ANALYSIS AND COMPARISON OF PERFORMANCE OF A SWINGING VANE WIND ROTOR

A DISSERTATION

Submitted in partial fulfilment of the requirements for the award of the degree

of

MASTER OF ENGINEERING

in

MECHANICAL ENGINEERING

(With Specialization in Thermal Engineering)

By

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FEBRUARY, 2001

CANDIDATE'S DECLARATION

I hereby declare that the work which is being presented in the dissertation entitled, **"ANALYSIS AND COMPARISON OF PERFORMANCE OF A SWINGING VANE WIND ROTOR"**, in partial fulfillment of the requirement for the award of degree of **MASTER OF ENGINEERING** in **MECHANICAL ENGINEERING** with specialization in **THERMAL ENGINEERING**, submitted in the Department of Mechanical and Industrial Engineering, University of Roorkee, Roorkee is an authentic record of my own work carried out from July 2000 to February 2001 under the supervision of **Dr. T.K. Bhattacharyya**, Professor in the Department of Mechanical and Industrial Engineering, University of Roorkee, Roorkee.

The matter embodied in this dissertation has not been submitted by me for the award of any other degree or diploma.

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CERTIFICATE

This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

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ACKNOWLEDGEMENTS

It gives me great pleasure to take this oppurtunity to thank and express my deep sense of gratitude to my guide **Dr. T.K. Bhattacharyya,** professor, Mechanical and Industrial Engineering Department, University of Roorkee, Roorkee, for his valuable suggestions, guidance and constant encouragement during the course of the dissertation work.

I would like to thank my friends and well wishers who helped me directly or indirectly in making this report.

Finally, I express my regards to my parents, whose blessings have always been my biggest assets.

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ABSTRACT

Analysis of a vertical axis wind rotor using two and three flat swinging vanes has been carried out in this work.

Conventional horizontal axis small wind turbines are prohibitively costly and mostly based on imported sophisticated technology. This does not allow extensive use in our country for small scale, individual purpose. Apart from this, the efficient high cost wind mills require comparitively large starting wind velocity, which is not available in many states of India.

Considering all these, the development of an extremely simple vertical axis type wind mill using a new concept of few swinging vanes has been undertaken. This rotor is analyzed for performance coefficients and the results are compared with available experimental data.

NOMENCLATURE

SYMBOLS

A	Sectional area of the vane (m^2)
A_s	Swept area (m^2)
A_v	Area of the vane (m^2)
B	Number of vanes
C_D	Drag coefficient
C_{Di}	Sectional drag coefficient
C_L	Lift coefficient
C_{Li}	Sectional lift coefficient
C_T	Torque coefficient
C_P	Power coefficient
F_D	Drag force (N)
F_{Di}	Sectional drag force (N)
F_L	Lift force (N)
F_{Li}	Sectional lift force (N)
F_N	Resultant normal force (N)
F_{Ni}	Sectional normal force (N)
g	acceleration due to gravity (m/s^2)
H	Height of vane (m)
h	Manometric head (mm)

M	Moment (N-m)
M_i	Moment at a point (N-m)
P	Power produced by the rotor (W)
P_{max}	Maximum wind power intercepted (W)
r	Radial distance along the vane (m)
dr	Section width (m)
r_p	Distance at which resultant normal force acts (m)
R	Total width of the vane
R_1	Distance from rotor axis to blade tip
S_m	Specific gravity of manometric fluid
S	Specific gravity of air
T	Torque (N-m)
T_{max}	Maximum torque (N-m)
V_b	vane velocity (m/s)
V_r	Relative velocity (m/s)
V_t	Tip velocity of the vane (m/s)
V_w	Free stream wind velocity (m/s)
X	Tip speed ratio

GREEK

ρ	Density of air (kg/m^3)
θ	Blade angle (deg)
θ_1	Angle between wind velocity and blade velocity (deg)

θ_s	Angle at which torque is produced (deg)
α	Angle of attack (deg)
ω	Angular velocity of the rotor (rad/sec)
ϕ	Manometer inclination (deg)
ψ_1	Angle between resultant and resultant of lift and drag (deg)
ψ_2	Angle between drag and resultant of lift and drag (deg)

Subscripts:

b	Blade
D	Drag
i	Section
L	Lift
Max	Maximum
N	Normal
r	Relative
s	Swept
t	Tip
v	Vane
w	Wind

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Chapter 1

INTRODUCTION

Rising pollution levels and worrying changes in climate, arising in great part from energy-producing processes, demand the reduction of ever increasing environmentally damaging emissions. Generating electricity, particularly by making use of renewable resources, allows the attainment of notable reductions [11].

1.1 *Wind Resources:*

Winds are the motion of air about the earth caused by its rotation and by the uneven heating of the planet's surface by the sun. During the daytime, the air over the earth's crust acts partly as an absorber and partly as a reflector. That is, some of the Sun's energy is absorbed by the land, but a larger portion is reflected back, heating the atmosphere.

Over the lakes and oceans, a great deal of this energy is absorbed by water or is involved in evaporation; hence, this air remains relatively cool. The warmed air over the land expands, becomes lighter and rises, causing the heavier, cooler air over the bodies of water to move in and replace it. Thus, local shoreline breezes are merely a displacement of warm bodies of air by cooler masses [8].

At night the breezes are reversed, since water cools at a slower rate than land. Similar breezes are generated in valleys and on mountains as warmer air rises along the heated slopes. At night, the cooler, heavier air descends into the valleys. Fig 1.1 illustrates the generation of land and ocean wind formations.

On a broader scale, large circulating streams of air are generated by the more intense heating of the earth's surface near the equator than at the poles. The hot air from the tropical regions rises and moves in the upper atmosphere toward the poles, while cool surface winds from the poles replace the warmer tropical air [8].

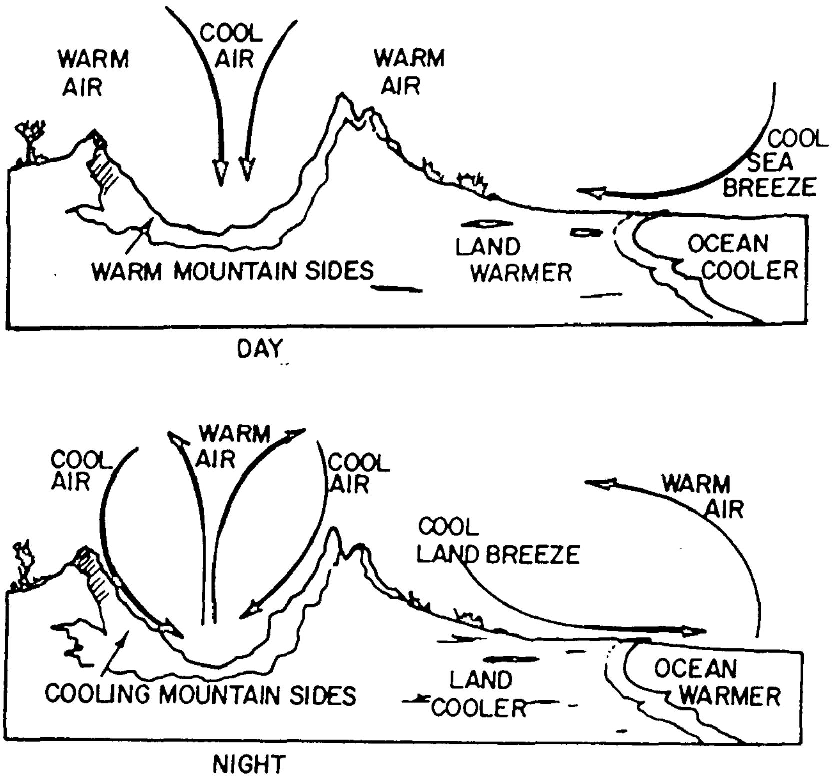

Fig. 1.1 Generation of Ocean and Land Winds

1.2 *Power in the Wind:*

Wind is merely air in motion. The air has mass though its density is low and when this mass has velocity the resulting wind has kinetic energy which is proportional to ½(mass x (velocity)^2). The mass of air passing in unit time is $\rho A_s V_w$ and the kinetic energy passing through the area in unit time is

$$P_{max}=1/2\rho A_s V_w^3$$

This is the total power available, in the wind, for extraction by a wind driven machine; only a fraction of this power can actually be extracted.

1.3 *Applications of Wind Energy:*

Energy extracted from the wind is initially energy in the form of rotary, translational or oscillatory mechanical motion. This mechanical motion can be used to pump fluids or can be converted to electricity, heat or fuel. Some of the most effective applications are those that use energy processing, conversion, or storage. However, if required, wind derived energy can be converted to other forms of energy or can be stored.

In any case, wind energy is one the most flexible and tractable of all available energy sources, since the mechanical energy derived directly from the wind can be readily and efficiently converted to other forms of energy. The efficiency of converting wind-derived mechanical energy to heat or electrical energy is usually much higher, for instance, than the efficiency of converting solar or fuel-derived heat energy since the efficiencies that can be attained when converting heat to mechanical or electrical energy are limited by the relatively low Carnot cycle efficiencies, which, even under optimum conditions, usually do not exceed 30 to 35% [3].

Some of applications are:

1. Water pumping.
2. Irrigation.
3. Grinding.
4. Large or small scale power generation.

1.4 *Advantages and Disadvantages of Wind Energy:*

1.4.1 *Advantages:*

1. It is a renewable source of energy.
2. Like all forms of Solar energy, wind power system, are non-polluting, so it has no adverse influence on the environment.

3. Wind energy systems avoid fuel provision and transport.
4. On large scales, costs are competitive with conventional electricity.

1.4.2 *Disadvantages:*

1. Wind energy is dilute and fluctuating in nature. Because of the dilute form, conversion machines have to be necessarily large.
2. Wind energy need storage means because of its irregularity.

1.5 *Cost of Energy:*

Important parameters in determining the cost of energy produced include the following [3]:

1. Wind availability at the selected site measured at some reference height (e.g., 30 feet above ground level) in terms of the annual average wind speed, or preferably in terms of the annual average velocity duration curves for that site, and including estimates of diurnal and seasonal variations in the wind speed.
2. Estimates of the expected service life time of the WECS.
3. Height above ground level and/or nearby obstructions, such as buildings, trees etc;
4. Capital costs of the WECS, include those of any energy storage or inverter units utilized by the WECS.
5. Rate structure for utility back up energy utilized, or cost of diesel generator or any other back up units utilized by the WECS.
6. Installation, operations, and maintenance costs for the WECS.
7. Interest rates on borrowed capital used to purchase the WECS.
8. Economic incentives provided by federal, state and/or local Governments, or other sources.

Capital costs are cost per rated KW of output power of the WECS. Here a factor known as 'capacity factor' is defined as ratio of the average power output of an energy system to its rated power output (fig.1.2).

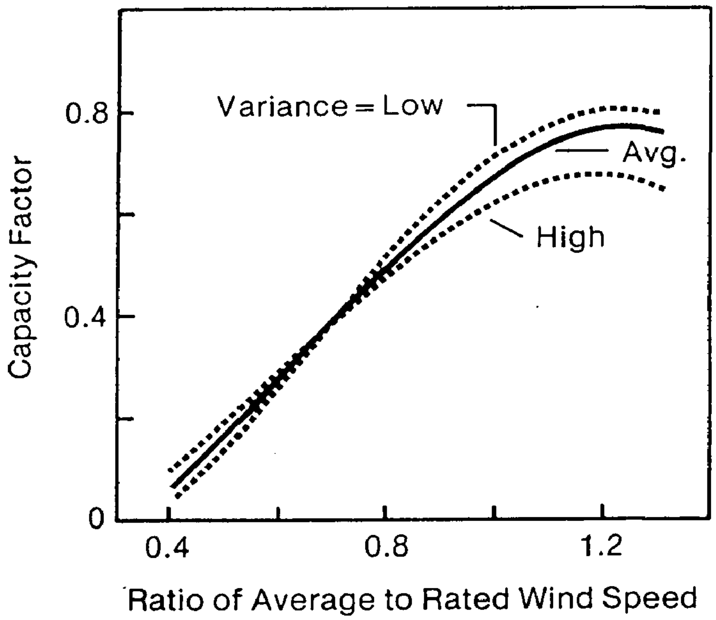

Fig. 1.2 Typical Capacity Factors for Wind Machines in Various Wind Regimes

It is often preferable to discuss capital costs in terms of average power output delivered by the system. Since wind machines may be rated at different wind speeds it may be necessary to normalize their rated output power, through the use of their estimated capacity factor for the selected site or by other means, in order to obtain useful comparisons of capital costs per unit of output power.

