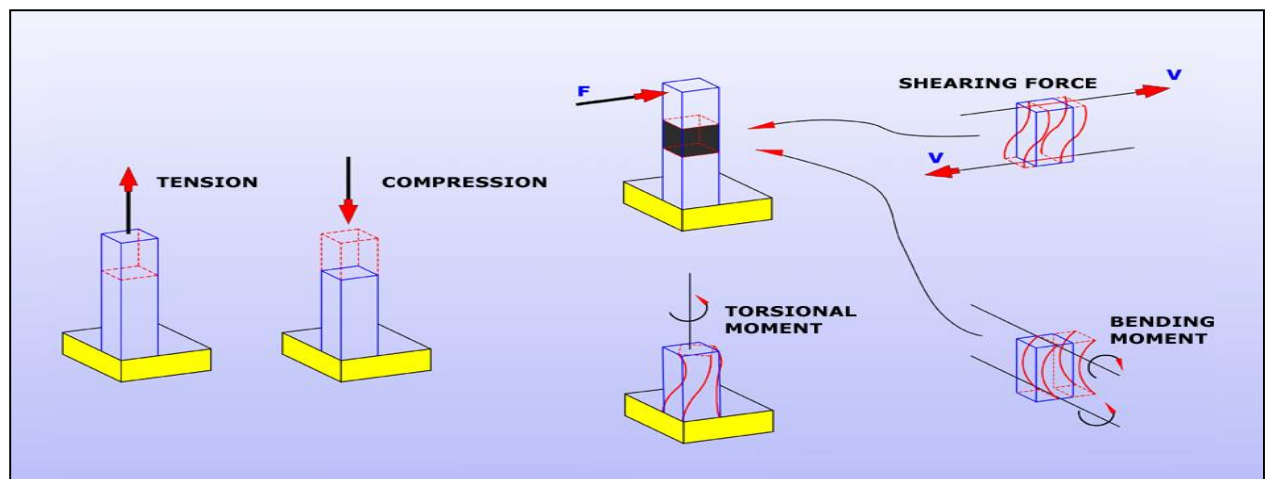


$$\text{Lift} = \frac{1}{2} \rho V^2 A C_L$$

$$\text{Drag} = \frac{1}{2} \rho V^2 A C_D$$

$$\text{Moment} = \frac{1}{2} \rho V^2 A B C_M$$

where  $A = \text{Projected area of the body on a plane normal to the wind direction}$   
 $A = B.L$   
 $C_D, C_L, C_M = \text{Aerodynamic drag, Lift, and moment coefficients}$



## Wind load induced oscillation

There are three forms of wind load induced motion as follows:-

**a) Galloping** - Galloping is transverse oscillations of some structures due to the development of aerodynamic forces which are in phase with the motion. It is characterized by the progressively increasing amplitude of transverse vibration with increase of wind speed.

**b) Flutter** - Flutter is unstable oscillatory motion of a structure due to coupling between aerodynamic force and elastic deformation of the structure. Perhaps the most common form is oscillatory motion due to *combined bending and torsion*. Long span suspension bridge decks or any member of a structure with large values of  $d/t$  ( where  $d$  is the depth of a structure or structural member parallel to wind stream and  $t$  is the least lateral dimension of a member ) are prone to low speed flutter.

**c)Ovalling:** This walled structures with open ends at one or both ends such as oil storage tanks, and natural draught cooling towers in which the ratio of the diameter of minimum lateral dimension to the wall thickness is of the order of 100 or more, are prone to ovalling oscillations. These oscillations are characterized by periodic radial deformation of the hollow structure.

## ENVIRONMENTAL WINDS IN CITY BLOCKS

Survey of wind flow in the urban area, especially within tall building in two terms is very important:

(1) Tall buildings can cause undesirable intensification of wind flow in urban streets and open spaces (square).

(2) On the other hand also have the ability to avoid wind flow in urban spaces.

In both cases, depending on various conditions, wind flow or wind stagnation could be favorable or not favorable. So in the polluted urban environments, increased air flow to prevent stagnation and accumulation of the pollution is very useful while for pedestrian and visitors in open space are undesirable and uncomfortable. Generally buildings depending on how their exposure to wind flow, create dual effects including wind flow is increased or recession. Flow rate set points with a recession in the wind and the tall buildings can deal with the accumulation of air pollution on residents to stop. Also, despite these points can reduce the adverse environmental wind flow can be exploited. If the distance between buildings is appropriate, the

aerodynamic areas of each building to act individually and not interfere of wind flow in these areas, the impact of tall building on wind flow reaches minimum level. But if the distance between buildings is not appropriate the aerodynamic take effect, whatever set is denser and more compact, the behaviors of wind flow and the impact on the speed are required more complex analysis and apparent negative occurs.

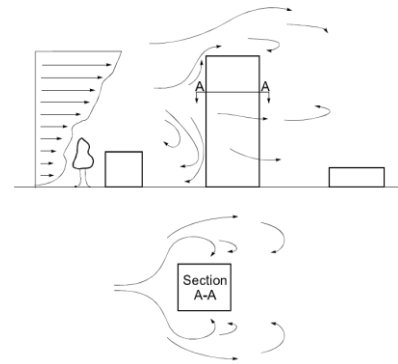
Tall buildings effect on the air flow and pollution parameters is not distributed consequently the air pollution in cites are increasing. In addition to obstruction of visibility and confined spaces and also play a key role in changing winds direction. But regarding population growth of cities and land shortages and high prices make them inevitable. Other advantages of the towers can save energy and prevent pollution increases. Therefore, the appropriate principles and standards in height, properly locate them, the scale tall buildings, technical rules in making them, Immunization, Landscaping and creating green space around the towers, how exposure to towers for wind flow, appropriate distance to the other buildings, how to design them in terms of urban landscape must be considered to reduce the negative effects of tall buildings. In order to remove or reduce the environmental impact, create green spaces in floors and roofs of buildings are helpful to reduce environmental problems which is named environmentally friendly buildings and green architecture.

Today, tall building is a phenomenon that the world particularly large cities are facing. The tall buildings in order to exploit the land with having the negative affects in the environment create new problems including increasing congestion population, environmental pollution, reduce citizen access to fresh air and sunlight. However, regarding to population increasing and land shortage, tall buildings could not be avoided. This paper investigates the relationship of tall buildings with urban air pollution as well as the possible reducing of negative affects of tall building on environmental pollution with respect to geographical position, technical rules, immunization, green space, direct of wind, appropriate distance to other buildings, design in terms of visibility and landscape and urban appearance were reviewed. The study showed that the tall buildings cause increasing the air pollution in large urban area due to changing in wind and its direction and also congestion of tall buildings as a pollution sources. Therefore some techniques to design the tall building must be considered to reduce the negative affects of the tall

buildings on environmental pollution. Unfortunately the lack of the construction roles in term of environmental protection and also control of the rules in construction process causing the environmental pollution particularly air pollution. It is suggested that the re-evaluate of the rules with restricted control can improve the air quality in the large cities and also utilization of green spaces in floors and roofs of buildings as environmentally friendly buildings which are attempt to reduce environmental problems.

## SPECIAL PROBLEMS OF TALL BUILDINGS

Wind is a phenomenon of great complexity because of the many flow situations arising from the interaction of wind with structures. Wind is composed of a multitude of eddies of varying sizes and rotational characteristics carried along in a general stream of air moving relative to the earth's surface. These eddies give wind its gusty or turbulent character. The gustiness of strong winds in the lower levels of the atmosphere largely arises from interaction with surface features. The average wind speed over a time period of the order of ten minutes or more, tends to increase with height, while the gustiness tends to decrease with height. The wind vector at a point may be regarded as the sum of the mean wind vector (static component) and a dynamic, or turbulence, component



$$V(z, t) = \bar{V}(z) + v(z, t)$$

A consequence of turbulence is that dynamic loading on a structure depends on the size of eddies. Large eddies, whose dimensions are comparable with the structure, give rise to well correlated pressures as they envelop the structure. On the other hand, small eddies result in pressures on various parts of a structure that become practically uncorrelated with distance of separation. Eddies generated around a typical structure are shown in Fig.

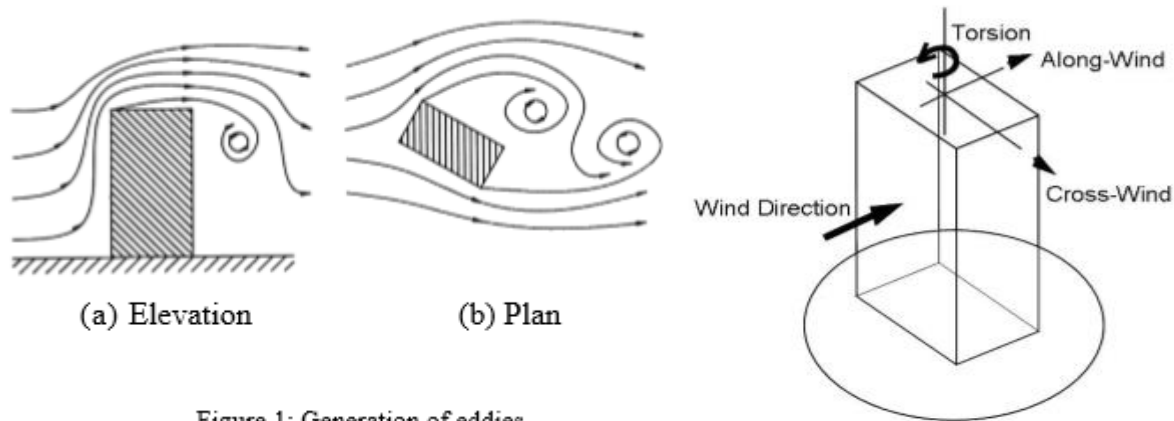


Figure 1: Generation of eddies.

Some structures, particularly those that are tall or slender, respond dynamically to the effects of wind. The best known structural collapse due to wind was the Tacoma Narrows Bridge which occurred in 1940 at a wind speed of only about 19 m/s. It failed after it had developed a coupled torsional and flexural mode of oscillation. There are several different phenomena giving rise to dynamic response of structures in wind. These include buffeting, vortex shedding, galloping and flutter. Slender structures are likely to be sensitive to dynamic response in line with the wind direction as a consequence of turbulence buffeting. Transverse or cross-wind response is more likely to arise from vortex shedding or galloping but may also result from excitation by turbulence buffeting. Flutter is a coupled motion, often being a combination of bending and torsion, and can result in instability. For building structures flutter and galloping are generally not an issue. An important problem associated with wind-induced motion of buildings is concerned with human response to vibration and perception of motion. At this point it will suffice to note that humans are surprisingly sensitive to vibration to the extent that motions may feel uncomfortable even if they correspond to relatively low levels of stress and strain. Therefore, for most tall buildings serviceability considerations govern the design and not strength issues.

**Vortex Shedding:** The most common source of crosswind excitation is that associated with ‘vortex shedding’. Tall buildings are bluff (as opposed to streamlined) bodies that cause the flow to separate from the surface of the structure, rather than follow the body contour. For a particular structure, the shed vortices have a dominant periodicity that is defined by the Strouhal number. Hence, the structure is subjected to a periodic cross pressure loading, which results in an alternating crosswind force. If the natural frequency of the structure coincides with the shedding

frequency of the vortices, large amplitude displacement response may occur and this is often referred to as the critical velocity effect. The asymmetric pressure distribution, created by the vortices around the cross section, results in an alternating transverse force as these vortices are shed. If the structure is flexible, oscillation will occur transverse to the wind and the conditions for resonance would exist if the vortex shedding frequency coincides with the natural frequency of the structure. This situation can give rise to very large oscillations and possibly failure.

*Shedding frequency  $N$  is given by*

$$N = S \frac{U}{b}$$

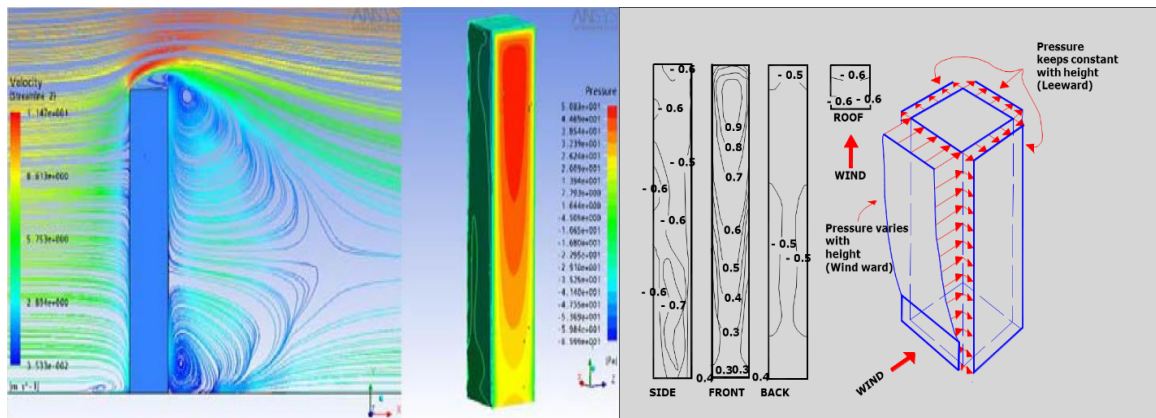
Where,

$S$  = Strouhal number

$U$  = wind speed

$b$  = building width

### Pressure coefficients on high-rise buildings



## **BUILDING CODES**

- Building codes are set of rules and regulation, provisions that must be observed in the design, construction and maintenance of buildings.
- Purpose is to ensure that in a disaster:
  - Lives are protected.
  - Physical damage is limited.