1.6 *Present Work:*

The present work carries out the theoretical analysis of the 'swinging vane wind rotor', which is a vertical axis wind rotor, the working principle of which is explained in chapter 4. The theoretical analysis is carried out to obtain the performance coefficients (torque and power coefficients) at various tip speed ratios and for various free stream wind velocities and the comparison is carried out with the experimental results which are available.

Chapter 2

CLASSIFICATION OF WIND MACHINES

The precise date when man first used a 'machine' to assist him in his daily work would be virtually impossible to determine, but it seems clear that the earliest machines were based on the principle of rotation as a means of providing continuous motion for routine tasks such as grinding corn or pumping water. Thus there were the mills, driven by animal -or man-power, in which the rotating shaft was vertical and was driven by a long-horizontal beam, fixed to it, and pulled or pushed round by the animal walking round-and-round in circular path. Another form was the treadmill which was driven by treading or 'walking' on vanes or paddles attached radially to its horizontal shaft [6].

2.1 History of Wind Machines:

The first wind turbines were probably simple vertical-axis panemones, such as those used in Persia as early as about 200B.C. for grinding grain.

By eleventh century A.D, wind mills were in extensive use in the Middle East and were introduced to Europe in the thirteenth century by returning crusaders. By the fourteenth century, the Dutch had taken the lead in improving the design of wind mills and used them extensively. The Dutch introduced many improvements in the design of wind mills and, in particular, the rotors [3]. Wind mills from then had many changes in the design and they are mainly classified as follows.

2.2 *Classification of Wind Machines:*

A wind turbine, is a device which uses the natural movement of free air to produce mechanical power through continuous shaft rotation. Designs use various combinations of the different parameters available, which include blade shape, number of blades, blade pitch (fixed or variable) and transmission gear ratio, in attempts to produce higher efficiency, greater reliability or reduced cost [11].

Wind machines are classified mainly in terms of the orientation of their axis of rotation, relative to wind stream.

2.2.1 *Horizontal-Axis Wind Machines:*

These are the machines for which the axis of rotation is parallel to the direction of the wind stream; typical of conventional windmills. Horizontal-axis rotors can be either lift or drag devices. Lift devices are generally preferred, since for a given swept area, high rotational speeds and more output power can be developed by lift than by drag forces. In general, a drag device cannot move faster than wind velocity, while a lift device can. Thus a lifting surface can obtain higher tip-speed ratios and, consequently, a higher power output to weight ratio.

Horizontal-axis wind machines, include the traditional corn grinding windmill, the multi-blade wind pump and the modern propeller like turbine. Either lift or drag-type rotors can be designed with different numbers of blades, ranging from one-bladed devices with a counter weight to devices with large number of blades, i.e., up to 50 or more [3].

Some horizontal-axis rotors are designed to be yaw-fixed; i.e., they cannot be rotated around a vertical axis perpendicular to the wind stream. Generally this type would only be used where there are prevailing winds from one directions. Most types are yaw-active and will "track" the changing direction of the wind. Many small-scale systems have been designed to yaw using a tail-vane, where as larger systems are often designed as down-wind rotors.

From the fig 2.1, by sweeping the blades down wind, designers gave the spinning rotor the shape of a shallow cone with its apex at the nacelle. The spinning cone naturally orients itself down wind. Coning also attempts to balance the centrifugal force of the spinning rotor against the wind's thrust on the blades to reduce the bending forces on the blade root. The coning angle varies from 1 to 2° for heavy blades to 6 to 8° for light blades [5].

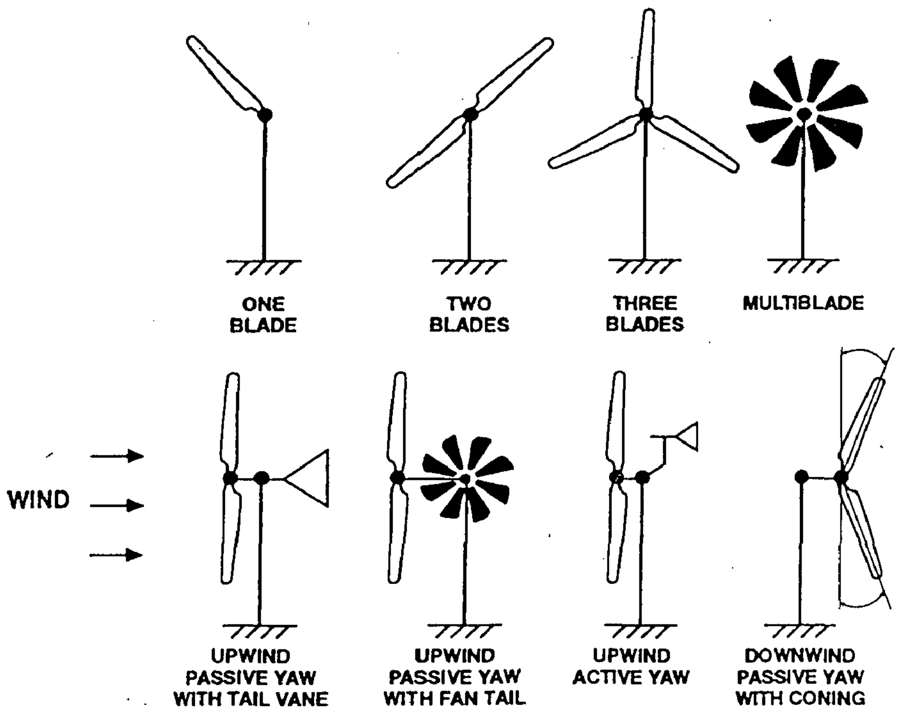

Fig. 2.1 Horizontal-Axis Wind Turbine Configurations

2.2.2 Vertical-Axis Wind Machines:

In general, vertical-axis rotors are those machines which have their axis of rotation at right angles to both the earth's surface and the direction of the wind.

The one major advantage that these systems have over the horizontal-axis rotors is that they do not have to be turned into the wind as the direction of the wind stream varies. This reduces the design complexity of the system and decreases gyro forces on the rotors, when yawing, that stress the blades, bearings, shafts, towers, and other components that are used in horizontal-axis rotors systems. Various types of vertical-axis panemones have been developed in the past that use drag forces to turn rotors of different shapes [3]. The major types of vertical-axis wind rotors are:

2.2.2.1 <u>Savonius Rotors</u>:

The Savonius-type rotors which are self-starting generally employed s-shaped blades-a minimum of two curved blades (fig.2.2). The Savonius models, like most of the various types of vertical-axis systems, are primarily drag devices, although this design does actually provide some lift force. Such devices have relatively high starting torques compared to lift devices because of their higher solidity but have relatively low tip-speed ratios than the horizontal-axis lift systems, which means lower power outputs for a given rotor size and weight [3].

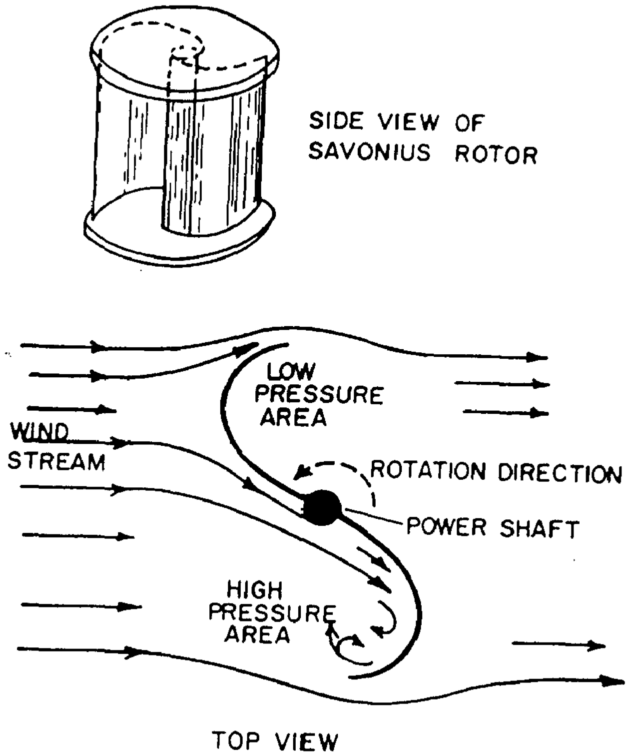

Fig. 2.2 Savonius Rotor

2.2.2.2 <u>*Darrieus Rotor:*</u>

This was invented by G.J.M.Darrieus of France in 1920's.This design is now considered a potential major competitor to the horizontal-axis propeller type systems. Darrieus-type rotors are lift devices, characterized by curved blades with airfoil cross-sections. Darrieus rotors have relatively low solidity and low starting torques, but high tip-speed ratios and, therefore, relatively high power outputs per given rotor weight and cost. Various types of Darrieus rotor configurations have been conceived including the ϕ-Darrieus and the Δ-Darrieus (fig.2.3). Such Darrieus rotors can be designed to operate with one, two, three, four or more blades. The speed of rotation of the Darrieus is primarily dependent on the machine's overall diameter. The interesting characteristic of this design is that outermost parts of the blades revolve at 3 to 4 times the wind velocity [3]. Further, in both horizontal-axis and vertical-axis groups an important sub division can be made between types having high and low solidity.

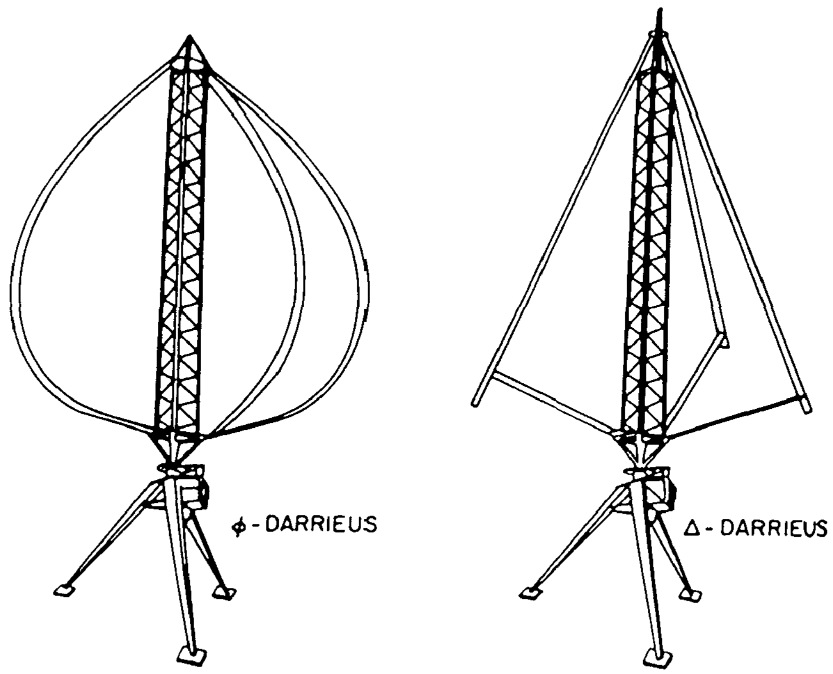

Fig. 2.3 Darrieus Rotors

2.2.3 Solidity:

The ratio of the projected area of a rotor (on a plane perpendicular to its axis of rotation) to the swept area of the rotor is known as the "solidity" of the rotor. For multi-vane fan-type rotors such as American farm windmill, a typical solidity is 0.7. For high speed lift-type propellers, on the other hand, the solidity is usually much lower, i.e., 0.1 to 0.01 [3]. Taking horizontal-axis first, the high solidity type is characterized by the traditional wind pump, having a large number of broad metal blades. This type of turbine does operate fundamentally through aerodynamic lift. The turbine is relatively heavy in construction, and torque or power control is difficult. These features possibly impose a relatively low upper limit on the size of turbine that can be successfully built in this class. However, inter-blade aerodynamic interference is high and imposes some inherent limitation on the torque and speed developed in high winds. These turbines operate at relatively large values of tip-speed ratios, generally being less than 2 [12].

Vertical-axis turbines may like wise be classified into high and low solidity types. The former may take a wide variety of forms, the physical action being dominated by drag effects and blades usually travelling more slowly than the air passing them, resulting in tip-speed ratios less than unity. The arrival of high-speed low-solidity vertical-axis turbines came with advancements in aerodynamic theory. Low-solidity rotors do have a draw back, they may not be self-starting. One solution for rotors using fixed-pitch blades, is to spin the rotor up to a speed where it can drive itself [12].

In describing the principal classes of wind turbines it is helpful to refer not only to solidity but also to the tip speed ratio of the turbine.