- Structures critical to human welfare remain operational.
- Embody accumulated knowledge of leading scientists, engineers and building construction experts that will produce structures that are ‘Fit for purpose’.
- Provide the first line of defence against damage from natural hazards and help ensure public safety.
- Must be updated regularly to include new technological developments as well as new information after a disaster.
  - New Florida code after hurricane Andrew would have saved 60% of damage if available prior.
  - Buildings use 40% of a country's energy, so retrofitting older buildings for safety and energy use is critical.
- Building codes are generally intended to be applied by architects and engineers although this is not the case in the UK where Building Control Surveyors act as verifiers both in the public and private sector (Approved Inspectors), but are also used for various purposes by safety inspectors, environmental scientists, real estate developers, contractors and subcontractors, manufacturers of building products and materials, insurance companies, facility managers, tenants, and others.
- There are often additional codes or sections of the same building code that have more specific requirements that apply to dwellings and special construction objects such as canopies, signs, pedestrian walkways, parking lots, and radio and television antennas.

### **Importance of Building Codes**

- Building codes save lives
- Building codes protect your investment
- Building codes save on insurance
- Building codes increase disaster resilience
- Building codes enhances building stock



## BUILDING VENTILATION AERODYNAMICS

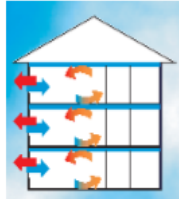
Ventilating is the process of "changing" or replacing air in any space to provide high indoor air quality (i.e. to control temperature, replenish oxygen, or remove moisture, odors, smoke, heat, dust, airborne bacteria, and carbon dioxide). Ventilation is used to remove unpleasant smells and excessive moisture, introduce outside air, to keep interior building air circulating, and to prevent stagnation of the interior air.

Ventilation includes both the exchange of air to the outside as well as circulation of air within the building. It is one of the most important factors for maintaining acceptable indoor air quality in buildings. Methods for ventilating a building may be divided into *mechanical/forced* and *natural* types.

**"Mechanical" or "forced" ventilation** is used to control indoor air quality. Excess humidity, odors, and contaminants can often be controlled via dilution or replacement with outside air. However, in humid climates much energy is required to remove excess moisture from ventilation air.

**Natural ventilation** is the ventilation of a building with outside air without the use of a fan or other mechanical system. It can be achieved with openable windows or trickle vents when the spaces to ventilate are small and the architecture permits. In more complex systems warm air in the building can be allowed to rise and flow out upper openings to the outside (stack effect) thus forcing cool outside air to be drawn into the building naturally through openings in the lower areas. These systems use very little energy but care must be taken to ensure the occupants' comfort. In warm or humid months, in many climates, maintaining thermal comfort solely via natural ventilation may not be possible so conventional air conditioning systems are used as backups. Air-side economizers perform the same function as natural ventilation, but use mechanical systems' fans, ducts, dampers, and control systems to introduce and distribute cool outdoor air when appropriate.

## Natural ventilation



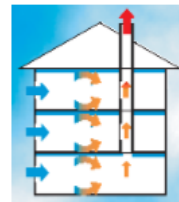
### Single sided ventilation

- supply and extraction through the same openings
- openings ~4% of floor area
- less efficient
- internal door remain closed



### Cross ventilation

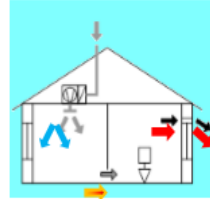
- supply and extraction at the same level in the building
- good result when wind exists
- internal doors opened or equipped with ventilation grilles



### Stack ventilation

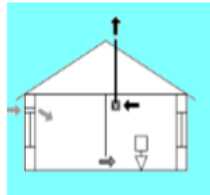
- air supply through louvers and extracted through chimneys
- wind not needed

## Mechanical ventilation



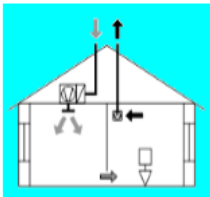
### Mechanical supply ventilation

- a fan supplies air to spaces
- ventilation openings in building's envelope are used for extraction
- usually used where high ventilation rates are needed and air has to be heated before entering the room



### Mechanical extract ventilation

- a fan draws air from spaces
- fresh outdoor air enters into rooms either through the leakage routes of building envelope or through ventilation openings in the building envelope



### Mechanical extract & supply ventilation

- a balanced ventilation system
- it must always include a supply and a return air fan
- an air heater is almost always installed in the supply air side

## BUILDING ARCHITECTURAL AERODYNAMICS

Architectural aerodynamics gains importance with the effect of rain, snow and fire and their impact on design of buildings and their impact on usage.

In the absence of wind, rain and snow fall vertically downwards. The effect of wind is to give the rain drops and snowflakes a horizontal component of velocity.

There are three consequences of this horizontal movement. The first is on the building where the rain can now impinge on non-horizontal surfaces and so cause staining, or allow mosses and lichens to grow, or can cause damp to penetrate the walls to the detriment of its inhabitants. The second effect is on the comfort of people because the rain can penetrate beneath canopies and other protective devices. The third is a combination of building and people: in the past the materials of which buildings were made could absorb water, and during a storm, the surface of a large building would absorb tons of water, water which would be evaporated by the wind once the rain had stopped. Canopies are placed over entrance doors to provide local shelter from the rain to people entering or leaving.

The basic approach for the containment of fire in a building, as far as the wind engineer is concerned, is that there shall be an internal volume at roof level, called a smoke reservoir, where the smoke from a fire can collect prior to being removed from the building. There are also considerations for false ceilings and escape routes.

The areas of openings in a fire situation should be sufficient to vent the smoke when there is no wind. This specifies the area of the openings which must work under buoyancy forces alone. The purpose of the wind engineer is to ensure that, under no circumstances, shall the wind inhibit this state of affairs.

Studies of fire situations are very similar to those for Ventilation with the exception that external flow is never allowed into smoke reservoirs. It is no good claiming that, on average, more air leaves a reservoir than enters it, because the air entering is cold, and when it mixes with the smoke, it will reduce the temperature of the smoke and cause it to lose its buoyancy, causing secondary flows which might bring the smoke into contact with people.

### **Tower and dome architecture:**

Due to the structural efficiency and economic benefit, the hemispherical dome is a common structural geometry shape for large span sports stadium or for storage purposes. The curve shape makes the accurate estimation of the wind pressure fluctuations on a hemispherical dome a difficult task due to the Reynolds number effects. In the past years, there have been reports of collapse of curve shaped storage domes during strong wind. The wind induced structural failure could be attributed to inadequate wind resistant design and/or poor quality construction

Additional complexity arises for curved bodies (e.g. hemisphere and cylinders) because the location of a separation point cannot be identified purely based on the geometry. This leads to a strong dependency on Reynolds number, boundary layer thickness and the turbulence intensity level of the approaching flow. A

reduction in the maximum pressure coefficient is occurred because the rough surface promotes

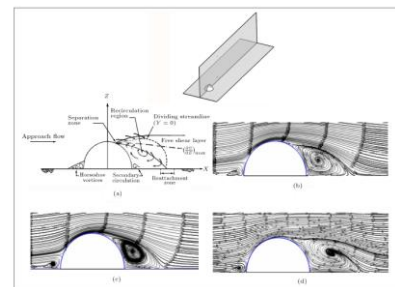


Figure 1b. Typical pathlines on streamwise plane of symmetry for  $L = 4.2D$ . a) Experiment [3], b)  $U = 5 \text{ m/s}$ , c)  $U = 7 \text{ m/s}$ , d)  $U = 8.5 \text{ m/s}$ .

the turbulent boundary layer over the dome and causes earlier separation over the dome. Consequently, the earlier separation over the dome reduced suction at the separation point, but led to more suction overall in the wake and increased drag.

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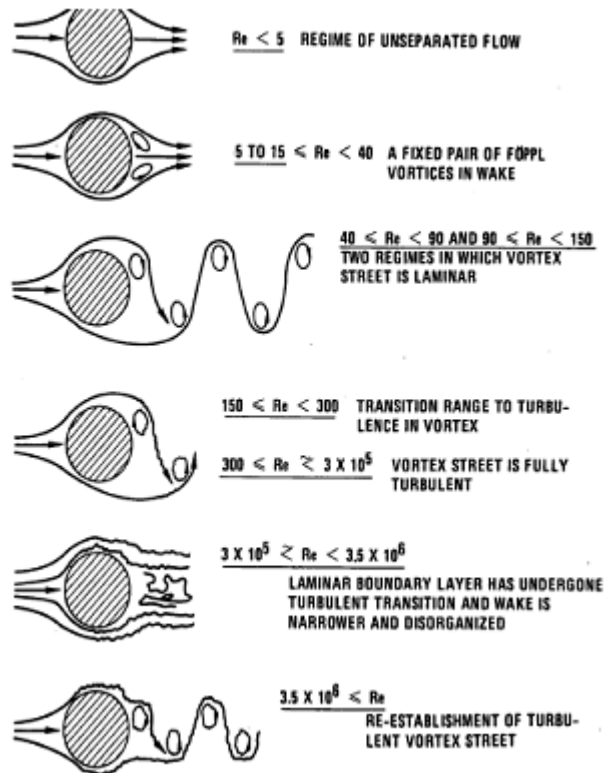
## Unit IV

### Flow Induced Vibrations

#### EFFECT OF REYNOLDS NUMBER ON WAKE FORMATION OF BLUFF SHAPES

A body moving through a fluid experiences a drag force, which is usually divided into two components: **frictional drag**, and **pressure drag**. Frictional drag comes from friction between the fluid and the surfaces over which it is flowing. This friction is associated with the development of boundary layers, and it scales with Reynolds number as we have seen above. Pressure drag comes from the eddying motions that are set up in the fluid by the passage of the body. This drag is associated with the formation of a wake, which can be readily seen behind a passing boat, and it is usually less

sensitive to Reynolds number than the frictional drag. Formally, both types of drag are due to viscosity (if the body was moving through an inviscid fluid there would be no drag at all), but the distinction is useful because the two types of drag are due to different flow phenomena. Frictional drag is important for attached flows (that is, there is no separation), and it is related to the surface area exposed to the flow. Pressure drag is important for separated flows, and it is related to the cross-sectional area of the body.

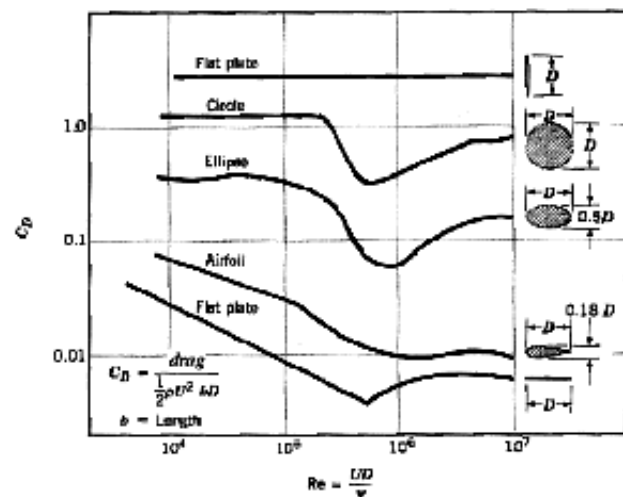


We can see the role played by friction drag (sometimes called viscous drag) and pressure drag (sometimes called form drag or profile drag) by considering an airfoil at different angles of attack. At small angles of attack, the boundary layers on the top and bottom surface experience only mild pressure gradients, and they remain attached along almost the entire chord length. The

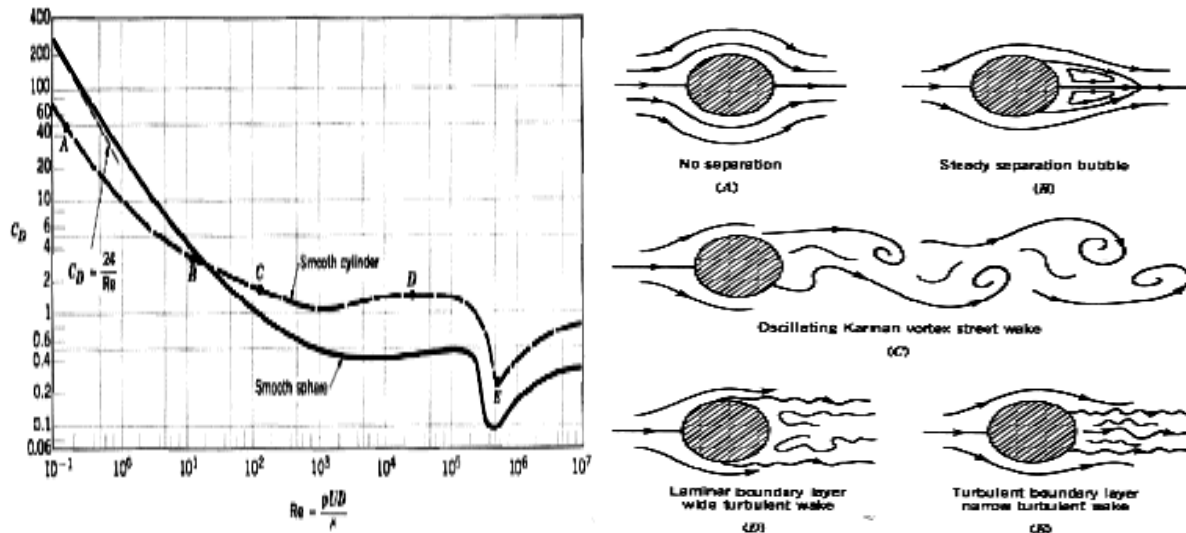
wake is very small, and the drag is dominated by the viscous friction inside the boundary layers. However, as the angle of attack increases, the pressure gradients on the airfoil increase in magnitude. In particular, the adverse pressure gradient on the top rear portion of the airfoil may become sufficiently strong to produce a separated flow. This separation will increase the size of the wake, and the pressure losses in the wake due to eddy formation. Therefore the pressure drag increases. At a higher angle of attack, a large fraction of the flow over the top surface of the airfoil may be separated, and the airfoil is said to be stalled. At this stage, the pressure drag is much greater than the viscous drag.