2.3 Tip-Speed Ratio:

It is defined as the ratio of the turbines peripheral speed to free stream wind speed.

$$X = V_t / V_w$$

Where V_t is the blade tip speed.

Although efficiency improves with increasing rotor speed, there are practical limits. Noise is directly proportional to the speed of the blade tip. Blade speed increases with rotor speed and radius. To maintain an optimum tip speed ratio for best aerodynamic performance, rotor speed will vary inversely with rotor diameter. As turbine increases in size, the speed of their rotors decrease [5]. Power coefficient versus tip speed ratio for various turbines are shown in fig. 2.4.

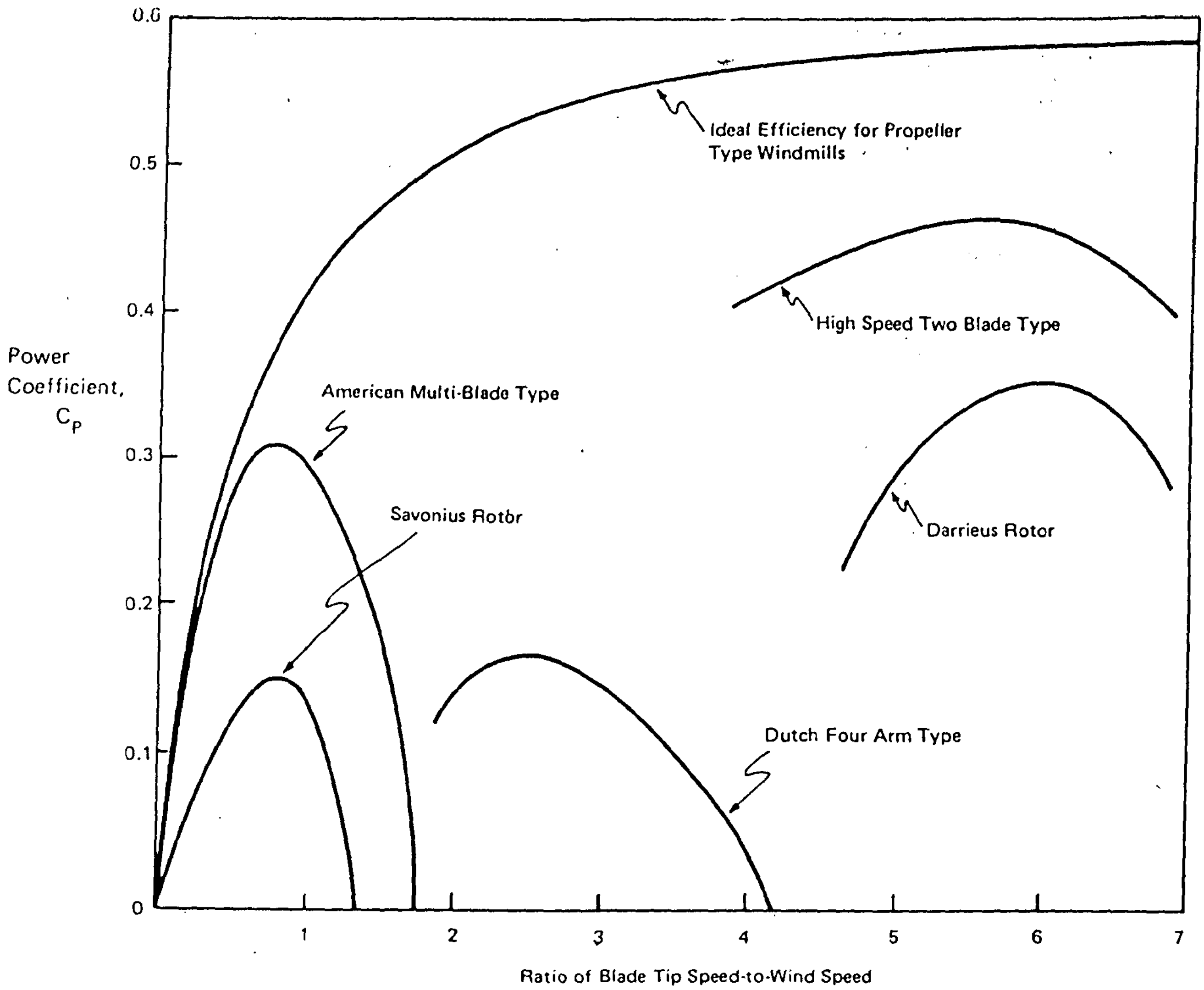

Fig. 2.4 **Typical Performances of Wind Machines**

2.4 Power Coefficient:

It is the ratio of power delivered by the system to the total power available in the cross-sectional area of wind stream subtended by the wind turbine.

$$C_P = Power/(1/2\rho A_s V_w^3)$$

Higher values of power coefficient can be achieved by making the blades of true airfoil section (there by increasing the lift and reducing the drag) and using relatively few blades, so that reasonably steady wind conditions are re-established as incident to each blade following the passage of and disturbance created by the previous one.

2.5 *Blade Materials:*

The material used for blades must be strong and yet light and must not be subjected to serious deterioration in bad climatic conditions. Blades can be made out of almost any material.

2.5.1 *Wood:*

Wood has been a popular choice. Wood is still the material of choice for many small wind machines. Laminated wood is preferable in slightly lager turbines for better control of the blade's strength and stiffness [5].

2.5.2 *Steel:*

Steel is strong, inexpensive, and well understood. Steel is limited by its great weight, and no commercial medium sized turbines use the material.

2.5.3 *Aluminum:*

Aluminum is lighter, and for its weight, stronger. Unfortunately, it has two limiting weaknesses.

(a). Al is expensive.

(b). Al is subjected to metal fatigue.

Another drawback of metal blades, whether of steel or aluminum, is television and radio interference.

2.5.4 *Fiber Glass:*

Most medium sized turbines use blades made of fiber glass [glass-fiber-reinforced polyester (GFRP)]. Like wood, fiber glass is strong, relatively inexpensive, and has good fatigue characteristics.

Rotor weight is a function of specific weight and number of blades. Most medium-sized wind turbines use three blades, because of the increased load on each blade, two-bladed turbines have typically been constructed of higher performance materials. Specific weight of a wind turbine blade (its mass relative to the area swept by the rotor) tends to increase with increasing rotor diameter, because of an exponential increase in the loads the blade must endure. Fiber glass blades are 1/3 to ½ the specific weight of blades built during the early 1980's [5].

2.6 Two or Three Blades:

A great debate rages among engineers as to whether wind turbines should use one, two or three blades. The dispute revolves around aerodynamic efficiency, complexity, cost, noise and aesthetics.

Only one blade is needed to capture the energy in the wind. To sweep the rotor disk effectively, a one-bladed turbine must operate at higher speeds than a two-bladed turbine, there by reducing the gear ratio required for the transmission, and its associated mass. But rotors using two or three blades are more efficient. British engineer John Armstrong argues that one blade captures 10% less energy than two blades. First, the blade on a one-bladed turbine must be stronger than a comparable blade on a two-bladed turbine, because it must capture twice as much energy in the wind for an equivalent output. Second, a one-bladed rotor must compensate for the weight of the missing blade by using a massive counter weight. Because of its higher speed greater aerodynamic loading, one blade will emit more noise than two. Ultimately, one-bladed rotors may provide no cost savings.

The advantages of rotors with two blades over those with three are similar to those of rotors with one blade over those with two. The rotor is cheaper, lighter, and operates at higher speeds, leading to lower-cost transmissions. Two blades are easier to install than three because they can be bolted to the hub on the ground in the position they will assume on the assembled turbine. The disadvantages of two blades are similar as well. Because of their higher speeds and greater rotor loading, they are typically noisier.

The dynamic or gyroscope imbalance of two-bladed turbines with changes in wind direction is a classic engineering challenge. The phenomenon can best be seen in the jerky or wobbly motion of small two-bladed turbines as they yaw with the wind. When the rotor is vertical, there is little resistance to yaw, but as rotor from reorienting itself reaches a maximum. Three blades effectively eliminate this imbalance, as does teetering the two-bladed rotor at the hub [5].

2.7 Over Speed Control:

The simplest method for controlling the rotor in high winds is to decrease the area of the rotor intercepting the wind. As frontal area decreases, less wind acts on the rotor. This not only reduces the power of the rotor but also reduces thrust on the blades and the tower.

When most people first consider the problem of controlling a rotor in high winds, they immediately think of changing blade pitch. Increasing or decreasing blade pitch will affect the amount of lift that the blade produces. Blades can be pitched toward stall or toward feather (fig 2.5). Twisting the blade until it is nearly parallel to its direction of travel (perpendicular to the wind) causes the airfoil to stall. Because the blade pitch is usually set a few degrees into the wind, the blade need change pitch only a few degrees to effect stall. Stall destroys the blade's lift, limiting the rotor's power, but does not reduce thrust on the rotor or the tower. On the upwind machines, thrust on the blades bend them towards the tower. Designs dependent on blade stall as the sole means of over speed protection have a poor survival record. Downwind turbines using stall regulation have had fewer problems, as the blades are forced to cone farther away from the tower. Still, they too have had an overall poor reliability record.

A blade can also be pitched toward feather by turning the blade until it is right angles to its direction of travel (a pitch of 90^0), or parallel to the wind. The pitch mechanism must act through a great distance to pitch a blade to feather than to stall. Pitching the blade to full feather cuts thrust on the blade in winds above the cut out speed to one-fifth that of a blade perpendicular to the wind.

Because controlling the pitch of the blade along its entire span requires a sophisticated pitch-change mechanism and large bearings where the blades meet the hub, variable pitch control has been limited to larger turbines. On a small upwind machine with a tail vane, the rotor can be prevented from destroying itself if it is furled out of the wind. Since tail vanes are limited to small turbines, medium-sized upwind machines and all fixed-pitch downwind machines must use a different strategy. Brakes are the most popular. In a typical fixed-pitch wind machine, the brake is applied at the cut out speed to stop the rotor. Brakes can be applied mechanically, electrically, or hydraulically. The problem with brakes is that they can fail [5].

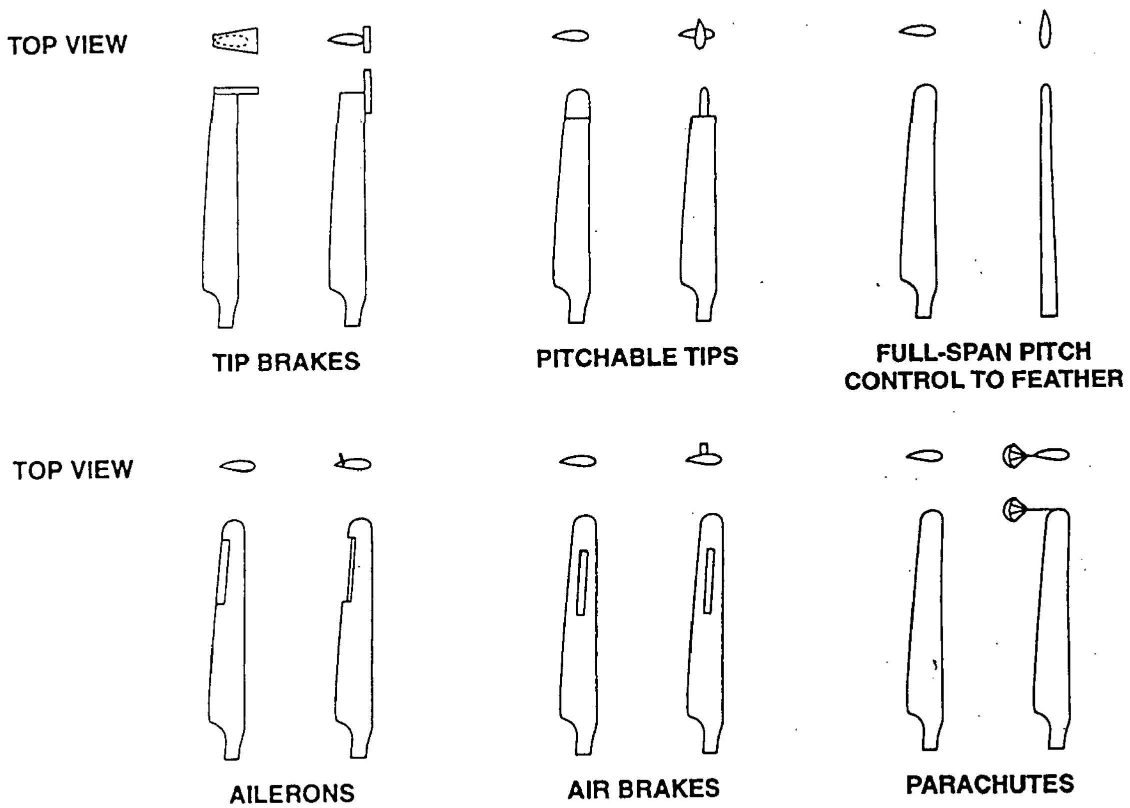

Fig. 2.5 Over Speed Control

There are three common choices for aerodynamic over speed protection on stall regulated medium-sized wind machines: tip brakes, pitchable tips, and spoilers. Tip brakes are plates attached to the end of the blade, which are activated by centrifugal force should the rotor reach excessive speed. When deployed, they increase the drag of the blade. They are simple and effective, and they have saved many a fixed-pitch rotor from destruction. Tip brakes keep the rotor from reaching destructive speeds but do nothing to reduce the lift of the blade or the thrust on the wind turbine and tower. Tip brakes are also noisy and reduce the performance of the rotor under operating conditions by increasing drag at the tip, where blade speed is greatest.

Most of the power captured from the wind is captured by the outer third of the blade. Consequently, it is unnecessary to change the pitch of the entire to limit the rotor's power. The performance of the blade in the tip region can be reduced by using spoilers or pitchable blade tips. Some medium-sized turbines have also used parachutes for emergency over speed control. Parachutes are unsatisfactory because they are difficult to reset [5].

2.8 Turbine Rating:

In this discussion, the measure of size has been rotor diameter not generator capacity. There is a good reason for this. Wind turbine ratings, in kilowatts, give only a crude indication of how much electricity a wind turbine can produce. Worse yet, ratings in kilowatts can deceive the unwary. Rotor diameter is always a much more reliable indicator.

Wind plants are dependent on the wind- the operator has no control over the fuel. All the plant operator can do is ensure that the turbines are in service when the wind is present. Sometimes the wind may not be blowing, and when it does the wind may often be insufficient to drive the turbine at its rated power. Unlike conventional plants, wind turbines seldom operate for long periods at their "rated" power.

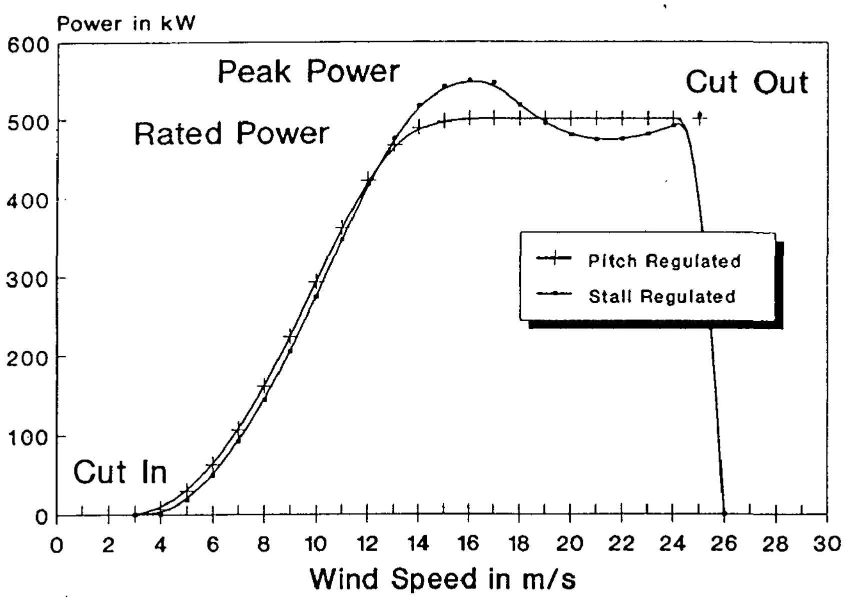

Fig. 2.6 Turbine Rating

Early wind turbine designers created a hybrid rating system that sufficed: the power output at some arbitrary wind speed. This method would work reasonably well if all agreed on the speed at which wind turbines would be "rated". But there is no international consensus on what this speed should be. Rated wind speeds vary from 10 to 16m/s. This results partly from tailoring wind turbines to different wind regimes and partly from different approaches to maximizing total generation. This rating approach also results from the early concept that turbines would reach their rated capacity, then limit output to the rated amount for wind speeds up to cutout when they would turn themselves off (fig.2.6). This is represented as a straight line on the power curve, a chart of the power produced at various wind speeds. Few wind turbines operates this neatly in the real world.

This is most apparent in wind turbines using aerodynamic stall to regulate power in high winds. Typically, power in these turbines peaks at higher than rated wind speeds, then declines until the cutout wind speed is reached. The "rated" power only approximates the power these turbines will produce at wind speeds above "rated". And among pitch-regulated turbines, the power will fluctuate above and below the rated value as the blade pitch mechanism adjusts to changing wind conditions.

Tailoring a wind turbine's performance to a specific wind regime does require a skillful matching of rotor and generator performance. If the rated speed is too low, at a very energitic site too much energy will be lost in high winds. Conversely, if the rating is too high, performance at a less energitic site will suffer. Picking a rated speed is as much an art as science, because gear boxes and generators not manufactured in continuous increments. Only discrete sizes are available. The rated capacity and the size of the gear-box and generator are partly determined by the manufacturers of the generator and gear-box [5].

Chapter 3

PERFORMANCE OF SWINGING VANE WIND ROTOR

Importance of swinging vane wind rotor is briefly outlined as follows [4]:

(i). The swinging vane wind rotor using plane swinging vanes has a simple design and fabrication does not require any sophisticated technology compared to other types of wind mills.

(ii). The swinging vane wind rotor is less costly compared to the other available types of wind mills using sophisticated design and components.

(iii). Installation, repair and maintenance of this type of wind mill can be carried out by local rural technology.

(iv). This swinging vane wind rotor works even at a low wind velocity.

3.1 Working Principle Of Swinging Vane Wind Rotor:

The working principle of the swinging vane wind rotor (fig 3.1) is best understood by considering two flat vertical vanes on two sides of the vertical axis of the rotor. The vanes are not directly attached to the vertical shaft, rather the radially outermost vertical edges of the vanes are pivoted on two arms fixed to the vertical shaft. Each vane can swing about its outer vertical edge, but stoppers are used so as to allow the vane to swing in one direction from its radial position but not in the other direction. The combined action of such two vanes on two sides of the vertical shaft is to allow free flow of wind through one side of the axis and to resist flow on other side all the time when wind blows over it. Thus the rotor goes on rotating in one direction while the vanes swing open and close as these change sides during each rotation .

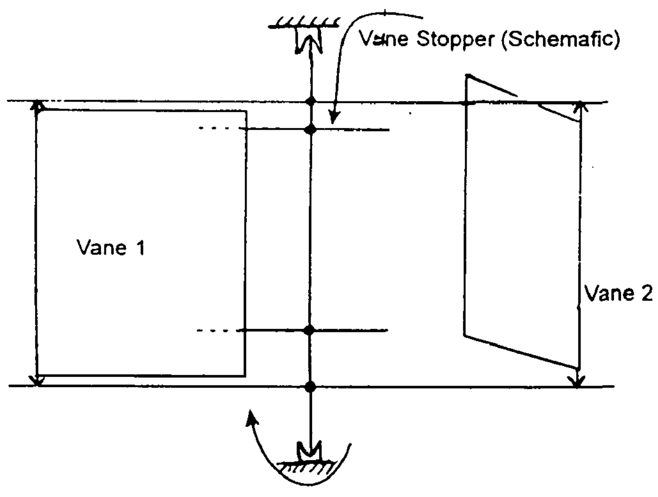

Fig. 3.1 Swinging Vane Wind Rotor-Working Principle

3.2 Lift and Drag Forces:

Lift force is the force of the wind perpendicular to the relative velocity of the wind (Fig 3.2).

$$F_L = C_L . 1/2 \rho A_v V_r^2 \quad \text{--------} \quad (3.1)$$

Drag force is the force along the relative velocity (Fig 3.2).

$$F_D = C_D . 1/2 \rho A_v V_r^2 \quad \text{---------} \quad (3.2)$$

Where C_L and C_D are the lift and drag coefficients respectively. These coefficients can be determined experimentally for any profile and they vary with the angle of attack 'α', which is the angle made by the relative velocity with the surface of the vane.

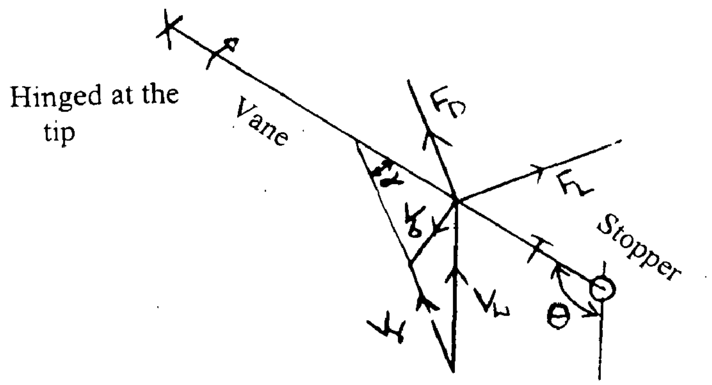

Fig. 3.2 **Lift and Drag Forces on Vane**

3.3 *Experimental Procedure to Determine Lift and Drag Coefficients:*

Analysis of the swinging vane wind rotor requires knowledge of lift and drag forces on a flat plate at various angles of attack. Such results are available in literature only for a limited range of angle of attack, say up to 20°. As such an experiment has been carried out to cover other angles of attack.

Experimental Set Up:

Experimental set up is shown in fig 3.3. The vane is suspended from a frame by four elastics at four corners of the vane. These four elastics are calibrated seperately and the calibration curves of the four elastics are shown in fig 3.4(a-d). Calibration is done by applying force using standard weights to the elastics and the elongation of the elastics are measured. Calibration curve is plotted as force versus elongation.

The elastics have tube and threads on both ends. At one end thread is attached to the frame and at the other, thread is attached to the vane. The whole frame is fixed to the base with nut and bolt, so that it can be rotated to any degree on the base on which degrees are marked (fig 3.5b). The whole set up is kept in front of a blower, from which wind is blown at a certain velocity, which is measured with Pitot-Static tube connected to an inclined manometer (fig 3.5a) with methyl alcohol. The velocity calculations are shown in the appendix-A. The plate is positioned at perpendicular to the wind direction, which is taken as zero degree. The plate gets displaced from its position as the wind acts on it, as the elastics gets expand. The x, y and z coordinates of the four corners of the vane are measured with the help of a stand (fig 3.5a). The resultant elongations of the elastics is obtained after removing the initial length, thread and tube lengths. So, the force on the vane can be obtained from the calibration curves of the elastics after knowing the final elongations at four points (fig 3.4 a to fig 3.4 d).