When the drag is dominated by viscous drag, we say the body is **streamlined**, and when it is dominated by pressure drag, we say the body is **bluff**. Whether the flow is viscous-drag dominated or pressure-drag dominated depends entirely on the shape of the body. A streamlined body looks like a fish, or an airfoil at small angles of attack, whereas a bluff body looks like a brick, a cylinder, or an airfoil at large

angles of attack. For streamlined bodies, frictional drag is the dominant source of air resistance. For a bluff body, the dominant source of drag is pressure drag. For a given frontal area and velocity, a streamlined body will always have a lower resistance than a bluff body. For example, the drag of a cylinder of diameter  $D$  can be ten times larger than a streamlined shape with the same thickness (see figure).



Cylinders and spheres are considered bluff bodies because at large Reynolds numbers the drag is dominated by the pressure losses in the wake. The variation of the drag coefficient with Reynolds number is shown in figure, and the corresponding flow patterns are shown in figure. We see that as the Reynolds number increases the variation in the drag coefficient (based on cross-sectional area) decreases, and over a large range in Reynolds number it is nearly constant.



(a) Drag coefficient as a function of Reynolds number for smooth circular cylinders and smooth spheres

(b) Flow patterns for flow over a cylinder: (A) Reynolds number = 0.2; (B) 12; (C) 120; (D) 30,000; (E) 500,000. Patterns correspond to the points marked on figure 2.

At a Reynolds number between  $10^5$  and  $10^6$ , the drag coefficient takes a sudden dip. The size of the wake decreases, indicating that the boundary layer separation on the cylinder or sphere occurs further along the surface than before. What has happened? The phenomenon is related to the differences between laminar and turbulent boundary layer. The boundary layer and its interaction with the local pressure gradient plays a major role in affecting the flow over a cylinder. In particular, near the shoulder, the pressure gradient changes from being negative (decreasing pressure) to positive (increasing pressure). The force due to pressure differences changes sign from being an accelerating force to being a retarding force. In response, the flow slows down. However, the fluid in the boundary layer has already given up some momentum because of viscous losses and viscous friction, and it does not have enough momentum to overcome the retarding force. Some fluid near the wall actually reverses direction, and the flow separates.

## VORTEX INDUCED VIBRATIONS

### Vortices:

A vortex is defined as the motion of multitude of fluid particles around a common center.

### Types of vortices:

- Forced Vortex
- Free Vortex

### Vortices in the Real World:

- Vortices in the real world like Tornados, Whirlpool in rivers are often a combination of free and forced vortices.
- Forced vortex flow occurs at and near the center of the vortex while free vortex conditions are approximated outside this region.

### Flow-Induced Vibration:

- The vibration caused by a fluid flowing around a body is known as flow-induced vibration.
- In the following examples, the vibration of the system continuously extracts energy from the source, leading to larger and larger amplitudes of vibration.

### Phenomena of Induced Vibration:

- Tall chimneys, Submarine periscopes, Electric transmission lines and nuclear fuel rods are found to vibrate violently under certain conditions of fluid flow around them.
- Similarly, water and oil pipe lines and tubes in air compressors undergo severe vibrations under certain conditions of fluid flow through them.
- In ice-covered electric transmission lines and the unstable vibration, known as *flutter*, of air foil sections.
- High frequency vibration known as *singing of transmission lines* occurs due to the phenomena of vortex shedding.

### Why Vortex Shedding Phenomena:

- Vortex shedding was the primary cause of failure of the Tacoma Narrows suspension bridge in the state of Washington in 1940.
- If the frequency of the vortex shedding is in resonance with the natural frequency of the member that produces it, large amplitudes of vibrations with resulting large stresses can develop.



- Experimental data show that regular vortex shedding occurs strongly in the range of Reynolds number (Re) from about 60 to 5000.
- Experiments shows also that the frequency of shedding is given in terms of Strouhal number (St), and this in turn is a function of the Reynolds number.
- Other cylindrical and two dimensional bodies can also shed vortices.

Vortex shedding dictated by the Strouhal number

$$S_t = f_s d / U$$

Where,

$f_s$  is the shedding frequency,

$d$  is diameter and

$U$  inflow speed

#### Additional VIV Parameters (Non-dimensional parameters)

##### ➤ Reynolds Number

$$Re = \frac{UD}{\nu} \approx \frac{\text{inertialeffects}}{\text{viscouseffects}}$$

##### ➤ Reduced Velocity

$$\frac{U}{fD} = \frac{\text{path length per cycle}}{\text{model width}} = \text{reduced velocity}$$

$$V_m = \frac{U}{f_n D}$$

##### ➤ Dimensional Amplitude

$$\frac{A_y}{D} = \frac{\text{vibration amplitude}}{\text{model width}} = \text{dimensionless amplitude.}$$

##### ➤ Vortex Shedding Frequency

$$f_s = \frac{SU}{D}$$

➤ **Mach Number**

Mach Number is a measure of the compressibility of the air.

$$M^2 = V^2 / dp/d\rho = V^2 / a^2,$$

where  $a$  is the speed of sound.

$$\begin{aligned} M^2 &\approx V^2 \rho / p \approx (V^2 \rho^2 L^6 / \text{time}^2) / (p \rho L^4 V^2) \approx (V^2 \rho^2 L^6 / \text{time}^2) / p^2 L^4 \\ &= (\text{inertia force})^2 / (\text{pressure force})^2. \end{aligned}$$

➤ **Froude Number**

The Froude Number is a measure of the effect of gravity upon the flow.

$$\begin{aligned} F^2 &= V^2 / (gL) \approx (\rho^2 V^2 L^6 / \text{time}^2) / (gL \rho^2 L^6 / \text{time}^2) \\ &= (\rho^2 V^2 L^6 / \text{time}^2) / (gL / \text{time}^2 \rho^2 L^6) \\ &= (\text{inertia force})^2 / (\text{gravitational force})^2. \end{aligned}$$

Froude Number is therefor only of significance when gravitational forces are important with respect to wind forces. This usually only occurs at interfaces of fluids of different densities.

➤ **Mass ratio**

$$\frac{m}{\rho D^2} = \frac{\text{mass per unit length of model}}{\text{fluid density} \times \text{model width}^2} = \text{mass ratio}$$

➤ **Damping factor**

$$\zeta = \frac{\text{energy dissipated per cycle}}{4\pi \times \text{total energy of structure}} = \text{damping factor}.$$

➤ **Reduced damping**

$$\frac{2m(2\pi\zeta)}{\rho D^2} = \text{reduced damping}.$$

➤ **Fineness ratio**

$$\frac{l}{D} = \frac{\text{length}}{\text{width}} = \text{fineness ratio}$$

**Lock-in**

A cylinder is said to be “locked in” when the frequency of oscillation is equal to the frequency of vortex shedding. In this region the largest amplitude oscillations occur.

Shedding frequency  $\omega_v = 2\pi f_v = 2\pi S_t (U/d)$

Natural frequency of oscillation  $\omega_n = \sqrt{\frac{k}{m + m_a}}$

**Types of in-stabilities:**

Name	Conditions	Type of motion	Type of section
Galloping	$H_1 > 0$	translational	Square section
‘Stall’ flutter	$A_2 > 0$	rotational	Rectangle, H-section
‘Classical’ flutter	$H_2 > 0, A_1 > 0$	coupled	Flat plate, airfoil

**Aerodynamic damping (along wind)**

Consider a body moving with velocity in a flow of speed  $\bar{U}$

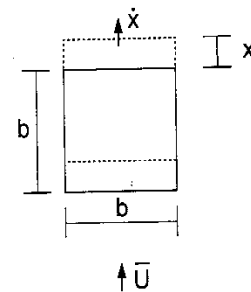
Relative velocity of air with respect to body =  $\bar{U} - \dot{x}$

Drag force (per unit length) =

$$D = C_D \frac{1}{2} \rho_a b (\bar{U} - \dot{x})^2 \cong C_D \frac{1}{2} \rho_a b \bar{U}^2 \left(1 - \frac{2\dot{x}}{\bar{U}}\right)$$

$$= C_D \frac{1}{2} \rho_a b \bar{U}^2 - C_D \rho_a b \bar{U} \dot{x}$$

for small  $\dot{x}/\bar{U}$



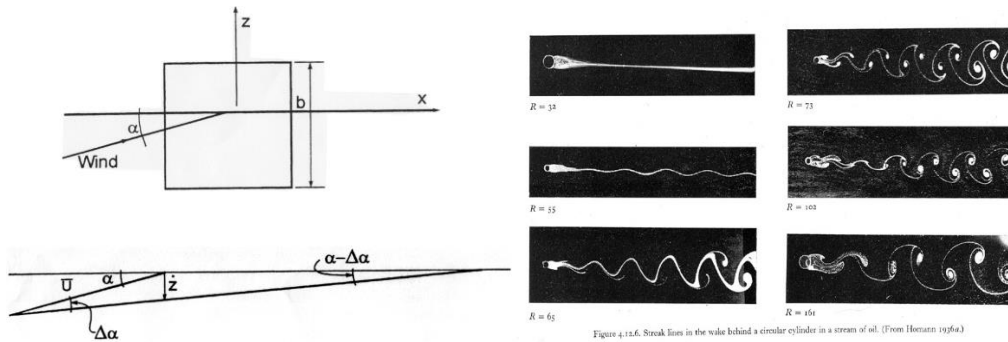
Transfer to left hand side of equation of motion:  $m\ddot{x} + c\dot{x} + kx = D(t)$

Total damping term:  $c\dot{x} + C_D \rho_a b \bar{U} \dot{x}$

Along-wind aerodynamic damping is *positive*

## Galloping

- ❖ Galloping is a result of a wake instability.
- ❖ Galloping is a form of aerodynamic instability caused by negative aerodynamic damping in the cross wind direction



Motion of body in  $z$  direction will generate an apparent reduction in angle of attack,  $\Delta\alpha$

From vector diagram:  $\Delta\alpha = -\dot{z}/\bar{U}$

Aerodynamic force per unit length in  $z$  direction (body axes):

$$\underline{F_z} = D \sin \alpha + L \cos \alpha = \frac{1}{2} \rho_a \bar{U}^2 b (C_D \sin \alpha + C_L \cos \alpha)$$

$$\frac{dF_z}{d\alpha} = \frac{1}{2} \rho_a \bar{U}^2 b (C_D \cos \alpha + \frac{dC_D}{d\alpha} \sin \alpha - C_L \sin \alpha + \frac{dC_L}{d\alpha} \cos \alpha)$$

$$\text{For } \alpha = 0 : \quad \frac{dF_z}{d\alpha} = \frac{1}{2} \rho_a \bar{U}^2 b (C_D + \frac{dC_L}{d\alpha})$$

$$\Delta F_z \cong \frac{1}{2} \rho_a \bar{U}^2 b (C_D + \frac{dC_L}{d\alpha}) \Delta \alpha$$

Substituting,  $\Delta\alpha = -\dot{z}/\bar{U}$

$$\begin{aligned}\Delta F_z &\cong \frac{1}{2}\rho_a \bar{U}^2 b \left(C_D + \frac{dC_L}{d\alpha}\right) \left(-\frac{\dot{z}}{\bar{U}}\right) \\ &= -\frac{1}{2}\rho_a \bar{U} b \left(C_D + \frac{dC_L}{d\alpha}\right) \dot{z}\end{aligned}$$

For  $(C_D + \frac{dC_L}{d\alpha}) < 0$ ,  $\Delta F_z$  is positive - acts in same direction as  $\dot{z}$

*negative* aerodynamic damping when transposed to left-hand side

$$\left(C_D + \frac{dC_L}{d\alpha}\right) < 0 \quad \text{den Hartog's Criterion}$$

critical wind speed for galloping,  $\bar{U}_{\text{crit}}$ , occurs when *total* damping is zero

$$c\dot{z} + \frac{1}{2}\rho_a \bar{U}_{\text{crit}} b \left(C_D + \frac{dC_L}{d\alpha}\right) \dot{z} = 0$$

$$\bar{U}_{\text{crit}} = \frac{2c}{-\rho_a b \left(C_D + \frac{dC_L}{d\alpha}\right)} \quad \bar{U}_{\text{crit}} = \frac{8\pi\eta m n_1}{-\rho_a b \left(C_D + \frac{dC_L}{d\alpha}\right)}$$

$$\text{Since } c = 2\eta\sqrt{(mk)} = 4\pi\eta m n_1$$

$m$  = mass per unit length

$n_1$  = first mode natural frequency

### Cross sections prone to galloping:

- ❖ Square section (zero angle of attack)
- ❖ D-shaped cross section
- ❖ Iced-up transmission line or guy cable
- ❖ Flexible Cylinders

### Galloping vs. VIV

- Galloping is low frequency
- Galloping is NOT self-limiting
- Once  $U > U_{\text{critical}}$  then the instability occurs ir-regardless of frequencies.

## Conductor galloping/ transmission lines galloping

**Conductor gallop** is the high-amplitude, low-frequency oscillation of overhead power lines due to wind. The movement of the wires occur most commonly in the vertical plane, although horizontal or rotational motion is also possible. The natural frequency mode tends to be around 1 Hz, leading the often graceful periodic motion to also be known as **conductor dancing**. The oscillations can exhibit amplitudes in excess of a metre, and the displacement is sometimes sufficient for the phase conductors to infringe operating clearances (coming too close to other objects), and causing flashover. The forceful motion also adds significantly to the loading stress on insulators and electricity pylons, raising the risk of mechanical failure of either.

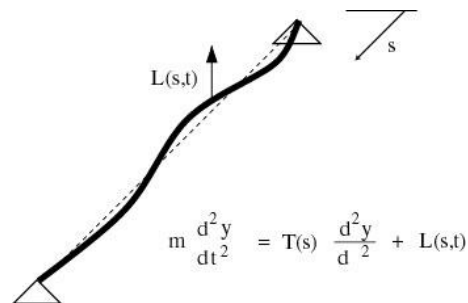
The mechanisms that initiate gallop are not always clear, though it is thought to be often caused by asymmetric conductor aerodynamics due to ice build up on one side of a wire.<sup>[3]</sup> The crescent of encrusted ice approximates an aerofoil, altering the normally round profile of the wire and increasing the tendency to oscillate.<sup>[3]</sup>

Gallop can be a significant problem for transmission system operators, particularly where lines cross open, windswept country and are at risk to ice loading. If gallop is likely to be a concern, designers can employ smooth-faced conductors, whose improved icing and aerodynamic characteristics reduce the motion.<sup>[4]</sup> Additionally, anti-gallop devices may be mounted to the line to convert the lateral motion to a less damaging twisting one. Increasing the tension in the line and adopting more rigid insulator attachments have the effect of reducing galloping motion. These measures can be costly, are often impractical after the line has been constructed, and can increase the tendency for the line to exhibit high frequency oscillations.<sup>[5]</sup>

Once gallop has started on a transmission line, an operator's options are more limited. If ice loading is suspected, it may be possible to increase power transfer on the line, and so raise its temperature by Joule heating, melting the ice.<sup>[3]</sup> The sudden loss of ice from a line can result in a phenomenon called "jump", in which the catenary dramatically rebounds upwards in response to the change in weight.<sup>[1][2]</sup> If the risk of trip is high, the operator may elect to pre-emptively switch out the line in a controlled manner rather than face an unexpected fault. The risk of mechanical failure of the line remains.<sup>[6]</sup>

## Main phenomena related to wind effects on cables/ropes vibration

- ❖ Vortex shedding: alternate formation of vortices in the downstream wake of the cable.
- ❖ Vibration due to turbulent wind (buffeting): mainly related to forcing effects due to variation of wind speed both in module and direction.



- ❖ Aero-elastic instability (galloping): irregular shape, due to ice deposits (ice galloping), can lead to modification of cable profile, and unstable oscillations can occur.
- ❖ Wake induced vibrations(bundle galloping): typical for cables fitted in bundles (grouped in 2, 3, 4, or more formation), as occurs in electrical power transmission lines

Considering a cable or a rope, different natural frequencies exist. In the case of sag much less than the span length, are according to the formula:

$$f_n = \frac{n}{2L} \sqrt{\frac{T}{m}}$$

$f_n$  = frequency of the n-th mode (Hz)

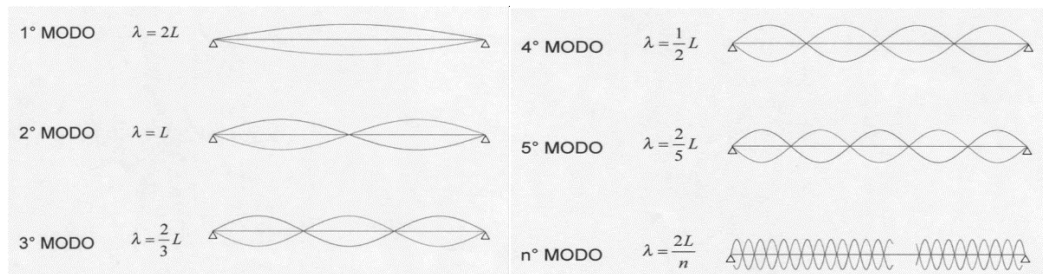
$n$  = order of the vibration mode

$L$  = span length (m)

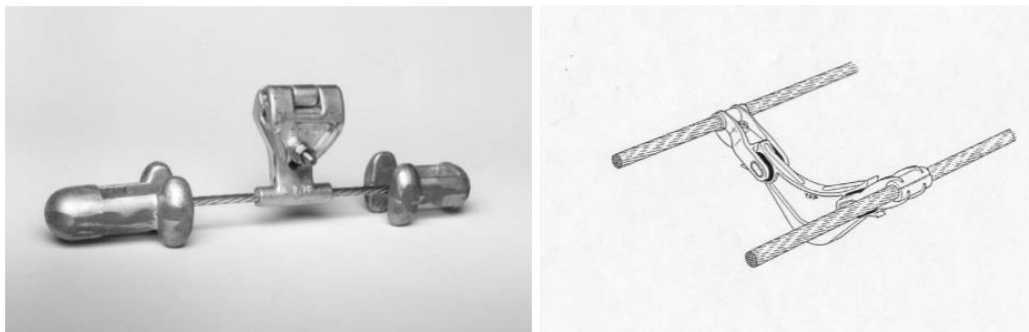
$T$  = cable tensile load ( N)

$m$  = cable/rope mass per unit length (Kg/m)

Vibration modes of a taut cable



Vibrations can be easily controlled by adding damping to the cable, in the form of dampers and spacer dampers and spacer-dampers. This is feasible for electric power transmission lines.



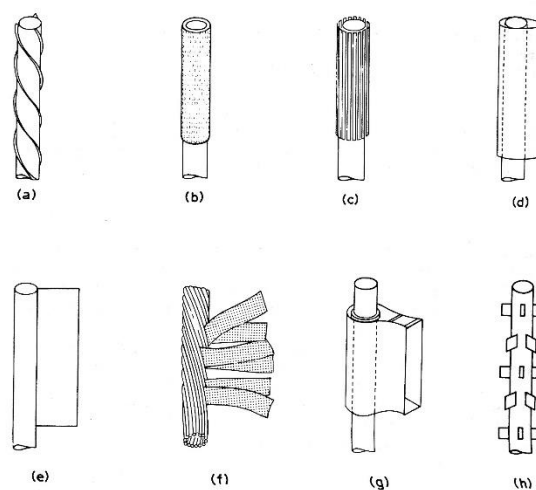
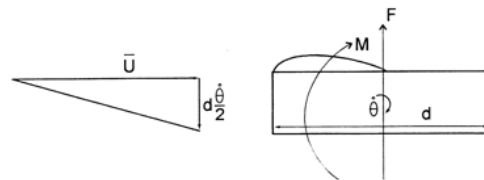


Fig. 3-23 Add-on devices for suppression of vortex-induced vibration of cylinders: (a) helical strake; (b) shroud; (c) axial slats; (d) streamlined fairing; (e) splitter; (f) ribbed cable; (g) pivoted guiding vane; (h) spoiler plates.

## FLUTTER

Flutter is a dangerous phenomenon encountered in flexible structures subjected to aerodynamic forces. This includes aircraft, buildings, telegraph wires, stop signs, and bridges. Flutter occurs as a result of interactions between aerodynamics, stiffness, and inertial forces on a structure. In an aircraft, as the speed of the wind increases, there may be a point at which the structural damping is insufficient to damp out the motions which are increasing due to aerodynamic energy being added to the structure. This vibration can cause structural failure and therefore considering flutter characteristics is an essential part of designing an aircraft.

Consider a two dimensional body rotating with angular velocity  $\dot{\theta}$



Vertical velocity at leading edge :  $\dot{\theta}d/2$

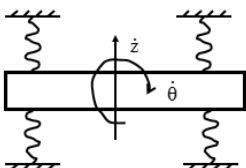
Apparent change in angle of attack :  $-\dot{\theta}d/2\bar{U}$

Can generate a cross-wind force and a moment

Aerodynamic instabilities involving rotation are called 'flutter'



General equations of motion for body free to rotate and translate :



$$\ddot{z} + 2\eta_z \omega_z \dot{z} + \omega_z^2 z = \frac{F_z(t)}{m} + \underset{\substack{\uparrow \\ \text{Flutter derivatives}}}{H_1} \dot{z} + \underset{\substack{\uparrow \\ \text{Flutter derivatives}}}{H_2} \dot{\theta} + \underset{\substack{\uparrow \\ \text{Flutter derivatives}}}{H_3} \theta \quad \text{per unit mass}$$

$$\ddot{\theta} + 2\eta_\theta \omega_\theta \dot{\theta} + \omega_\theta^2 \theta = \frac{M(t)}{I} + \underset{\substack{\uparrow \\ \text{Flutter derivatives}}}{A_1} \dot{z} + \underset{\substack{\uparrow \\ \text{Flutter derivatives}}}{A_2} \dot{\theta} + \underset{\substack{\uparrow \\ \text{Flutter derivatives}}}{A_3} \theta \quad \text{per unit mass moment of inertia}$$

## Flutter Motion

The basic type of flutter of aircraft wing is described here. Flutter may be initiated by a rotation of the airfoil (see  $t=0$  in Figure 1). As the increased force causes the airfoil to rise, the torsional stiffness of the structure returns the airfoil to zero rotation ( $t=T/4$  in Figure 1). The bending stiffness of the structure tries to return the airfoil to the neutral position, but now the airfoil rotates in a nose-down position ( $t=T/2$  in Figure 1). Again the increased force causes the airfoil to plunge and the torsional stiffness returns the airfoil to zero rotation ( $t=3T/4$ ). The cycle is completed when the airfoil returns to the neutral position with a nose-up rotation. Notice that the maximum rotation leads the maximum rise or plunge by 90 degrees ( $T/4$ ). As time increases, the plunge motion tends to damp out, but the rotation motion diverges. If the motion is allowed to continue, the forces due to the rotation will cause the structure to fail.

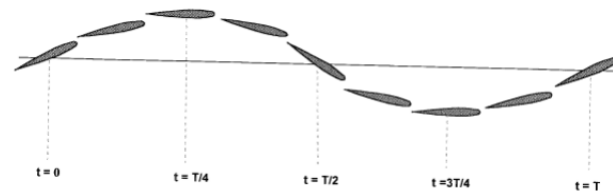


Figure Rotation and Plunge Motion for an Airfoil Exhibiting Flutter

This flutter is caused by the coalescence of two structural modes – pitch and plunge (or wing-bending) motion. This example wing has two basic degrees of freedom or natural modes of vibration: pitch and plunge (bending). The pitch mode is rotational and the bending mode is a vertical up and down motion at the wing tip. As the airfoil flies at increasing speed, the

frequencies of these modes coalesce or come together to create one mode at the flutter frequency and flutter condition. This is the flutter resonance.

## Types of Flutter

Airfoils are used in many places on an airplane. The most obvious is the wing, but airfoil shapes are also used in the tail, propellers and control surfaces such as ailerons, rudders and stabilizers. All of these conditions must be analyzed and tested to insure that flutter does not occur.

There is other flutter behavior that must be considered when designing aircraft: panel flutter, galloping flutter, stall flutter, limit cycle oscillations (LCO) or buzz, and propeller or engine whirl flutter. There can also be flutter due to stores mounted on the wing.

**Panel flutter** can occur when a surface is not adequately supported (think of the skin of an airplane acting like a drumhead). Figure 3 illustrates panel flutter motion.

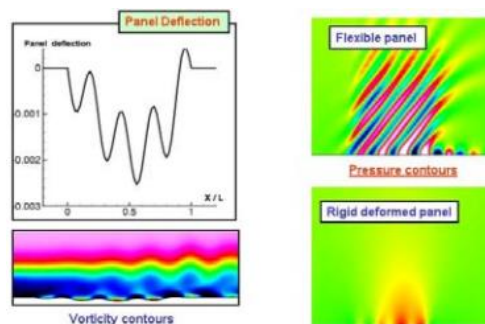


Figure Panel Flutter

**Galloping flutter, or wake vortex flutter**, was the cause of failure of the Tacoma Narrows Bridge. This phenomenon can be observed frequently along the roadside when telephone and power lines “gallop” due to strong winds. You may also observe car radio antenna aerials whipping under certain driving speeds. The cause of the galloping motion is formation of wake vortices downstream of the object. As shown in Figure 4, the vortices are shed alternately from one side of the object and then the other. These cause oscillatory forces and produce the back-and-forth motion. This type of flutter is an important design consideration for launch vehicles exposed to ground winds.

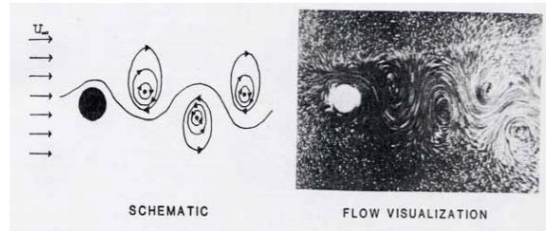


Figure 8-26 Wake Vortex Shedding from a Cylinder

**Stall flutter** is a torsional mode of flutter that occurs on wings at high loading conditions near the stall speed. Because the airflow separates during stall, this single degree-of- freedom flutter cannot be explained by classical flutter theory.

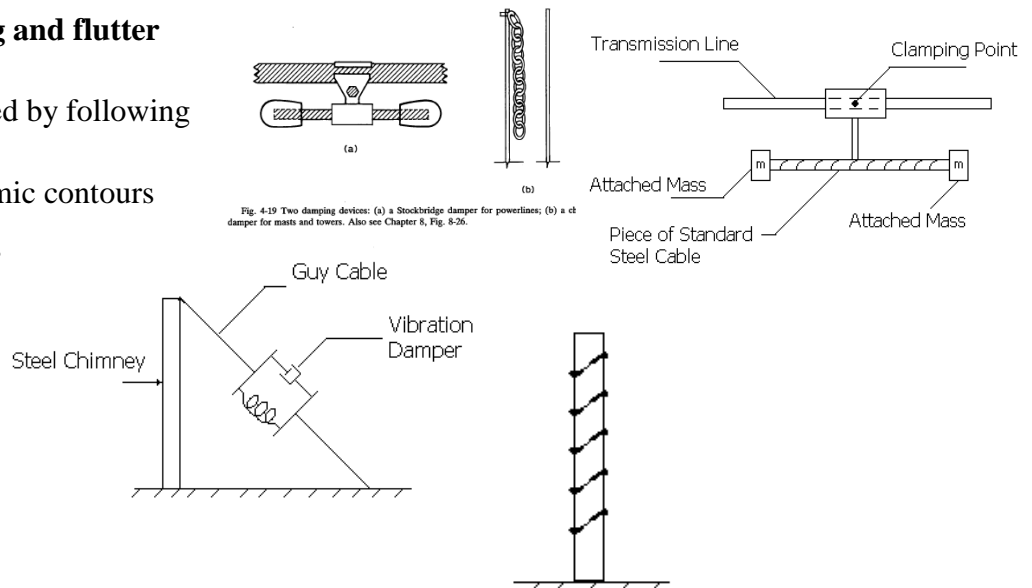
**Limit cycle oscillation (LCO)** behavior is characterized by constant amplitude, periodic structural response at frequencies that are those of the aeroelastically-loaded structure. LCO is typically limited to a narrow region in Mach number or angle-of-attack signaling the onset of flow separation.