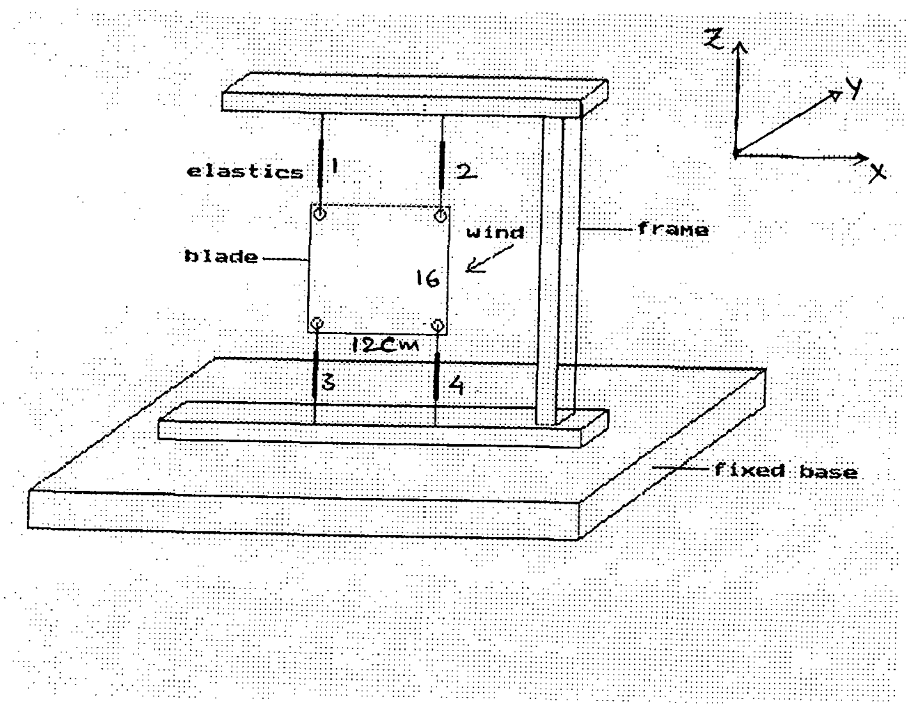

Fig. 3.3 Experimental Set Up

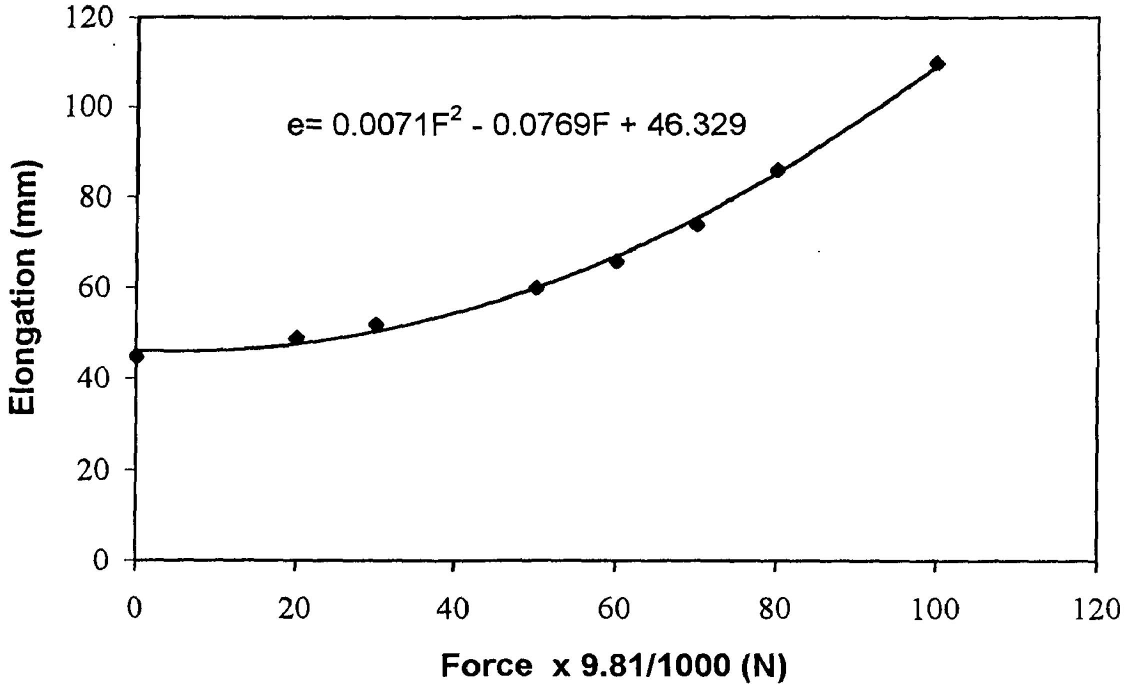

Fig. 3.4a Calibration Curve of Elastic-1

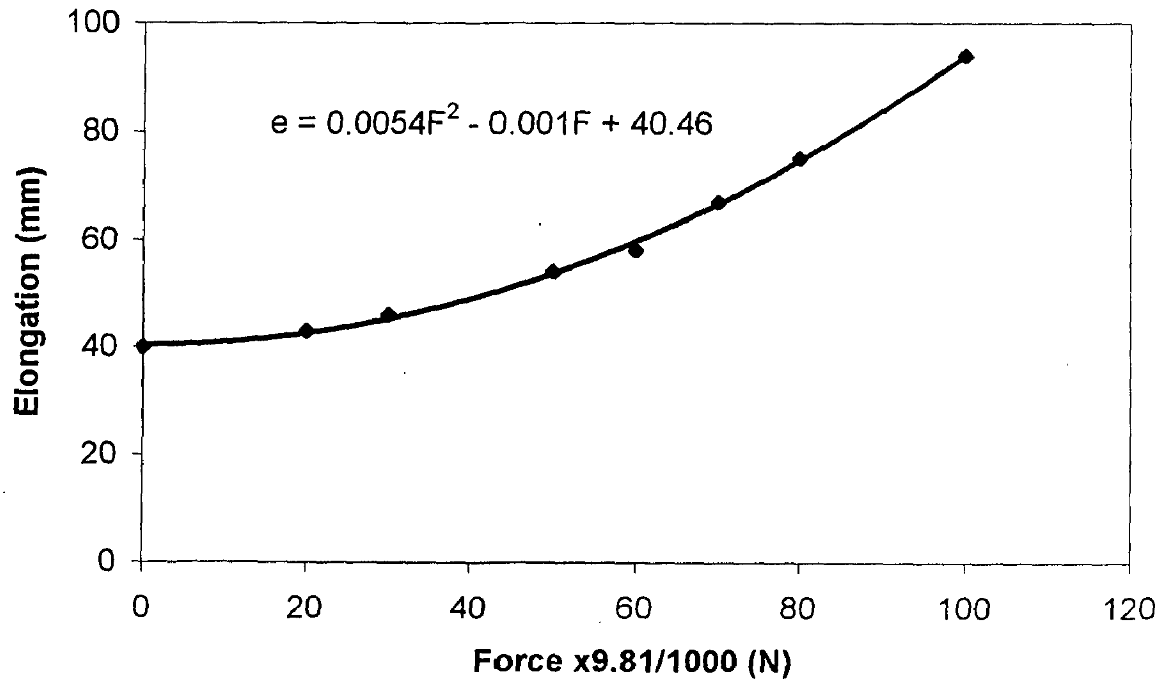

Fig. 3.4b Calibration Curve of Elastic-2

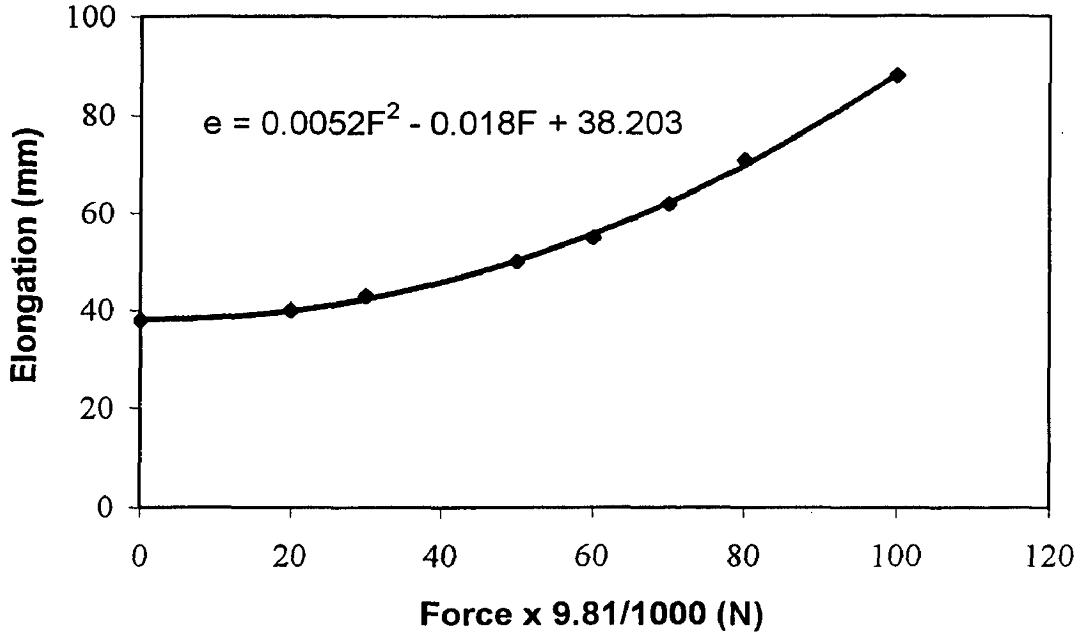

Fig. 3.4c Calibration Curve of Elastic-3

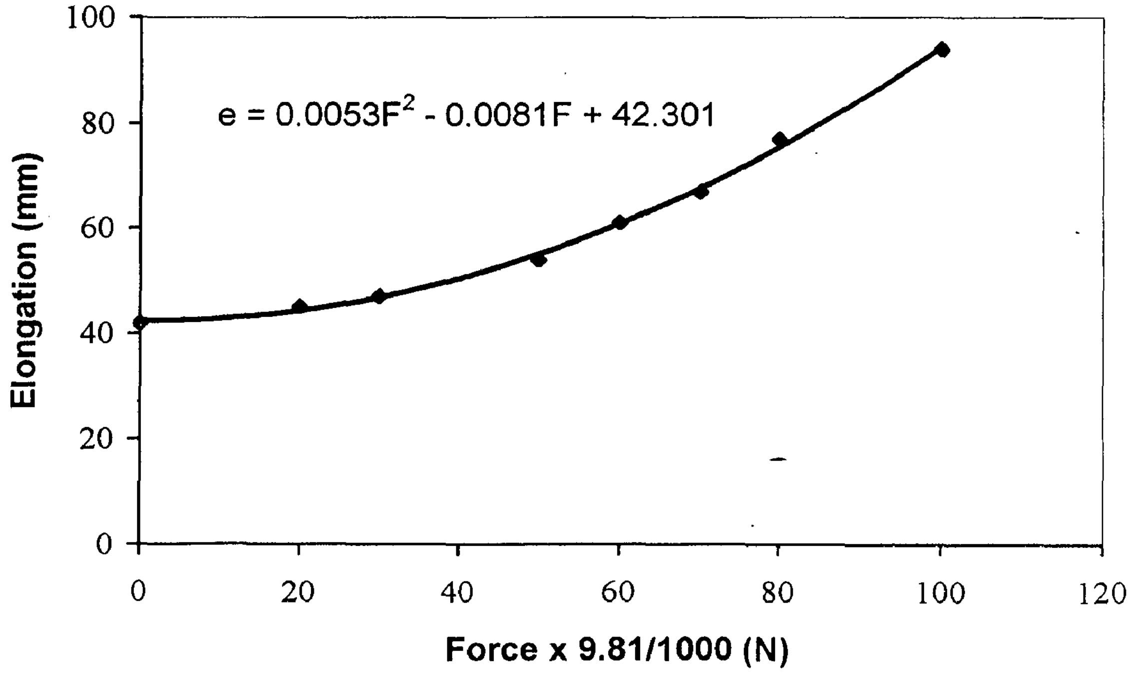

Fig. 3.4d Calibration Curve of Elastic-4

Fig. 3.5a Photograph of Experimental Set Up (front View)

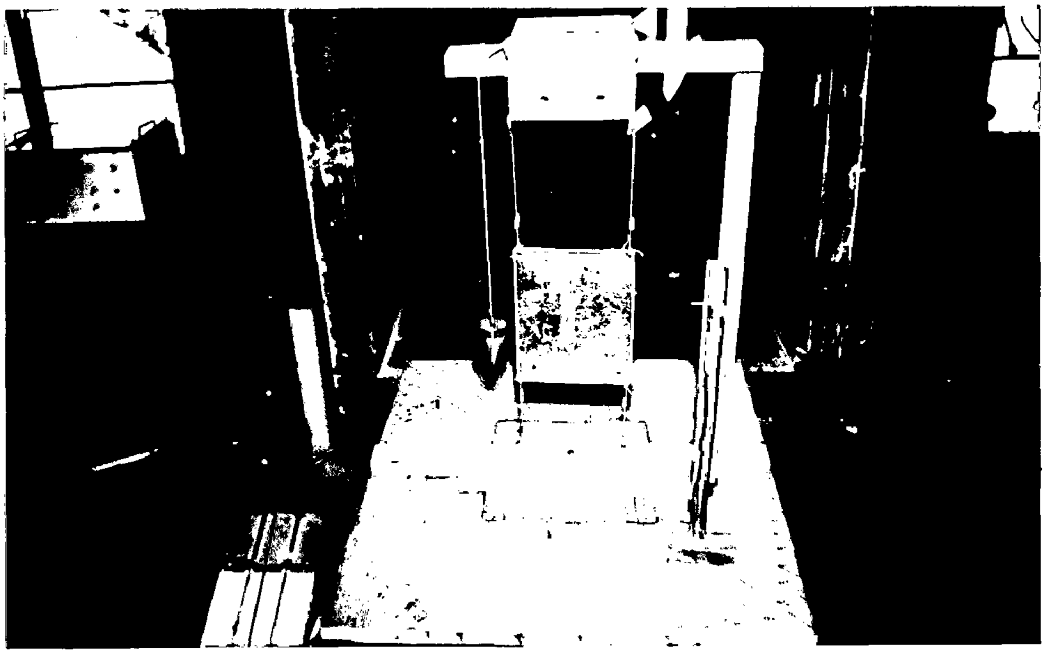

Fig. 3.5b Photograph of the Experimental Set Up (top view)