**Engine whirl flutter** is a precession-type instability that can occur on a flexibly mounted engine-propeller combination. The phenomenon involves a complex interaction of engine mount stiffness, gyroscopic torques of the engine and propeller combination, and the natural flutter frequency of the wing structure.

### Prevention of galloping and flutter

This can be accomplished by following

- Stable aerodynamic contours
- Stiffness or mass
- Damping



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## Unit V

# Industrial Gas Turbines

### Turbine

A turbine is a rotary mechanical device that extracts energy from a fluid flow and converts it into useful work. A turbine is a turbomachine with at least one moving part called a rotor assembly, which is a shaft or drum with blades attached. Moving fluid acts on the blades so that they move and impart rotational energy to the rotor.

### Operation theory

A working fluid contains potential energy (pressure head) and kinetic energy (velocity head). The fluid may be compressible or incompressible. Several physical principles are employed by turbines to collect this energy:

Impulse turbines change the direction of flow of a high velocity fluid or gas jet. The resulting impulse spins the turbine and leaves the fluid flow with diminished kinetic energy. There is no pressure change of the fluid or gas in the turbine blades (the moving blades), as in the case of a steam or gas turbine, all the pressure drop takes place in the stationary blades (the nozzles). Before reaching the turbine, the fluid's *pressure head* is changed to *velocity head* by accelerating the fluid with a nozzle. Pelton wheels and de Laval turbines use this process exclusively. Impulse turbines do not require a pressure casement around the rotor since the fluid jet is created by the nozzle prior to reaching the blades on the rotor. Newton's second law describes the transfer of energy for impulse turbines.

Reaction turbines develop torque by reacting to the gas or fluid's pressure or mass. The pressure of the gas or fluid changes as it passes through the turbine rotor blades. A pressure casement is needed to contain the working fluid as it acts on the turbine stage(s) or the turbine must be fully immersed in the fluid flow (such as with wind turbines). The casing contains and directs the working fluid and, for water turbines, maintains the suction imparted by the draft tube. Francis turbines and most steam turbines use this concept. For compressible working fluids,

multiple turbine stages are usually used to harness the expanding gas efficiently. Newton's third law describes the transfer of energy for reaction turbines.

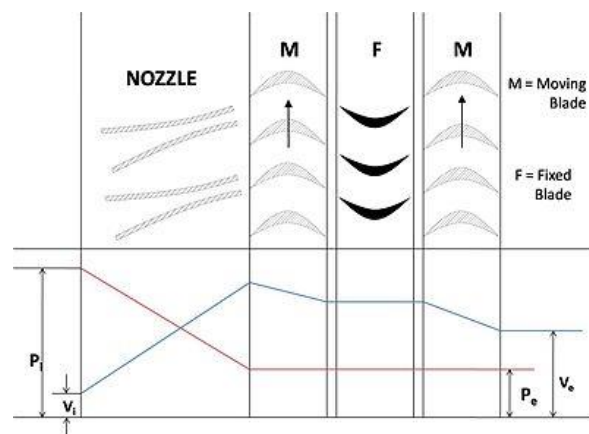
## Types of compounding

In an Impulse turbine compounding can be achieved in the following three ways: -

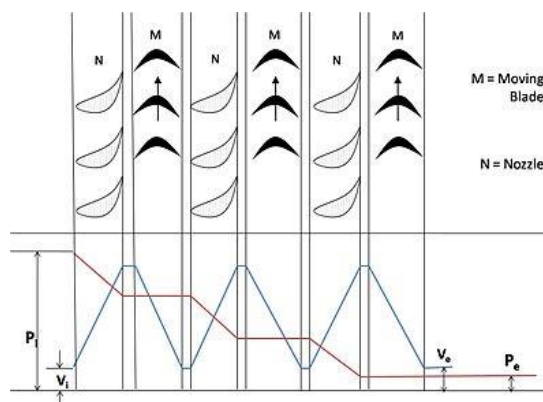
1. Velocity compounding
2. Pressure compounding
3. Pressure-Velocity Compounding

In a Reaction turbine compounding can be achieved only by Pressure compounding.

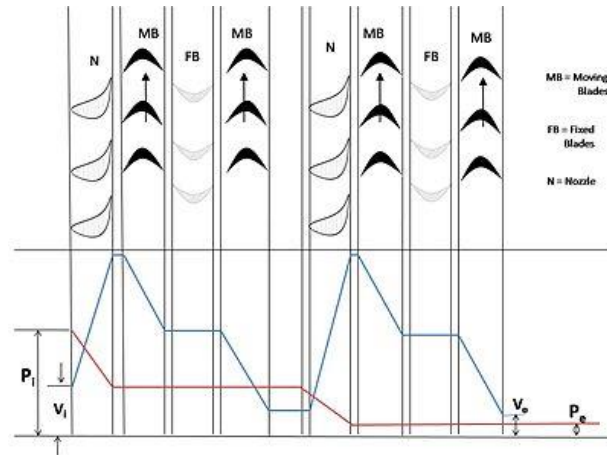
### Velocity compounding of Impulse Turbine



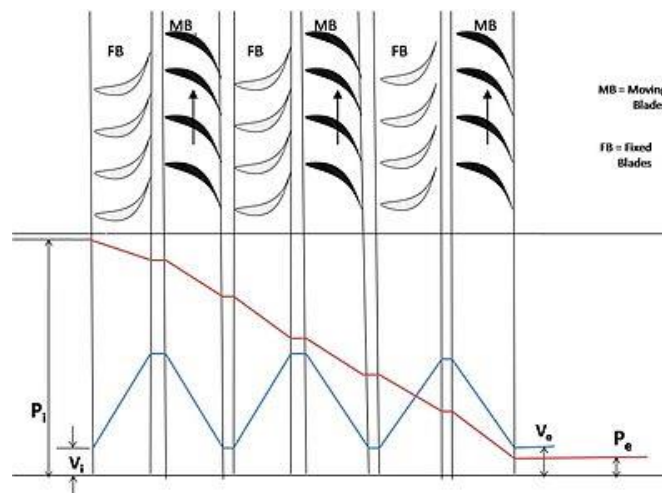
### Pressure compounding of Impulse Turbine



## Pressure-Velocity compounded Impulse Turbine



## Pressure compounding of Reaction Turbine



## Types based on working fluid

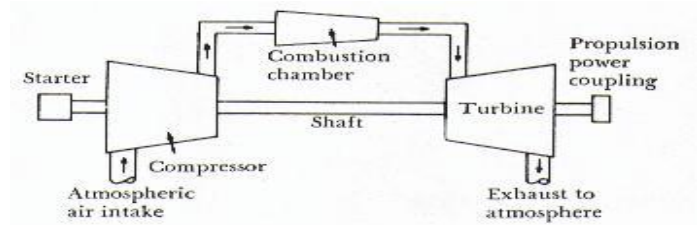
- Steam turbines** are used for the generation of electricity in thermal power plants, such as plants using coal, fuel oil or nuclear fuel. They were once used to directly drive mechanical devices such as ships' propellers but most such applications now use reduction gears or an intermediate electrical step, where the turbine is used to generate electricity, which then powers an electric motor connected to the mechanical load.

- **Gas turbines** are sometimes referred to as turbine engines. Such engines usually feature an inlet, fan, compressor, combustor and nozzle (possibly other assemblies) in addition to one or more turbines.
- **Water turbines**
  - Pelton turbine, a type of impulse water turbine.
  - Francis turbine, a type of widely used water turbine.
  - Kaplan turbine, a variation of the Francis Turbine.
  - Turgo turbine, a modified form of the Pelton wheel.
  - Cross-flow turbine, also known as Banki-Michell turbine, or Ossberger turbine.
- **Wind turbine:** These normally operate as a single stage without nozzle and interstage guide vanes.

## GAS TURBINE

A gas turbine, also called a combustion turbine, is a type of internal combustion engine. It has an upstream rotating compressor coupled to a downstream turbine, and a combustion chamber in-between.

The basic operation of the gas turbine is similar to that of the steam power plant except that air is used instead of water. Fresh atmospheric air flows through a compressor that brings it to higher pressure. Energy is then added by spraying fuel into the air and igniting it so the combustion generates a high-temperature flow. This high-temperature high-pressure gas enters a turbine, where it expands down to the exhaust pressure, producing a shaft work output in the process. The turbine shaft work is used to drive the compressor and other devices such as an electric generator that may be coupled to the shaft. The energy that is not used for shaft work comes out in the exhaust gases, so these have either a high temperature or a high velocity. The purpose of the gas turbine determines the design so that the most desirable energy form is maximized. Gas turbines are used to power aircraft, trains, ships, electrical generators, or even tanks.



## Classifications of gas turbines

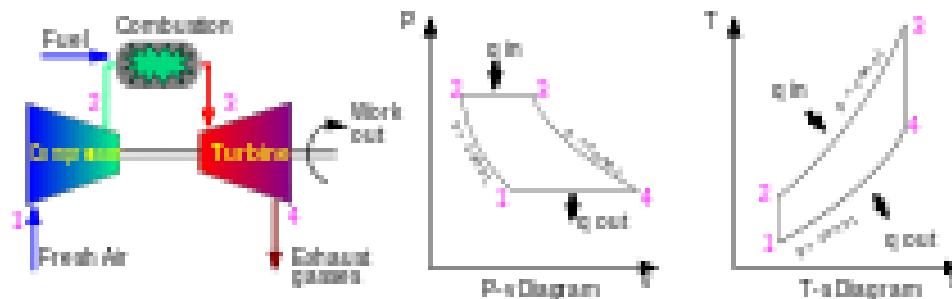
- Open cycle gas turbine
- Closed cycle gas turbine

## Theory of operation

In an ideal gas turbine, gases undergo three thermodynamic processes: an isentropic compression, an isobaric (constant pressure) combustion and an isentropic expansion. Together, these make up the Brayton cycle.

In a practical gas turbine, mechanical energy is irreversibly transformed into heat when gases are compressed (in either a centrifugal or axial compressor), due to internal friction and turbulence. Passage through the combustion chamber, where heat is added and the specific volume of the gases increases, is accompanied by a slight loss in pressure. During expansion amidst the stator and rotor blades of the turbine, irreversible energy transformation once again occurs.

If the device has been designed to power a shaft as with an industrial generator or a turboprop, the exit pressure will be as close to the entry pressure as possible. In practice it is necessary that some pressure remains at the outlet in order to fully expel the exhaust gases.



- Compressor - Dynamically Compress air
- Combustor - Heat addition through chemical reaction
- Turbine - Run the compressor and used for various application



## **Advantages of gas turbine**

- Very high power-to-weight ratio, compared to reciprocating engines;
- Smaller than most reciprocating engines of the same power rating.
- Moves in one direction only, with far less vibration than a reciprocating engine.
- Fewer moving parts than reciprocating engines.
- Greater reliability, particularly in applications where sustained high power output is required
- Waste heat is dissipated almost entirely in the exhaust.
- Low operating pressures.
- High operation speeds.
- Low lubricating oil cost and consumption.
- Can run on a wide variety of fuels.
- Very low toxic emissions of CO and HC due to excess air, complete combustion and no "quench" of the flame on cold surfaces

## **Disadvantages of gas turbine**

- Cost is very high
- Less efficient than reciprocating engines at idle speed
- Longer startup than reciprocating engines
- Less responsive to changes in power demand compared with reciprocating engines
- Characteristic whine can be hard to suppress

## **Application**

Thermal process industries, Petro-chemical industry, Aircrafts, Transportation and etc...

- electric power generation,
- mechanical drive systems,
- Supply of process heat and compressed air, pump drives for gas or liquid pipelines.
- jet propulsion,
- land and sea transport

## **SPECIAL FEATURES OF INDUSTRIAL AND STATIONARY GAS TURBINE AS COMPARED TO AIRCRAFT GAS TURBINE:**

Industrial gas turbines differ from aeronautical designs in that the frames, bearings, and blading are of heavier construction. They are also much more closely integrated with the devices they power— often an electric generator—and the secondary-energy equipment that is used to recover residual energy (largely heat).

- Long life
- Frontal area
- Space requirements
- Availability
- Thermal efficiency
- Pressure losses and other parameter of importance for the industry under consideration
- Continuous duty with large power requirements

The basic design parameters for heavy industrial gas turbine engines evolved from industrial steam turbines that have slower speeds, heavy rotors, and larger cases than jet engines to ensure longer life. These gas turbines are capable of burning the widest range of liquid or gas fuels.

The basic design parameters and technology used in aircraft turbines can be combined with some of the design aspects of heavy industrial gas turbines to produce a lighter-weight industrial turbine with a life approaching that of a heavy industrial gas turbine. These engines are called light industrial gas turbine engines.

Aircraft turbine engines or jet engines are designed with highly sophisticated construction for light weight specifically for powering aircraft. These designs require maximum horsepower or thrust with minimum weight and maximum fuel efficiency. Aircraft turbines have roller bearings and high firing temperatures requiring exotic metallurgy. They can be operated on a limited variation of fuels. When a jet engine is used in an industrial application, it must be coupled with an independent power turbine to produce shaft power. In the case of a jet engine only enough pressure and energy is extracted from the flow to drive the compressor and other components. The remaining high pressure gases are accelerated to provide a jet that can, for example, be used to propel an aircraft.