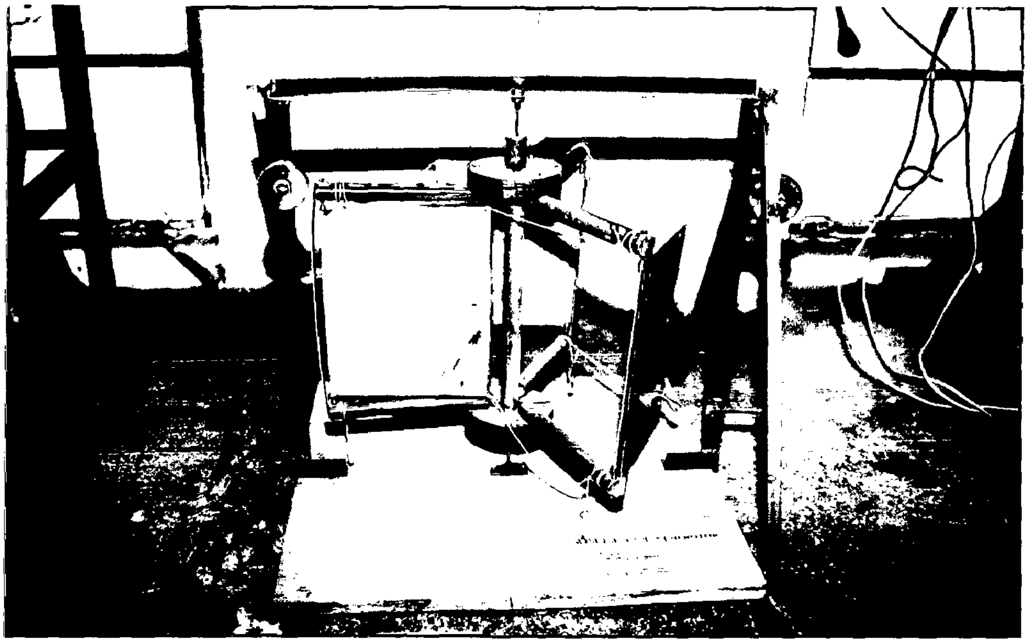

Fig.3.6 Photograph of Three Bladed Swinging vane Wind Rotor

Here, relative velocity is the free stream wind velocity and the force at every point is resolved into the lift and drag forces, which are perpendicular to the velocity and along the velocity. The total lift and drag forces are obtained by summing the forces at every point. The lift and drag coefficients are calculated as follows.

$$C_L=F_L/(0.5\rho A_v V_r^2) \quad \text{-------} \quad (3.3)$$

$$C_D=F_D/(0.5\rho A_v V_r^2) \quad \text{-------} \quad (3.4)$$

The above calculated lift and drag coefficients are for a particular angle of vane, which is zero here. The frame is then rotated to 5° which is marked on the base. The above procedure is repeated for the position of the vane up to 40° (that is for angle of attack from 90°-50°). For angles greater than 40°, it became difficult to take the measurements as vortices increased behind the vane which made the vane to oscillate.

The lift and drag coefficients are available from 0°-20° of the angle of attack for flat plate [1] and are shown in fig 3.7 and 3.8, for the flat plate which is 2-dimensional as the vane is of infinite span. Lift and drag coefficients for various angles of attack from 50°-90°, which are determined experimentally are shown in fig 3.9 and 3.10, for the vane which is 3-dimensional as the vane is of finite span [1]. The experimental uncertainty for these coefficients is found be 11.5% as detailed in Appendix-B. The lift and drag coefficients between 20°-50° angle of attack are approximated by simply curve fitting the results as vortex effects made experiment difficult.

A computer program is written for the entire procedure, to calculate the lift and drag coefficients. Experimental results and computer program are shown in Appendix-B and Appendix-C respectively.

Tab. 3.1 Calibration of Elastics

S.No	Force ×9.81/1000 (N)	Length (mm)			
		Elastic 1	Elastic 2	Elastic 3	Elastic4
1	20	49	43	40	45
2	30	53	46	43	47
3	50	60	54	50	54
4	60	66	58	55	61
5	70	74	67	62	67
6	80	86	75	71	77
7	100	110	94	88	94

Tab. 3.2 Lift and Drag Coefficients for flat plate from α =0° to α =20° (available)

S.No	Angle of Attack (deg)	Drag Coefficient	Lift Coefficient
1	0	0.01	0
2	2.5	0.025	0.25
3	5.0	0.055	0.48
4	7.5	0.11	0.57
5	10.0	0.138	0.61
6	12.5	0.183	0.68
7	15.0	0.24	0.71
8	17.5	0.29	0.73
9	20.0	0.31	0.74

Tab. 3.3 Lift and Drag Coefficient for Flat Plate from α =50° to α =90°
(from Experimental)

S.No	Angle of Attack (deg)	Drag Coefficient	Lift Coefficient
1	50	0.928	0.5200
2	55	1.085	0.5940
3	60	1.004	0.465
4	65	1.062	0.4024
5	70	1.136	0.3680
6	75	1.209	0.2515
7	80	1.236	0.2110
8	85	1.267	0.1143
9	90	1.280	0.0080

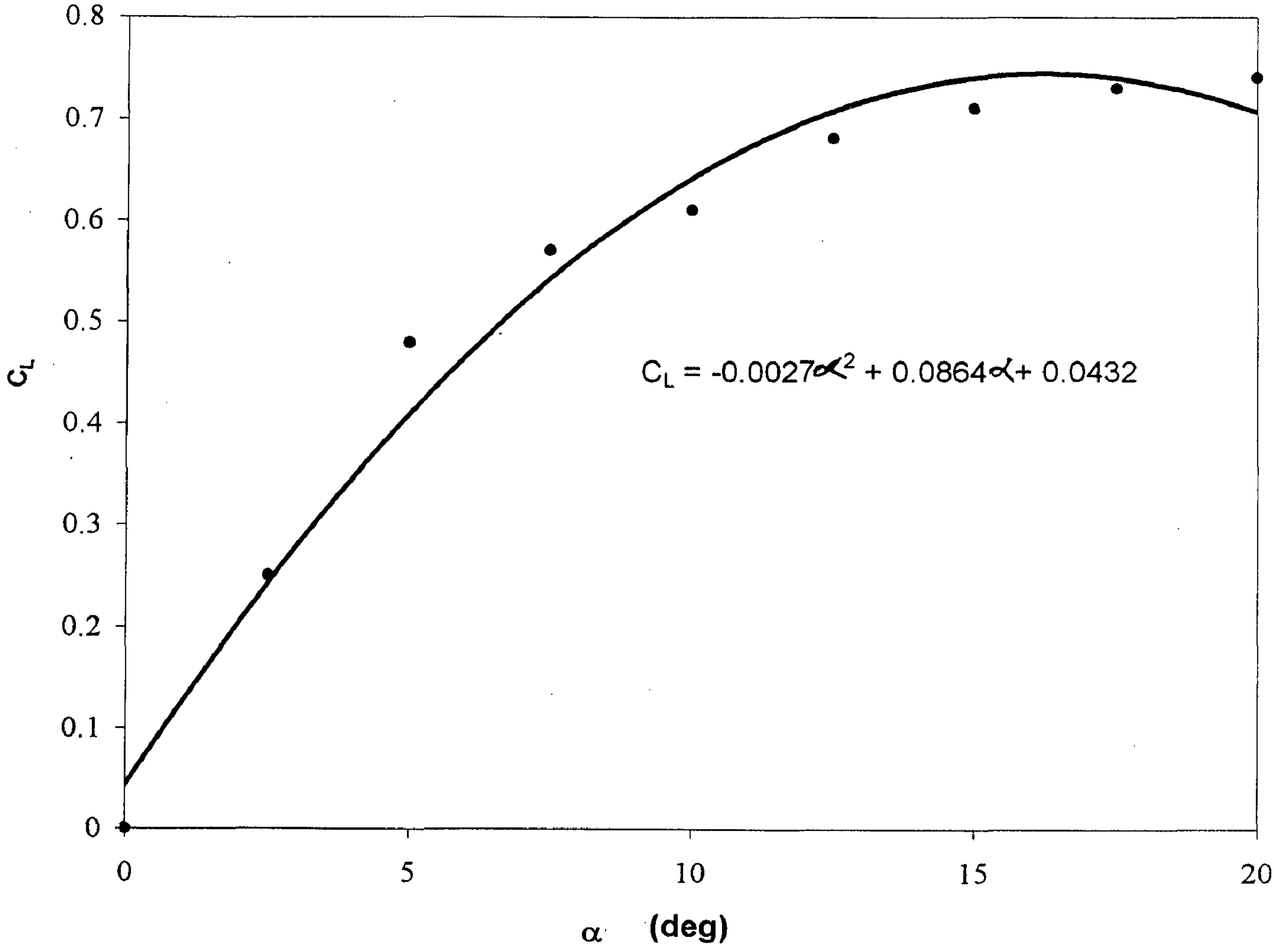

Fig. 3.7 Lift Coefficient for $\alpha = 0°\text{-}20°$

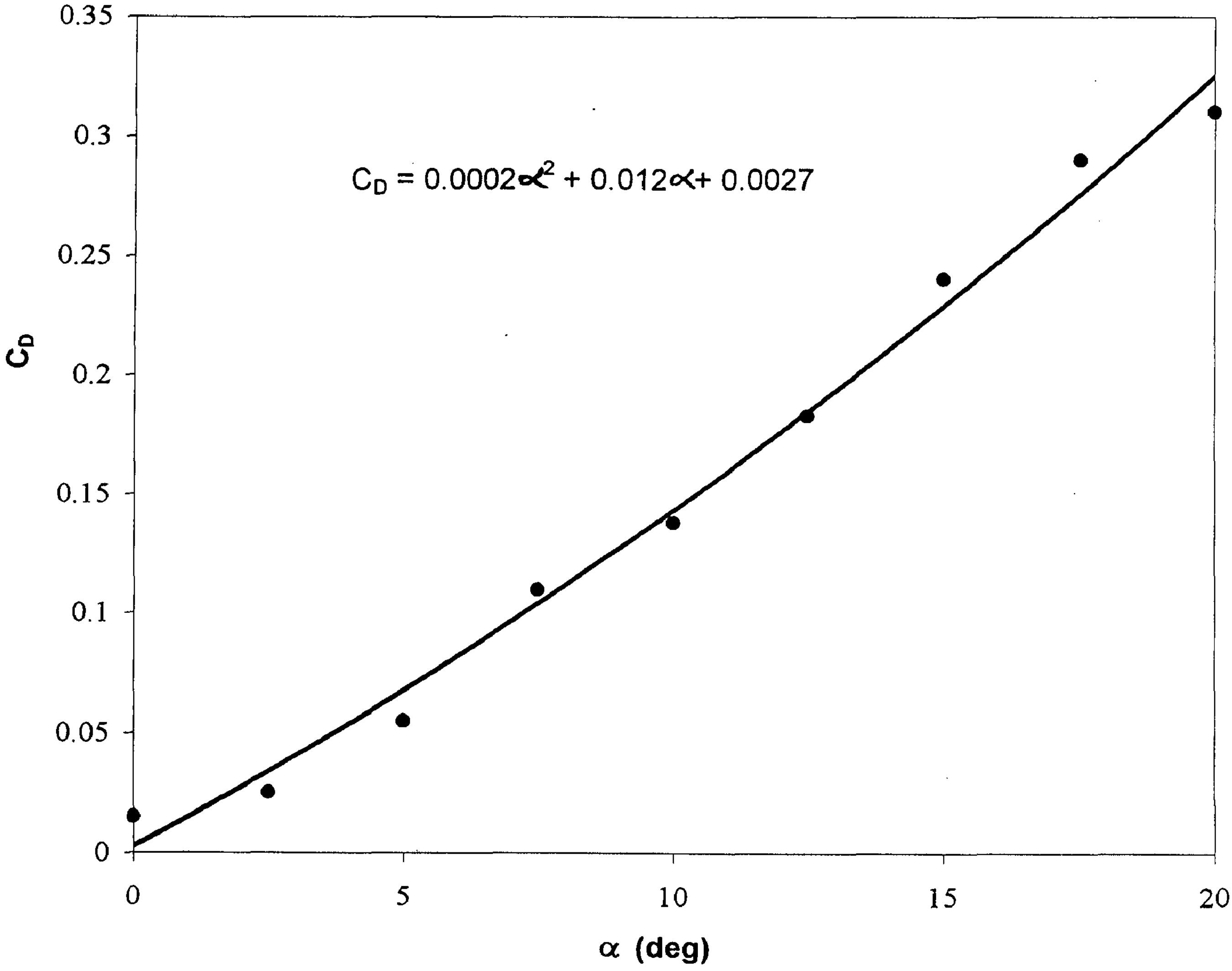

Fig. 3.8 Drag Coefficient for $\alpha = 0°$-$20°$

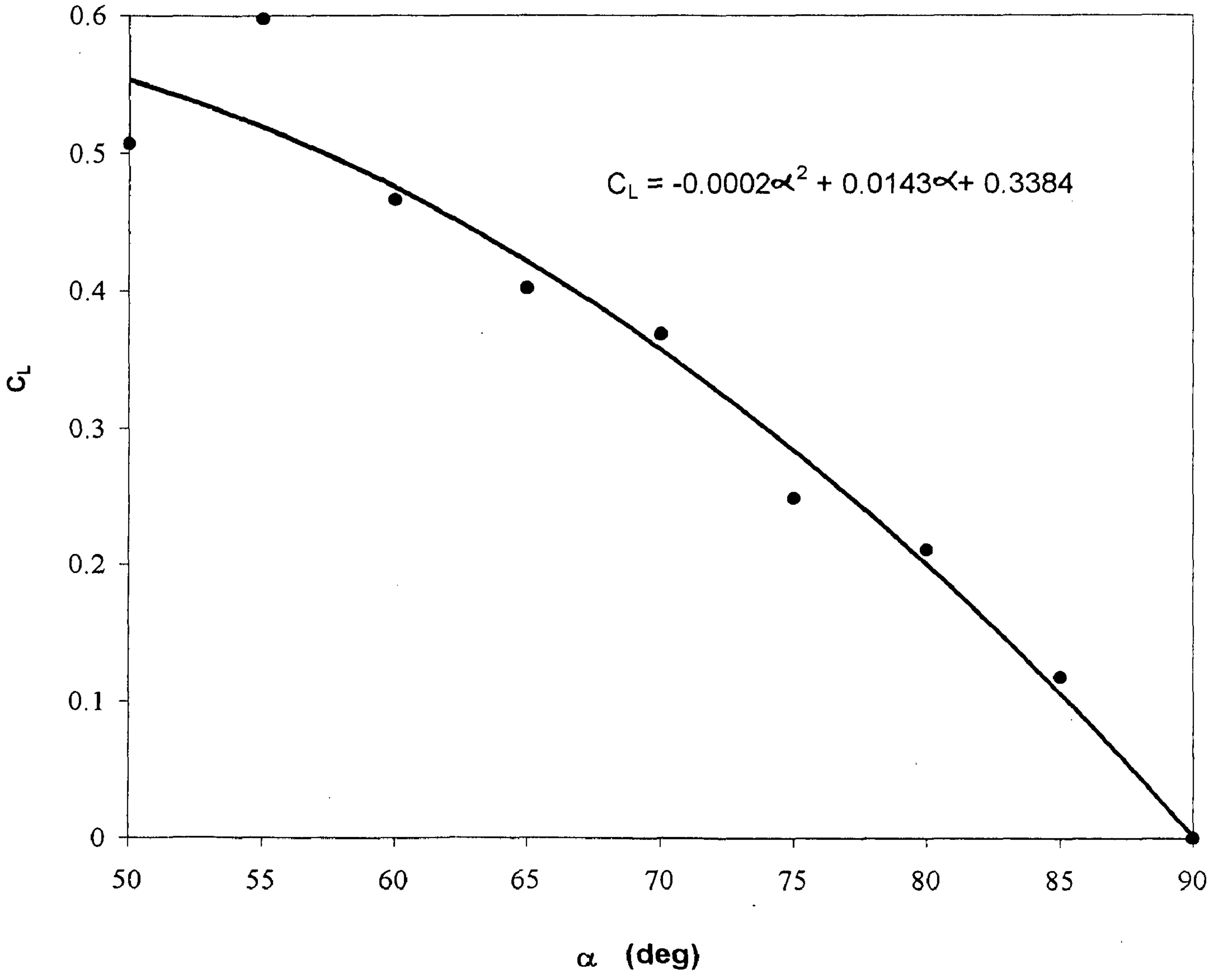

Fig. 3.9 Lift Coefficient for $\alpha = 50°\text{-}90°$

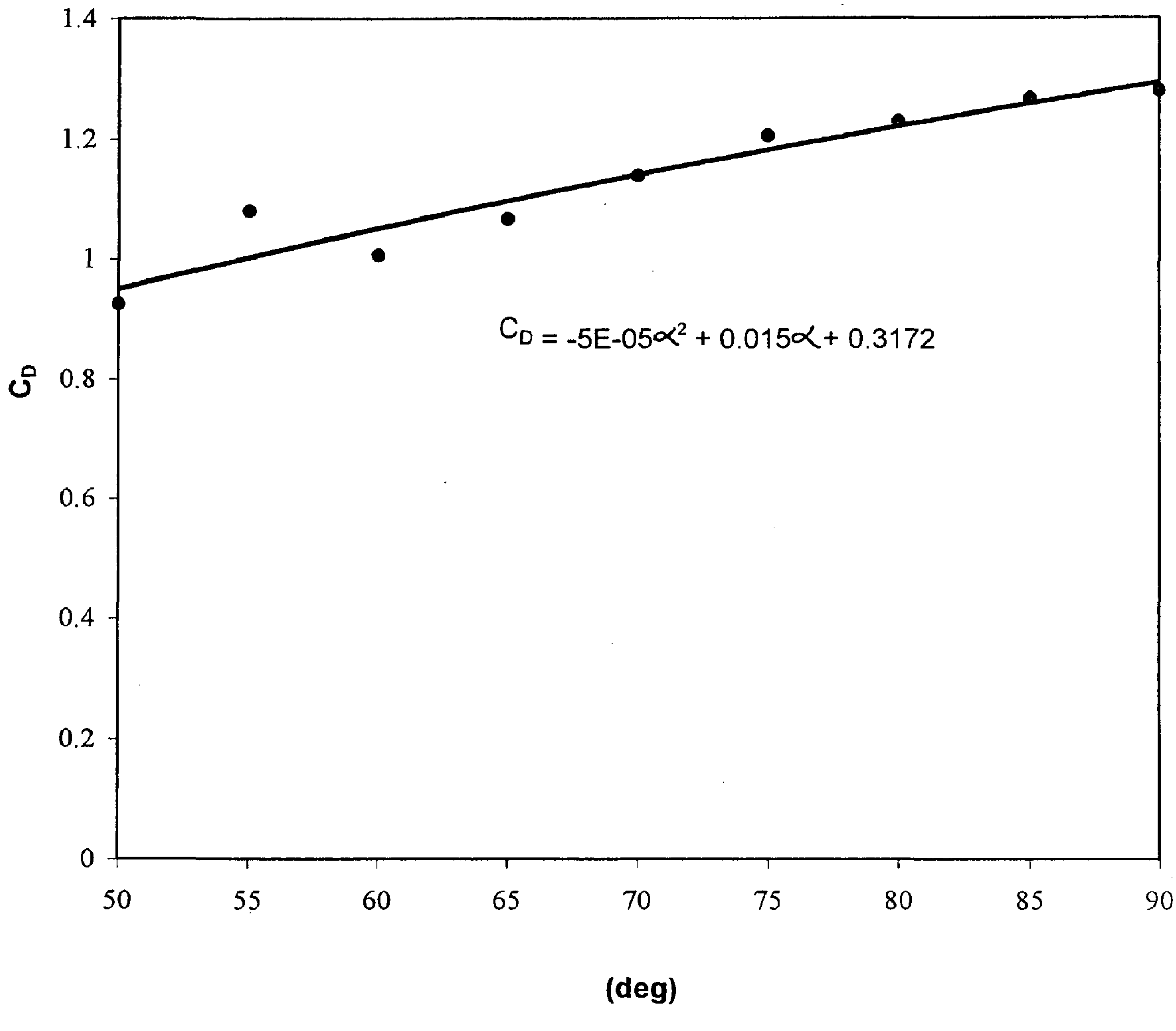

Fig. 3.10 Drag Coefficient for $\alpha = 50°\text{-}90°$

3.4 *Methods for Predicting The Performance:*

Some of the methods for predicting the performance of propellers or windmills are outlined as follows:

AirScrew Theory :

An airscrew may be defined as any type of mechanism with radial blades designed to rotate about its axis during its motion relative to the air, and such airscrews may be used for a variety of purposes. The principal types of airscrews are propeller, windmill, fan and anemometer. From an early period the development of theory followed two independent lines of thought, which may conveniently called the momentum theory and the blade element theory respectively [ ].

Axial Momentum theory:

The function of a propeller or any similar propulsive system is to give a forward thrust along its axis, and this thrust is obtained by imparting a backward motion to the fluid in which it operates. The production of the thrust is therefore inevitably associated with a certain loss of energy which is represented by the kinetic energy of the motion of the fluid [2].

General Momentum Theory:

The axial momentum theory was developed on the assumption that there was no rotational motion in the slipstream and that the propeller could be replaced by an actuator disc which produced a sudden increase of pressure in the fluid with out any change in velocity. To extend the theory to include the effects of this rotational motion it is necessary to modify the qualities of the actuator disc by assuming that it can also impart a rotational component to the fluid velocity while the axial and radial components remain unaltered [2].

Blade Element Theory:

The momentum theory of propeller, is based on a consideration of the mean axial and rotational velocity in the slipstream, and determines the thrust and torque of a propeller from the rate of increase of momentum of the fluid. An alternative method of determining the performance of propeller is to estimate directly the forces experienced by the blades of the propeller due to their motion through the air [2].

Vortex theory:

The vortex theory is based on the conception that trailing vortices spring from the rotating blades of the propeller and pass down the slipstream in the form of helical vortex sheets. The interference velocity experienced by the blades of the propeller must be calculated as the induced velocity of this vortex system, and the aerodynamic reaction on any blade element is derived from this modified system of velocities in association with airfoil characteristics corresponding to two-dimensional motion. The calculation of these induced velocities is very complex and the analysis is therefore usually based on the assumption that the propeller has a large number of blades [2].

3.5 Analysis using Blade Element Theory:

A relatively simple method of predicting the performance of wind mills, is the use of Blade Element Theory. In this method the vane is divided into number of independent sections along the length. At each section, normal force is found using 2-dimensional sectional drag and lift coefficients.

When θ>=0° and θ<=180°

Angle of attack is calculated for $V_w > V_b.\cos\theta_1$, here θ_1 is the angle between the wind and blade velocity.

$$\alpha = \tan^{-1}((V_w - V_b.\cos\theta_1)/(V_b.\sin\theta_1)) \text{ ------- } (3.5)$$

$$\theta_1 = 90\text{-}\theta \text{ (for } \theta\text{>=0 and } \theta\text{<=90)}$$

$$\theta_1 = \theta\text{-}90 \text{ (for } \theta\text{>90 and } \theta\text{<=180)}$$

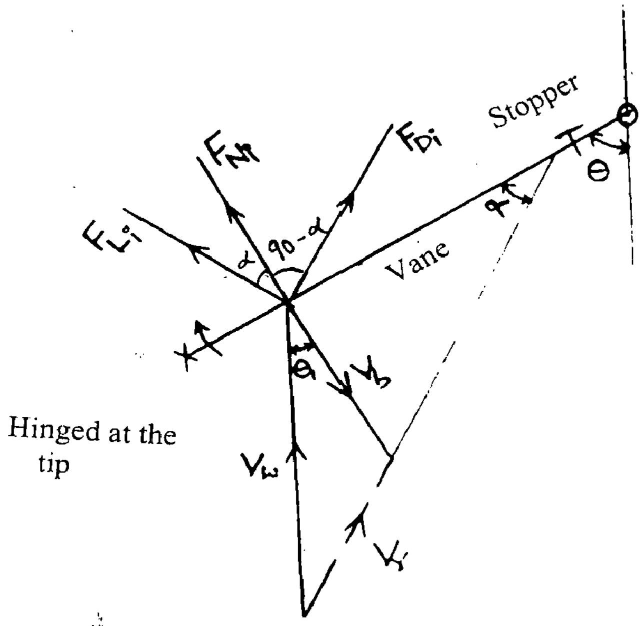

Fig. 3.11a Normal Force on the Vane for θ< 90°

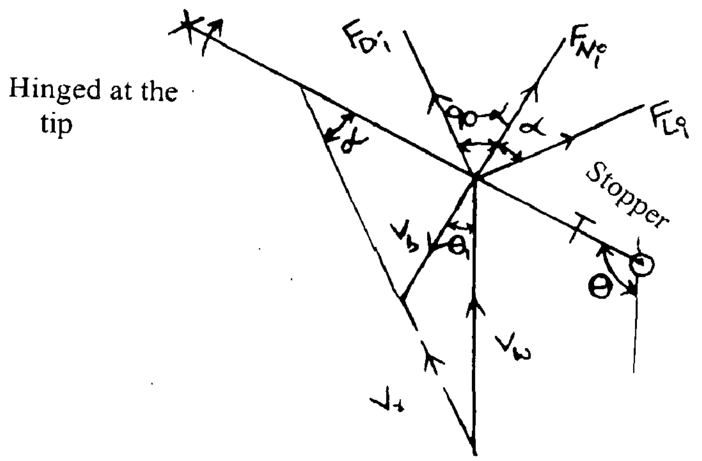

Fig. 3.11b Normal Force on the Vane for θ> 90°

Section normal force is calculated as

$$F_{Ni} = F_{Di}.\cos(90-\alpha) + F_{Li}.\cos\alpha$$

$$F_{Ni} = (C_{Di}.\sin\alpha + C_{Li}.\cos\alpha).1/2\rho AV_r^2 \text{ -------(3.6)}$$

Where $V_r = V_w - V_b.\cos\theta_1$

C_{Di} and C_{Li} are the 2-dimensional sectional drag and lift coefficients which are experimentally found, but the experimentally found values are 3-dimensional drag and lift coefficients. Here, 3-dimensional drag is converted to 2-dimensional drag coefficient by multiplying the 3-dimensional drag coefficient with a constant [1].