\*\*\*\*\*

Questions	opt1	opt2	opt3	opt4	opt5	opt6	Answer
Fixed control volume in space is known as _____method	a. Lagrangian	b. Eulerian	c. Rayleigh	d. Fanno			<b>Eulerian</b>
Thermodynamic properties do not change with respect to time in _____.	a. Steady flow	b. Flow	c. Incompressible flow	d. Stream line flow			<b>Steady flow</b>
A vortex line in a fluid has constant	a. straight line	b. circulation	c. Streamlines	d. equipotential lines			<b>circulation</b>
The _____ relates the velocity induced by a vortex filament to its strength and orientation	a. Second law of TD	b. first law of TD	c. Biot-Savart law	d. Zeroth law			<b>Biot-Savart law</b>
_____ is the science of fluid motion	a. Fluid dynamics	b. structural dynamics	c. Aerodynamic	d. kinematics			<b>Fluid dynamics</b>
For an over expanding nozzle, _____.	a. $P_b < P_e$	b. $P_b > P_e$	c. $P_b = P_e$	d. $P_b \leq P_e$			<b><math>P_b &lt; P_e</math></b>
_____ are curves that are everywhere tangent to the velocity vector	a. pathline	b. Streamlines	c. equipotential lines	d. circulation			<b>Streamlines</b>
A _____ is the trajectory followed by an individual particle.	a. pathline	b. Streamlines	c. equipotential lines	d. circulation			<b>pathline</b>
_____ is a measure of the degree of local rotation in the fluid.	a. Vorticity	b. circulation	c. Streamlines	d. equipotential lines			<b>Vorticity</b>
When $P_b = P_e$ _____.	a. Flow takes place slowly	b. Flow takes place rapidly	c. No flow takes place	d. Flow takes place at isentropic			<b>Flow takes place at isentropic</b>
Supersonic flow occurs in_____.	a. Convergent nozzle	b. Divergent nozzle	c. Under expanding nozzle	d. Choked nozzle			<b>Under expanding nozzle</b>
Equation for state for perfect gas is _____.	a. $Pv = RT$	b. $P/v = RT$	c. $P + v = R + T$	d. $P - v = R - T$			<b><math>Pv = RT</math></b>
The shock can always from supersonic to subsonic because of _____.	a. First law of thermodynamics	b. Newton's law of motion	c. Second law of thermodynamics	d. Newton's third law			<b>Second law of thermodynamics</b>
Shock is a _____ across fluid flow properties	a. Continuity	b. discontinuity	c. both(a) and(b)	d. all of the above			<b>discontinuity</b>
$a^*$ refers to _____.	a. $M < 1$	b. $M > 1$	c. $M = 1$	d. $M = 0$			<b><math>M = 1</math></b>
Normal shock occurs only from_____.	a. $V_2 = V_1$	b. $V_2 > V_1$	c. $V_1 = V_2 = 1$	d. $V_2 < V_1$			<b><math>V_2 &lt; V_1</math></b>
The sonic velocity is the _____ property of the fluid	a. Static	b. Hydrodynamic	c. Thermo dynamic	d. Aerodynamic			<b>Thermodynamic</b>
For isentropic flows, stagnation enthalpy and stagnation temperature are_____.	a. Zero	b. constants	c. variables	d. unity			<b>constants</b>
The change in pressure with respect to the change in velocity is always_____.	a. Zero	b. positive	c. unity	d. negative			<b>negative</b>
In a converging area duct with a subsonic flow, the fluid flows out with a_____.	a. high velocity	b. high density	c. high pressure	d. high viscosity			<b>high velocity</b>
In stagnation state, the fluid is brought to a state of zero velocity in_____.	a. Adiabatic manner	b. isentropic manner	c. polytropic manner	d. isobaric manner			<b>isentropic manner</b>
In a finite wing, the strong vortices produced at _____ .	a. tip of the wing	b. wing	c. produced	d. edge of the wing			<b>tip of the wing</b>
What is the advantage of using blow-down wind tunnel?	a. no need of pressure regulator	b. high mach capability	c. noise free operation	d. longer			<b>high mach capability</b>
The Mach Number at which the aerodynamic drag increases rapidly is known as_____.	a. Upper Critical Mach Number	b. Lower Critical Mach Number	c. Drag divergence	d. Center of pressure			<b>Drag divergence</b>
The chord-wise length about which the pitching moment is independent of the lift co-efficient and the angle of attack is known as_____.	a. Aerodynamic center	b. Center of pressure	c. Stagnation point	d. a and b			<b>Aerodynamic center</b>
The small perturbation equations for subsonic and supersonic flows are_____.	a. Linear	b. non-linear	c. Rotational	d. irrotational			<b>Linear</b>
Diffusers are used to _____ the velocity of inlet air.	a. decrease	b. increase	c. Zero	d. constant			<b>decrease</b>
Subsonic flows through a diverging nozzle will have_____ velocity	a. Steady flow	b. Flow	c. Incompressible flow	d. Streamline flow			<b>Incompressible flow</b>
Supersonic flow can be converted in to subsonic using _____ nozzle	a. Diverging	b. Expanding	c. Converging	d. Converging-diverging			<b>Converging</b>
For under expanding nozzle _____.	a. $P_b < P_e$	b. $P_b > P_e$	c. $P_b = P_e$	d. All of the above			<b><math>P_b &lt; P_e</math></b>
Subsonic flow over the wedge body produces _____ shock.	a. Oblique	b. normal	c. expansion	d. No			<b>Oblique</b>
Total temperature is constant across a stationary _____ shock.	a. Oblique	b. normal	c. expansion	d. No			<b>b</b>
A gas with constant specific heats is known as_____.	a. Thermally perfect gas	b. Calorically perfect gas	c. Ideal gas	d. Mach			<b>normal</b>
Prandtl relation for normal shock is_____.	a. $V_1 * V_2 = (a^*)^2$	b. $V_1 / V_2 = (a^*)^2$	c. $V_1 + V_2 = (a^*)^2$	d. $V_1 - V_2 = (a^*)^2$			<b><math>V_1 * V_2 = (a^*)^2</math></b>
Normal shock is _____ to flow direction.	a. parallel	b. perpendicular	c. inclined	d. all of the above			<b>perpendicular</b>
Lift produce is directly proportional to _____ pressure.	a. Dynamic	b. Static	c. total	d. all of the above			<b>Static</b>
When the velocity increases lift produced will _____.	a. decrease	b. constant	c. increase	d. independent			<b>increase</b>
The expansion takes place across a continuous succession of Mach waves is _____.	a. isentropic	b. adiabatic	c. isothermal	d. isobaric			<b>isentropic</b>
When the oblique shock is reflected from the solid surface,it will produce _____ shock.	a. Oblique	b. normal	c. expansion	d. No			<b>Oblique</b>
In a finite wing, the strong vortices produced at _____.	a. tip of the wing	b. wing	c. produced	d. edge of the wing			<b>tip of the wing</b>
Can isentropic condition be applied across a normal shock wave?	a. yes	b. no	c. no because of loss in $P_{t0}$	d. no because of $P_{t0}$ is constant			<b>no because of <math>P_{t0}</math> is constant</b>
Back pressure is the pressure _____.	a. outside the nozzle plane	b. inside the nozzle plane	c. inlet pressure	d. exit pressure			<b>outside the nozzle plane</b>
The critical mach number is increased by using _____.	a. Thinner and Swept wing	b. Thicker Delta wing	c. Thinner wing only	d. Thicker wing only			<b>Thinner and Swept wing</b>
In a blow down wind tunnel, _____ is used to produce air flow.	a. compressor	b. Turbine	c. Duct fan	d. All the above			<b>Duct fan</b>
The feature of blow down configuration is _____.	a. High Mach Capability	b. Less noise operation	c. Continuous operation	d. All the above			<b>High Mach Capability</b>
There is no need for _____ in the indraft tunnel.	a. Pressure regulator	b. Chamber	c. Noise reducer	d. Plenum Chamber			<b>Noise reducer</b>
Nozzles are used to _____ the velocity of inlet air.	a. decrease	b. increase	c. zero	d. constant			<b>increase</b>

- Subsonic flows through a converging nozzle will \_\_\_\_\_ velocity.
- When  $P_b < P_e$ , Convergent-Divergent duct is known as \_\_\_\_\_ nozzle.
- In a converging – diverging nozzle, mach no in the throat is always \_\_\_\_\_.
- a. decrease

b. increase

c. zero

d. neutralize

**increase**
- a. Under expanding

b. Expanding

c. Converging

d. over expanding

**Under expanding**
- a.  $M = 0$

b.  $M = 1$

c.  $M > 1$

d.  $M < 1$

**$M = 1$**

Questions		opt1		opt2		opt3		opt4		Answer
Shock will always occur in flow with_____.	a.	M = 0	b.	M = 1	c.	M > 1	d.	M < 1		<b>M &gt; 1</b>
When flow cross the normal shock wave, total pressure will be _____.	a.	decreased	b.	increased	c.	zero	d.	Constant		<b>decreased</b>
Detached shock wave occurs in a flow over _____ body.	a.	blunt	b.	sharp	c.	wedge	d.	Constant		<b>blunt</b>
Flow across the expansion wave , velocity will be _____.	a.	decreased	b.	increased	c.	zero	d.	Constant		<b>increased</b>
In a compressible flow density is _____.	a.	decreased	b.	increased	c.	Variable one	d.	Constant		<b>Constant</b>
The Weak pressure disturbance is known as _____.	a.	Normal shock	b.	Oblique shock	c.	Sound Wave	d.	Mach wave		<b>Sound Wave</b>
The lift produced by the airfoil is due to _____ of velocity.	a.	decreased	b.	increased	c.	zero	d.	Constant		<b>increased</b>
Relation between the mach no(M) and mach angle (μ) _____.	a.	$\mu = \sin^{-1} M$	b.	$\sin \mu = M$	c.	$\sin \mu = 1/M$	d.	$\mu = M$		<b><math>\sin \mu = 1/M</math></b>
The Value Of the Characteristic Mach Number will be _____ if Mach Number tends to infinity.	a.	0	b.	2.449	c.	2.65	d.	1		<b>2.449</b>
Critical Mach number is defined as _____.	a.	$M^*=a/c^*$	b.	$M = c/a^*$	c.	$M^*=c/a^*$	d.	$M^*=c^*/a^*$		<b><math>M^*=c^*/a^*</math></b>
Normal shocks are always_____.	a.	one-dimensional	b.	two-dimensional	c.	three-dimensional	d.	all the above		<b>one-dimensional</b>
An incident shock gets reflected as a shock from a solid boundary is called _____.	a.	like reflections	b.	simple regions	c.	unlike reflections	d.	non-simple regions		<b>like reflections</b>
The advantage of Blow down wind tunnel is _____.	a.	High Mach Capability	b.	Shock –free operation	c.	Muffler	d.	Continuous operation		<b>High Mach Capability</b>
The Shock wave may occur in _____.	a.	Blow down	b.	Induction tunnel	c.	Shock tube	d.	All the above		<b>All the above</b>
The supersonic wind tunnel produces_____.	a.	M = 0	b.	M = 1	c.	M > 1	d.	M < 1		<b>M &gt; 1</b>
The Component used to straighten the airflow in the wind tunnel is _____	a.	Settling chamber	b.	Pressure regulator	c.	diffuser	d.	test section		<b>Settling chamber</b>
In supersonic flow, converging nozzle is used to _____ velocity.	a.	decrease	b.	increase	c.	zero	d.	constant		<b>increase</b>
Velocity of sound(a) is give by_____.	a.	$\gamma RT$	b.	RT	c.	$\sqrt{(\gamma RT)}$	d.	$(\gamma RT)^2$		<b><math>\sqrt{(\gamma RT)}</math></b>
According to continuity equation, in a flow _____.	a.	Total energy remains constant	b.	Mass flow rate remains constant	c.	Velocity remains constant	d.	Density remains constant		<b>Mass flow rate remains constant</b>
In a converging – diverging nozzle, condition of M = 1 occur at _____.	a.	inlet	b.	exit	c.	throat	d.	Every where		<b>throat</b>
When flow cross the normal shock wave total temperature _____.	a.	decrease	b.	increase	c.	zero	d.	constant		<b>constant</b>
Which one of the following condition is true when flow cross normal shock wave_____	a.	$V_1=V_2$	b.	$V_1>V_2$	c.	$V_1<V_2$	d.	$V_1=V_2=1$		<b><math>V_1&gt;V_2</math></b>
Oblique shock is _____ to flow direction	a.	parallel	b.	perpendicular	c.	Inclined	d.	All the above		<b>Inclined</b>
One dimensional flow with friction is known as _____.	a.	Fanno flow	b.	Steady flow	c.	Rayleigh flow	d.	Laminar flow		<b>Fanno flow</b>
The three-dimensional Shock is known as _____.	a.	Normal shock	b.	Oblique shock	c.	Expansion wave	d.	Mach wave		<b>Expansion wave</b>
Lift produced in a body due to flow over it is directly proportion all to_____.	a.	V	b.	$V^2$	c.	$V^3$	d.	All the above		<b><math>V^2</math></b>
Aerodynamic center is the point at which the moment produced will_____.	a.	Always vary	b.	Remains constant	c.	Not consider	d.	be zero		<b>Remains constant</b>
The mach no (M) and mach angle (μ) can be related as _____.	a.	$\mu = \sin^{-1} M$	b.	$\sin \mu = M$	c.	$\sin \mu = 1/M$	d.	$\mu = M$		<b><math>\sin \mu = 1/M</math></b>
The Process inside the Sound wave is _____.	a.	isentropic	b.	adiabatic	c.	isobaric	d.	isothermal		<b>isothermal</b>
One-dimensional Flow with heat addition is known as_____.	a.	Rayleigh Flow	b.	Fanno Flow	c.	Irreversible flow	d.	No wave		<b>Rayleigh Flow</b>
The one-dimensional motion of a shock wave in a tube of constant area are called_____.	a.	wave motion	b.	plane waves	c.	wave speed	d.	All the above		<b>plane waves</b>
In a finite wing, the strong vortices produced at _____.	a.	tip of the wing	b.	centre of the wing	c.	no vortices produced	d.	edge of the wing		<b>tip of the wing</b>
The small perturbation equations are _____ upto $M \leq 1$ .	a.	linear	b.	non-linear	c.	rotational	d.	irrotational		<b>linear</b>
Critical velocity in converging-diverging nozzle occur at _____.	a.	Velocity at the exit	b.	Maximum velocity	c.	Velocity at the throat	d.	Velocity at the inlet		<b>Velocity at the throat</b>
Smaller loads on model during startup because of faster starts is a feature of_____	a.	Indraft	b.	Blow down	c.	Gun tunnel	d.	Helium Tunnel		<b>Blow down</b>
Flow across the normal shock wave is _____.	a.	isentropic	b.	iso baric	c.	non isentropic	d.	reversible adiabatic		<b>non isentropic</b>
For over expanding nozzle _____.	a.	$P_b < P_e$	b.	$P_b > P_e$	c.	$P_b = P_e$	d.	$P_b \leq P_e$		<b><math>P_b &lt; P_e</math></b>
Thermodynamic properties do not change with respect to time in _____.	a.	Steady flow	b.	Compressible Flow	c.	Incompressible flow	d.	Streamline flow		<b>Steady flow</b>
Constant Pressure process is known as _____.	a.	Isobaric	b.	Isothermal	c.	Adiabatic	d.	Isentropic		<b>Isobaric</b>
When $P_b = P_e$ _____.	a.	Flow takes place slowly	b.	Flow takes place rapidly	c.	No flow takes place	d.	Flow takes place at isentropic		<b>Flow takes place at isentropic</b>

Diffuser are used to _____ the velocity of inlet air.	a.	decrease	b.	increase	c.	zero	d.	constant		<b>decrease</b>
Subsonic flows through a diverging nozzle will _____ velocity.	a.	Steady flow	b.	Compressible Flow	c.	Incompressible flow	d.	Streamline flow		<b>Incompressible flow</b>
Subsonic can be converted in to Supersonic flow using _____ nozzle	a.	Convergent nozzle	b.	Divergent nozzle	c.	convergent - divergent nozzle	d.	Choked nozzle		<b>convergent - divergent nozzle</b>
For under expanding nozzle _____.	a.	$P_b < P_e$	b.	$P_b > P_e$	c.	$P_b = P_e$	d.	$P_b \leq P_e$		<b><math>P_b &gt; P_e</math></b>
When velocity of flow over an airfoil increases, then lift produced by the airfoil will	a.	decrease	b.	increase	c.	zero	d.	constant		
Upper critical Mach number is defined as the free stream mach number for which the entire flow around the body is_____.	a.	sonic	b.	Subsonic	c.	Transonic	d.			<b>Transonic</b>
Normal shocks are always created at _____.	a.	subsonic flow	b.	supersonic flow	c.	Transonic flow	d.	hypersonic flow		<b>supersonic flow</b>
At _____ the airflow over some point of the aircraft reaches the speed of sound .	a.	Critical Mach number	b.	subcritical	c.	normal	d.	lower critical		<b>Critical Mach number</b>
The small perturbation equations for subsonic and supersonic flows are_____.	a.	linear	b.	non-linear	c.	Drag divergence	d.	irrotational		<b>linear</b>

Questions		opt1		opt2		opt3		opt4		Answer	
Critical velocity in converging-diverging nozzle occur at _____.	a.	Velocity at the exit	b.	Maximum velocity	c.	rotational	d.	Velocity at the inlet		Velocity at the throat	
For analysis of flows past ballistic missiles,_____ is used.	a.	Blow down	b.	Gun tunnel	c.	Velocity at the throat	d.	Helium tunnel		Gun tunnel	
When flow pass the normal shock wave, it follows _____ process.	a.	isentropic	b.	iso baric	c.	In draft tunnel	d.	reversible adiabatic		non isentropic	
psi is a unit of	a.	pressure	b.	temperature	c.	non isentropic	d.	energy		pressure	
A high-lift subsonic aerofoil section has a thickness/chord ratio approximately	a.	12%	b.	6%	c.	15%	d.	25%		12%	
Lift increase with	a.	air density	b.	AOA, within the stalling limit	c.	18%	d.	all of the above		all of the above	
A rectangular wing with unsymmetrical aerofoil section stalls in clean configuration when the AOA is	a.	between 4° and 8°	b.	between 12° and	c.	Aspecr Ratio	d.	between 45° and 60°			
The direction of lift is	a.	vertically upward	b.	axis	c.	between 30° and 35°	d.	90° to the flight path		vertically upward	
Sound propagation is	a.	isothermal process	b.	Isentropic process	c.	90° to the wing mean chord	d.	Isochoric process		Isentropic process	
When the Mach number ahead of a normal shock is infinity the Mach number behind the normal shock is	a.	infinity	b.	high supersonic	c.	Isobaric process	d.	low subsonic		low subsonic	
The lowest value of shock angle for oblique shocks is	a.	Zero	b.	12.5 deg	c.	Zero	d.	15 deg		Mach angle	
The maximum possible turning angle through Prandtl_Meyer expansion is	a.	130.5 deg	b.	180 deg	c.	Mach angle	d.	165 deg		130.5 deg	
Isothermal compressibility of a compressible gas at a given pressure is	a.	Directly proportional to the	b.	Reciprocal of the pressure	c.	145 deg	d.	All of the above		Reciprocal of the pressure	
is a pressure drag resulting from static pressure components located to either side of compression or shock waves	a.	pressure drag	b.	Wave Drag	c.	proportional to the square of the	d.	All of the above		Wave Drag	
are airfoils developed to increase the increment between the critical Mach number and the drag divergent Mach number.	a.	critical	b.	subcritical	c.	skinfr	d.	optimum		Supercritical airfoils	
The free stream Mach number at which sonic speed is first achieved somewhere on the surface of a body it is called	a.	critical Mach number.	b.	subcritical	c.	Supercritical airfoils	d.	transonic		critical Mach number.	
The difference in effective downwash angle for the two tail spans for sweptback wings at high angles of attack when the tips stall is	a.	tip loss	b.	vorticity	c.	Drag divergence	d.	incident		tip effects	
The free stream Mach number at which the entire flow around the surface is in subsonic flow is called as	a.	Lower critical Mach number.	b.	upper critical Mach number.	c.	tip effects	d.	super critical		Lower critical Mach number.	
The free stream Mach number at which the entire flow around the surface is in supersonic flow is called as	a.	Lower critical Mach number.	b.	subcritical	c.	subcritical	d.	upper critical Mach number.		upper critical Mach number.	
is a simple statement that the cross sectional area of the body should have a smooth variation along the longitudinal distance of the body	a.	supersonic	b.	Transonic are rule	c.	super critical	d.	supercritical		Transonic are rule	
Swept wings are used to increase the	a.	critical Mach number	b.	critical Mach number.	c.	subsonic	d.	Drag divergence		critical Mach number	
rupture of a diaphragm separating a high pressure gas from a low pressure gas.	a.	shock tube	b.	baurdon tube	c.	subcritical	d.	pressure transducers		shock tube	
is a powerful tool in experimental fluid mechanics	a.	Flow Visualisation	b.	Pressure regulator	c.	pitot tube	d.	pressure transducers		Flow Visualisation	
separation point and wake formation can be analysed due to increase in angle of attack.	a.	subsonic wind tunnel	b.	supersonic wind tunnel	c.	pitot tube	d.	cascade tunnel		Flow Visualisation	
A _____ is a wind tunnel that produces supersonic speeds (1.2<M<5)	a.	subsonic wind tunnel	b.	supersonic wind tunnel	c.	Flow Visualisation	d.	Interferometer		supersonic wind tunnel	
_____system gives a picture or an image representative of the variation of density throughout the complete flow field.	a.	supersonic wind tunnel	b.	Schlieren	c.	Schlieren	d.	Schlieren		Schlieren	
and supersonic Mach number. This employed for field with strong shock waves.	a.	Schlieren	b.	Interferometer	c.	Interferometer	d.	supersonic wind tunnel		Shadowgraph	
transonic and supersonic Mach numbers. This gives a qualitative estimate of flow density in the field.	a.	Schlieren	b.	Interferometer	c.	Shadowgraph	d.	supersonic wind tunnel		Interferometer	
The model must be accommodated inside the rhombus formed by the incident and reflected shocks, for proper measurements is known as	a.	geometric test	b.	dynamic test	c.	Shadowgraph	d.	kinematic		principles of model testing	
is a device used to measure forces, moments, pressure, shear stress, heat transfer and flow field	a.	optical visualization	b.	Wind tunnel	c.	principles of model testing	d.	particle velocimetry		Wind tunnel	
The instruments used to measure the fluctuating pressures are	a.	optical visualization	b.	Turbulence sphere	c.	dye injection	d.	particle velocimetry		Turbulence sphere	
The air is pumped into a closed high pressure chamber upstream of the plenum.	a.	Induction	b.	Wind tunnel	c.	dye injection	d.	Blow down tunnels		Blow down tunnels	
type energy stored in the form of pressure in a reservoir	a.	wind tunnel	b.	Induction	c.	dye injection	d.	Blow down tunnels		Intermittent	
type energy stored in the form of Vacuum in a reservoir.	a.	Induction	b.	Intermittent	c.	Intermittent	d.	vaccum tunnel		Induction	
The pressure to be measured are usually to large to be measured instead of water or alcohol.	a.	shock tube	b.	baurdon tube	c.	blow down	d.	pressure transducers		pressure transducers	
is used for testing medium bathing aircraft and reentering spacecraft	a.	shock tube	b.	Helium tunnel	c.	pitot tube	d.	Intermittent		Helium tunnel	
Sensitive to the change of Displacement	a.	Shadowgraph	b.	Schieren	c.	Induction	d.	dye injection		Shadowgraph	
Sensitive to the change of Angular deflection	a.	dye injection	b.	Shadowgraph	c.	Interferometer	d.	Interferometer		Schieren	
Sensitive to the change of Phase change	a.	Shadowgraph	b.	Schieren	c.	Schieren	d.	Interferometer		Interferometer	
The starting shock crossing the diffuser throat and remaining in its divergent part is called the	a.	Drying	b.	Liquefaction	c.	dye injection	d.	Mach reflection.		swallowing of the starting shock.	
the working fluid is the best way to avoid condensation.	a.	swallowing of the starting shock.	b.	Drying	c.	swallowing of the starting shock.	d.	sublimation		Drying	
How can condensation be avoided/reduced in supersonic wind tunnels?	a.	vapourisation	b.	sublimation	c.	Liquefaction	d.	Liquefaction		Drying	
troubles might start around M=4 if high pressure air is expanded from room temperature.	a.	vapourisation	b.	sublimation	c.	Drying	d.	Liquefaction		Liquefaction	
a reflected left running oblique shock in order to bring the flow into the original direction are called	a.	Mach absorption	b.	Mach reflection.	c.	Liquefaction	d.	simple		Mach reflection.	

Supersonic expansion or compression with mach lines which are straight is called	a.	simple region	b.	non simple region	c.	injection	d.	curved			simple region	
The intersection of mach lines of different form, lies leads to_____ where all the mach lines are not straight but curved.	a.	curve	b.	simple region	c.	Mach reflection.	d.	Mach reflection.			non simple region	
Assumptions made to derive Normal Shock relation	a.	Flow is 1-D, inviscid	b.	Flow is 2-D, inviscid	c.	non simple region	d.	Flow is 3-D, inviscid			Flow is 1-D, inviscid	
is the weak limit of an oblique shock wave	a.	Mach wave	b.	normal shock	c.	Flow is 2-D, viscous	d.	shock			Mach wave	
shock waves in the flow over the wing and tail plane are sufficient to stall the wing, make control surfaces ineffective or lead to loss of control such as	a.	Mach angle	b.	Mach tuck	c.	Mach angle	d.	normal shock			Mach tuck	
The phenomena associated with problems at the critical Mach number became known as	a.	compressibility	b.	incompressible	c.	Mach wave	d.	vapourisation			compressibility	



Questions	opt1	opt2	opt3	opt4			Answer	
beyond the span wise axis, generally used to delay the drag rise caused by fluid compressibility	a. delta wing	b. Straight wing	c. expansion	d. Swept wings			<b>Swept wings</b>	
_____as a means of reducing wave drag were first used on jet fighter aircraft	a. delta wing	b. Straight wing	c. elliptical wing	d. elliptical wing			<b>Swept wings</b>	
The four-engine propeller-driven _____ aircraft has swept wings.	a. A-10	b. A380	c. Swept wings	d. TU-95			<b>TU-95</b>	
The _____ is that free-stream Mach number at which sonic flow is first encountered on the airfoil.	a. subcritical	b. critical Mach number	c. pushpak	d. supercritical			<b>critical Mach number</b>	
The _____ gradient induced by the shock tends to separate the boundary layer on the top surface, causing a large pressure drag	a. adverse pressure	b. reverse pressure	c. Drag divergence	d. high pressure			<b>adverse pressure</b>	
_____is the Mach number at which the aerodynamic drag on an airfoil or airframe begins to increase rapidly as the Mach number continues to increase	a. critical	b. drag divergence	c. favourable pressure	d. supercritical			<b>drag divergence</b>	
can cause the drag coefficient to rise to more than ten times its low speed value.	a. subcritical	b. supercritical	c. subcritical	d. drag divergence			<b>drag divergence</b>	
The value of the drag divergence Mach number is typically greater than	a. 0.3	b. 1	c. critical	d. 2			<b>0.6</b>	
A change of state is called a _____ in thermodynamics	a. steady state	b. Process	c. 0.6	d. cycle			<b>Process</b>	
is a branch of natural science concerned with heat and its relation to energy and work.	a. cycle	b. steady state	c. unsteady state	d. unsteady state			<b>Thermodynamics</b>	
is defined as a quantity of matter or a region in space chosen for study.	a. cycle	b. system	c. Thermodynamics	d. steady state			<b>system</b>	
The mass or region outside the system is called the _____	a. system	b. Process	c. process	d. surroundings			<b>surroundings</b>	
The _____ is the total energy contained by a thermodynamic system	a. electrical energy	b. heat energy	c. boundary	d. potential energy			<b>internal energy</b>	
_____the real or imaginary surface that separates the system from its surroundings. The boundaries of a system can be fixed or movable.	a. system	b. Boundary	c. internal energy	d. wall			<b>Boundary</b>	
A closed system that does not communicate with the surroundings by any means _____	a. Isolated system	b. closed	c. surrounding	d. cycle			<b>Isolated system</b>	
A closed system that communicates with the surroundings by heat Only	a. flexible	b. adiabatic	c. open	d. Rigid system			<b>Rigid system</b>	
A closed or open system that does not exchange energy with the surroundings by heat	a. Isolated system	b. Adiabatic system	c. insulated system	d. Rigid system			<b>Adiabatic system</b>	
are those that are independent of the size (mass) of a system, such as temperature, pressure, and density.	a. Intensive properties	b. Adiabatic system	c. insulated system	d. Isolated system			<b>Intensive properties</b>	
values that are dependant on size of the system such as mass, volume, and total energy U.	a. Adiabatic system	b. Extensive properties	c. Extensive properties	d. Isolated system			<b>Extensive properties</b>	
when the temperature is the same throughout the entire system.	a. enthalphy	b. entropy	c. Intensive properties	d. Thermal equilibrium			<b>Thermal equilibrium</b>	
is a process during which the temperature remains constant	a. isentropic	b. Isobaric	c. equilibrium	d. Isochoric process			<b>Isothermal</b>	
is a process during which the pressure remains constant	a. Isothermal	b. Isobaric	c. Isothermal	d. Isochoric process			<b>Isobaric</b>	
is process during which the specific volume remains constant	a. isentropic	b. Isochoric process	c. isentropic	d. polytropic			<b>Isometric</b>	
states that if two bodies are in thermal equilibrium with a third body, they are also in thermal equilibrium with each other.	a. charles law	b. Second law of thermodynamics	c. Isometric	d. First law of thermodynamics			<b>0th law of thermodynamics</b>	
It simply states that during an interaction, energy can change from one form to another but the total amount of energy remains constant.	a. First law of thermodynamics	b. 0th law of thermodynamics	c. 0th law of thermodynamics	d. boyles law			<b>First law of thermodynamics</b>	
energy has quality as well as quantity, and actual processes occur in the direction of decreasing quality of energy.	a. First law of thermodynamics	b. Second law of thermodynamics	c. Second law of thermodynamics	d. charles law			<b>Second law of thermodynamics</b>	
The speed of sound as a function of	a. pressure	b. density	c. 0th law of thermodynamics	d. Static temperature			<b>temperature</b>	
it is proportional to the square root of the temperature	a. speed of light	b. speed of sound	c. Total temperature	d. change in density			<b>speed of sound</b>	
the speed of sound is about _____ of the average molecular velocity.	a. three-quarters	b. one-quarters	c. molecular velocity	d. quarters			<b>three-quarters</b>	
Flow is said to be subsonic flow if	a. $M < 1$	b. $M = 1$	c. two-quarters	d. $M > 5$			<b><math>M &lt; 1</math></b>	
Flow is said to be sonic flow if	a. $M < 1$	b. $M = 1$	c. $M > 1$	d. $M > 5$			<b><math>M = 1</math></b>	
Flow is said to be supersonic flow if	a. $M < 1$	b. $M = 1$	c. $M > 1$	d. $M > 5$			<b><math>M &gt; 1</math></b>	
Flow is said to be Hypersonic flow if	a. $M = 1$	b. $M > 1$	c. $M > 1$	d. $M < 1$			<b><math>M &gt; 5</math></b>	
Mach number was defined as the ratio of	a. $V/2a$	b. $2V/a$	c. $M > 5$	d. $V/a$			<b><math>V/a</math></b>	
For calorically perfect gas the square of the _____ is proportional to the ratio of kinetic to internal energy	a. Static temperature	b. Mach number	c. $3V/a$	d. density			<b>Mach number</b>	
For $0 < M < 1$ (subsonic flow), an increase in velocity (positive du) is associated with a decrease in	a. diverging duct	b. velocity	c. pressure	d. area			<b>area</b>	
For $M > 1$ (supersonic flow), an increase in _____ is associated with an increase in area	a. converging duct	b. velocity	c. converging duct	d. diverging duct			<b>velocity</b>	
For supersonic flow, the velocity increases in a diverging duct and decreases in a	a. velocity	b. converging duct	c. area	d. diverging duct			<b>converging duct</b>	
A expansion fan is a centered expansion process, which turns a supersonic flow around a	a. convex corner	b. concave	c. area	d. curved			<b>convex corner</b>	
Across the expansion fan, the flow accelerates and the Mach number _____	a. increases	b. decrease	c. sharp corner	d. negative			<b>increases</b>	
Across the expansion fan, the static pressure, temperature and density _____	a. decrease	b. constant	c. constant	d. negative			<b>decrease</b>	
The process is isentropic, the stagnation properties remain constant across the	a. expansion fan	b. Normal shock	c. increases	d. reflected wave			<b>expansion fan</b>	
The fan consists of an infinite number of Mach waves, diverging from a	a. sharp corner	b. convex corner	c. oblique shocks	d. flat			<b>sharp corner</b>	
Straight _____ are also attached to the tip of a sharp cone in supersonic flow	a. expansion fan	b. Normal shock	c. concave	d. reflected wave			<b>oblique shocks</b>	

velocities on a graph which uses Vx and Vy velocity components is called the	a.	hodograph plane	b.	shock polars	c.	oblique shocks	d.	subsonic			<b>hodograph plane</b>	
In the shock polars inside the circle, all velocities are subsonic, outside it, all velocities are _____	a.	supersonic	b.	less	c.	Intersection of shock waves	d.	hypersonic			<b>supersonic</b>	
In the shock polars inside the circle, all velocities are _____,outside it, all velocities are supersonic	a.	supersonic	b.	less	c.	subsonic	d.	hypersonic			<b>subsonic</b>	
The pressure is continuous but the entropy is discontinuous at the slip line in	a.	shock polars	b.	Intersection of shock waves	c.	subsonic	d.	hypersonic			<b>Intersection of shock waves</b>	
Reflected waves form a like pattern throughout the exhaust jet	a.	rectangle	b.	diamond	c.	subsonic	d.	concave			<b>diamond</b>	
_____ co-ordinates are more convenient for elongated bodies and bodies of revolution	a.	Cylindrical	b.	spherical	c.	convex corner	d.	rectangular			<b>Cylindrical</b>	

Questions		opt1		opt2		opt3		opt4		Answer
_____ theory is frequently linear theory	a.	linearised flow theory	b.	Small-perturbation	c.	cartesian	d.	Compressible Flow theory		<b>Small-perturbation</b>
The _____ where the assumption of small perturbations allowed a linearized solution	a.	Small-perturbation	b.	Compressible Flow theory	c.	Small-perturbation	d.	linearised flow theory		<b>acoustic theory</b>
_____ for a symmetrical airfoil in supersonic flow is predicted at the mid-chord point	a.	Aerodynamic center	b.	center of pressure	c.	acoustic theory	d.	coefficient of drag		<b>center of pressure</b>
_____ is a design technique used to reduce an aircraft's drag at transonic	a.	Whitcomb area rule	b.	area rule	c.	coefficient of pressure	d.	thick aerofoil		<b>Whitcomb area rule</b>
_____ is a design technique used to reduce an aircraft's drag at transonic and supersonic speeds, particularly between Mach 0.75 and 1.2	a.	subsonic area rule	b.	subcritical	c.	thumbrule	d.	transonic area rule		<b>transonic area rule</b>
change in cross sectional area as smoothly as possible. This leads to a perfect aerodynamic shape known as the	a.	shark lets	b.	Sears-Haack body	c.	Supercritical	d.	winglet		<b>Sears-Haack body</b>
The Mach number in the test section of blow down tunnel is determined by pressure and temperature in the	a.	settling chamber	b.	diaphragm	c.	Wing tip vortices	d.	filter		<b>plenum</b>
Test times are limited in _____ wind tunnels	a.	suction	b.	blowdown	c.	plenum	d.	indraft tunnels		<b>blowdown</b>
A _____ is often employed downstream of the test section to shock down the supersonic flow to subsonic before entering the low pressure chamber.	a.	second throat	b.	first throat	c.	subsonic	d.	settling chamber		<b>second throat</b>
is shown in the figure, but there are other configurations of blowdown tunnels. Some blowdown tunnels, called	a.	suction	b.	blowdown	c.	third throat	d.	subsonic		<b>indraft tunnels</b>
High subsonic wind tunnels opertated at	a.	(1.2<M<5)	b.	(0.4 < M < 0.75)	c.	indraft tunnels	d.	(0.75 < M < 1.2)		<b>(0.4 &lt; M &lt; 0.75)</b>
transonic wind tunnels opertated at	a.	(1.2<M<5)	b.	(0.4 < M < 0.75)	c.	M=1	d.	(0.75 < M < 1.2)		<b>(0.75 &lt; M &lt; 1.2)</b>
A supersonic wind tunnel is a wind tunnel that produces supersonic speeds	a.	(1.2<M<5)	b.	(0.4 < M < 0.75)	c.	M=1	d.	M=1		<b>(1.2&lt;M&lt;5)</b>
_____ have short test times (usually less than one second), relatively high Reynolds number, and low power requirements	a.	Ludwig tube	b.	shock tubes	c.	(0.75 < M < 1.2)	d.	bourdan tube		<b>Ludwig tube</b>
provide test Mach numbers from 6 to 15 for run durations on the order of 1 minute	a.	3500° F	b.	3500°C	c.	density tube	d.	2500° F		<b>3500° F</b>
allow the study of fluid flow at temperatures and pressures that would be difficult to obtain in wind tunnels	a.	pitot tube	b.	Shock tubes	c.	1500° F	d.	bourdan tube		<b>Shock tubes</b>
Aerodynamics of a spinning cricket ball is related to	a.	Bernoulli's principle	b.	Magnus effect	c.	density tube	d.	Newton's second law		<b>Magnus effect</b>
Velocity potential is valid for	a.	Viscous flow	b.	Real flow	c.	Kutta condition	d.	Irrotational flow		<b>Irrotational flow</b>
Streamlined body is one for which	a.	more than skin friction drag	b.	more than profile drag	c.	Rotational flow	d.	All of the above		<b>drag is more than ressure</b>
Stalling in an incompressible flow is due to	a.	sudden expansion	b.	flow separation	c.	is more than ressure drag	d.	Isentropic expansion		<b>flow separation</b>
Lifting flow over circular cylinder is obtained by the combination of	a.	Uniform flow + source + vortex	b.	Uniform flow + sink + vortex	c.	Adiabatic compression	d.	Uniform flow + doublet + vortex		<b>Uniform flow + doublet + vortex</b>
NACA 0014 implies the airfoil is	a.	Symmetric	b.	Positively cambered	c.	Source + Sink + Uniform flow	d.	Cusped		<b>Symmetric</b>
Kutta-Joukowski theorem gives the dependence of lift per unit span on	a.	Total pressure	b.	Temperature	c.	Negatively cambered	d.	All of the above		<b>Circulation</b>
Aerodynamic center of an airfoil is the point about which	a.	Pitching moment is zero	b.	Pitching moment is constant	c.	Circulation	d.	Pitching moment is negative		<b>Pitching moment is zero</b>
Sound propagation is	a.	Isothermal process	b.	Isentropic process	c.	Pitching moment is positive	d.	Isochoric process		<b>Isentropic process</b>
When the Mach number ahead of a normal shock is Infinity the Mach number behind the normal shock is	a.	Infinity	b.	High supersonic	c.	Isobaric process	d.	Low subsonic		<b>Low subsonic</b>
The lowest value of shock angle for oblique shocks is	a.	Zero	b.	12.5 deg	c.	Zero	d.	115 deg		<b>Mach angle</b>
The maximum possible turning angle through Prandtl_Meyer expansion is	a.	130.5 deg	b.	180 deg	c.	Mach angle	d.	115 deg		<b>130.5 deg</b>
When the Mach number ahead of a normal shock is infinity the ratio of static density before and after the normal shock is	a.	infinity	b.	Finite	c.	145 deg	d.	Zero		<b>Finite</b>
corner of turning angle nearly equal to zero the shock angle is	a.	Zero	b.	45 deg	c.	proportional to the square of	d.	12.5 deg		<b>30 deg</b>
Transonic area rule is applied to the following component of airplane	a.	Wings	b.	Tail	c.	30 deg	d.	Power plants		<b>Fuselage</b>
Prandtl's relation for a normal shock is an equation consisting of	a.	Characteristic Mach numbers	b.	Static pressures	c.	Fuselage	d.	density		<b>Characteristic Mach numbers</b>
The maximum possible value of Characteristic Mach number is	a.	Infinity	b.	2.45	c.	Total pressures	d.	1		<b>2.45</b>
Mach angle is the lowest possible value of	a.	Flow turning angle	b.	shock angle	c.	2.45	d.	Characteristic Mach numbers		<b>shock angle</b>
Prandtl-Glauert rule gives the relation between	a.	Viscous and inviscid flow	b.	line integral and surface integral	c.	Angle of incidence	d.	compressible flow characteristics		<b>and compressible</b>
Small perturbation theory is applicable for	a.	circular cylinders	b.	slender bodies	c.	Streamlines and equipotential lines	d.	compressible flow characteristics		<b>slender bodies</b>
In free vortex flow the tangential velocity is	a.	proportional to radial distance	b.	proportional to radial distance	c.	spherical bodies	d.	Zero		<b>proportional to radial distance</b>
Incompressible inviscid flow can be represented by	a.	second order polynomial	b.	Fourier series	c.	independent of radial distance	d.	<b>Laplace equation</b>		<b>Laplace equation</b>
Curl of velocity vector is	a.	Acceleration	b.	component of velocity	c.	Laplace equation	d.	momentum		<b>Vorticity</b>
Viscosity of gases	a.	increases with temperature	b.	increasing temperature	c.	Vorticity	d.	increasing temperature		<b>increases with temperature</b>
Stream function is related to	a.	Volume flow rate	b.	Circulation	c.	is independent of temperature	d.	momentum		<b>Volume flow rate</b>
Sweep back results in	a.	less directional stability	b.	less longitudinal stability	c.	Angular velocity	d.	higher directional stability		<b>directional stability</b>

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