So, the normal force for every section is found and the summation gives the resultant normal force.

$$F_N = \Sigma F_{Ni} \text{ -------- (3.7)}$$

The moments at all points are calculated as

$$M_i = F_{Ni}.r_i \text{ --------- (3.8)}$$

The total moment is given as

$$M = \Sigma M_i \text{ --------- (3.9)}$$

The point of application of the resultant normal force is determined as follows

$$r_p = M/F_N \text{ --------- (3.10)}$$

After determining the point of application, torque is determined as

$$T_j = F_N.(r_p+(R_1-R)) \text{ --------- (3.11)}$$

The whole rotation of the rotor is divided into number of angular divisions. The above calculated torque is for a particular degree. At every blade angle the torque is calculated from 3.11, for one complete rotation of the rotor.

A_s, is the swept area which is R.H for two bladed rotor as well as three bladed rotor as it assumed that the wind flows freely on the right side of the axis.

Torque coefficient C_T, is calculated for 2- and 3-bladed rotor as follows :

First the average torque on the rotor is calculated after calculating the total torque for one revolution of the rotor. The total torque is the sum of the individual torques at every blade angle, for the first 180° revolution of the rotor one vane will produce the torque, and for the next 180° second vane will produce the torque. For three bladed rotor each vane will produce the torque for 120°. The torque coefficient is then calculated as follows

$$\text{Average torque} = \text{total torque}/360 \text{ -------- } (3.12)$$

$$C_T = \text{average torque}/(0.5\rho A_s V_w^2 R_1) \text{ ----- } (3.13)$$

The power coefficient for the rotor at a particular angular velocity is determined as:

After calculating the average torque power coefficient is calculated as follows

$$\text{Power} = \text{average torque} \times \text{angular velocity} \text{ ----- } (3.14)$$

$$C_P = \text{Power}/(0.5\rho A_s V_w^3) \text{ ------ } (3.15)$$

Like wise, torque, power, torque coefficients and power coefficients for various angular velocities and for various wind velocities are determined. The results are presented in results and discussion chapter.

A computer program is made to determine the performance of 'swinging vane wind rotor' which is given in Appendix-D.

ALGORITHM FOR PROGRAM 2

Step1: Free stream wind velocity, vane dimensions, width of sections on the vane, angular divisions are input to the program.

Step2: The first loop assumes angular velocity of the rotor.

Step3: Using the inner for loop, sectional normal force at evry section on the vane is calculated from equation 3.6, in which angle of attack is obtained from equation 3.5 according to the blade angle and sectional lift and drag coefficients are calculated by knowing the angle of attack from equations fitted from the figs 3.7 to 3.10.

Step 4: Step 3 is repeated until the condition $V_w > V_b \cos\theta_1$ is satisfied and the total normal force is obtained as the sum of the sectional normal forces.

Step 5: Similarly moments at every point are calculated from equation 3.8 and total moment is obtained as sum of the individual moments. Then the point of application of resultant normal force is obtained from equation 3.10. Torque is calculated as the resultant force times the point of application from the rotor axis from equation 3.11.

Step 6: Steps 3,4 and 5 are repeated for different blade angles using the middle for loop and the total torque is obtained as the sum of all the toruqes, then average torque is obtained.

Step 7: Torque, power, Torque and power coefficients are obtained from the equations for two and three bladed rotor.

Step 8: Steps 3, 4, 5, 6 and 7 are repeated for different angular velocities using the outer for loop.

Chapter 4

RESULTS AND DISCUSSION

After analysing the swinging vane wind rotor theoretically for performance coefficients, the results are presented for various wind velocities and at various tip speed ratios (Table.4.1 to 4.6).

4.1 Effect of Free Steam Wind Velocity on Performance Coefficients:

After obtaining the curves for performance coefficients, it is observed there is not much variation in performance coefficients with variation in free stream wind velocities, but in actual case the performance coefficients are high at low wind velocities and decreases as wind velocities increases. In the theoretical analysis wake effects are not considered, which are actually present, which decreases the performance of the rotor and as the wind velocity increases that is at higher velocities turbulence increases and wake effects are increased and this the reason for the low power coefficients at higher wind velocities in actual case.

4.2 Effect of Tip Speed Ratio on Performance Coefficients:

As the tip speed ratio increases, power coefficient increases up to a certain value and then decreases, if further tip speed ratios are increased (fig 4.4 to 4.6). Unlike power coefficient, the torque coefficient does not have ups and downs but it decreases continuously with increase in tip speed ratios (fig 4.1 to 4.3). This trend is observed for both experimental results and theoretical results, but at a certain tip speed ratio, which is different for both two and three bladed rotor, the power coefficient and torque coefficients are becoming zero for experimental results. The performance coefficients in

Tab. 4.1 Performance Coefficients for Two Bladed Rotor at V_w = 2.0m/s

Max Torque=0.01558 N-m ; Max Power=0.1623 W

S.No	Tip speed ratio	Torque (N-m)	Power (W)	Torque coefficient	Power coefficient
1	0.0001	0.01255	0.00012	0.80569	0.0007
2	0.289	0.01000	0.03010	0.64324	0.1854
3	0.577	0.00790	0.04748	0.50712	0.2925
4	0.865	0.00618	0.05569	0.39675	0.3431
5	1.153	0.00377	0.04536	0.24245	0.2795
6	1.440	0.00227	0.03406	0.14567	0.2099
7	1.729	0.00125	0.02261	0.08058	0.1393
8	2.017	0.00877	0.01844	0.05634	0.1136

Tab.4.2 Performance Coefficients for Two Bladed Rotor at V_w = 3.0m/s

Max Torque=0.03505 N-m ; Max Power=0.5477 W

S.No	Tip Speed Ratio	Torque (N-m)	Power (W)	Torque Coefficient	Power Coefficient
1	0.0001	0.02948	0.00030	0.84122	0.0005
2	0.192	0.02707	0.08148	0.77235	0.1487
3	0.384	0.02349	0.14117	0.67023	0.2577
4	0.576	0.01973	0.17776	0.56312	0.3245
5	0.768	0.01612	0.19360	0.46013	0.3535
6	0.960	0.01196	0.17952	0.34124	0.3277
7	1.152	0.00853	0.15362	0.24356	0.2805
8	1.344	0.00650	0.13656	0.18543	0.2493
9	1.536	0.00493	0.11837	0.14078	0.2161
10	1.728	0.00302	0.08157	0.08634	0.1490
11	1.920	0.00238	0.07142	0.06788	0.1304

Tab.4.3 Performance Coefficients for Two Bladed Rotor at V_w = 5.0m/s

Max Torque=0.09737 N-m ; Max Power =2.5357 W

S.No	Tip speed Ratio	Torque (N-m)	Power (W)	Torque Coefficient	Power Coefficient
1	0.0004	0.08686	0.00087	0.89213	0.0003
2	0.1160	0.08134	0.24485	0.83543	0.0965
3	0.2300	0.07603	0.45693	0.78082	0.1802
4	0.3460	0.06946	0.62588	0.71342	0.2468
5	0.4610	0.06371	0.76517	0.65432	0.3017
6	0.5760	0.05683	0.85312	0.58372	0.3364
7	0.6910	0.04881	0.87908	0.50129	0.3467
8	0.8060	0.04405	0.92559	0.45245	0.3650
9	0.9220	0.03782	0.90807	0.38842	0.3581
10	1.0370	0.03093	0.83543	0.31766	0.3294
11	1.1520	0.02555	0.76669	0.26238	0.3023
12	1.2670	0.02217	0.73203	0.22775	0.2886
13	1.3830	0.01856	0.66847	0.19065	0.2636
14	1.4980	0.01531	0.59737	0.15727	0.2356
15	1.6130	0.01193	0.50125	0.12254	0.1967

Tab. 4.4 Performance Coeffcients for Three Bladed Rotor at V_w =2.0m/s

Max Torque=0.01558 N-m ;   Max Power=0.1623 W

S.No	Tip Speed Ratio	Torque (N-m)	Power (W)	Torque Coefficient	Power Coefficient
1	0.0001	0.01302	0.00013	0.83569	0.0008
2	0.289	0.01043	0.03140	0.66954	0.1935
3	0.577	0.00850	0.05110	0.54578	0.3148
4	0.865	0.00673	0.06068	0.43231	0.3739
5	1.153	0.00404	0.04858	0.25965	0.2993
6	1.440	0.00237	0.03557	0.15214	0.2192
7	1.729	0.00141	0.02541	0.09058	0.1566
8	2.017	0.01033	0.02171	0.06634	0.1338

Tab.4.5 Performance Coefficients for Three Bladed Rotor at V_w = 3.0m/s

Max Torque=0.03505 N-m ; Max Power=0.5477 W

S.No	Tip Speed Ratio	Torque (N-m)	Power (W)	Torque Coefficient	Power Coefficient
1	0.0001	0.03058	0.00030	0.87243	0.0006
2	0.192	0.02869	0.08636	0.81876	0.1576
3	0.384	0.02463	0.14802	0.70287	0.2702
4	0.576	0.02069	0.18641	0.59034	0.3403
5	0.768	0.01717	0.20621	0.48988	0.3765
6	0.960	0.01319	0.19798	0.37635	0.3615
7	1.152	0.01000	0.18010	0.28543	0.3288
8	1.344	0.00727	0.15274	0.20764	0.2788
9	1.536	0.00563	0.13517	0.16076	0.2468
10	1.728	0.00386	0.10425	0.11035	0.1903
11	1.920	0.00318	0.09543	0.09078	0.1742

Tab.4.6 Performance Coefficients for Three Bladed Rotor at V_w = 5.0m/s

Max Torque=0.09737 N-m; Max Power=2.5357 W

S.No	Tip Speed Ratio	Torque (N-m)	Power (W)	Torque Coefficient	Power Coefficient
1	0.0004	0.08887	0.00088	0.91271	0.0003
2	0.1160	0.08317	0.25036	0.85423	0.0987
3	0.2300	0.07846	0.47156	0.80582	0.1859
4	0.3460	0.07238	0.65220	0.74342	0.2572
5	0.4610	0.06690	0.80350	0.68710	0.3168
6	0.5760	0.06015	0.90291	0.61779	0.3560
7	0.6910	0.05174	0.93191	0.53142	0.3675
8	0.8060	0.04564	0.95896	0.46876	0.3782
9	0.9220	0.03892	0.93458	0.39976	0.3685
10	1.0370	0.03195	0.86297	0.32813	0.3403
11	1.1520	0.02708	0.81286	0.27818	0.3206
12	1.2670	0.02335	0.77088	0.23984	0.3040
13	1.3830	0.02010	0.72412	0.20652	0.2856
14	1.4980	0.01688	0.65868	0.17341	0.2597
15	1.6130	0.01373	0.57684	0.14102	0.2274

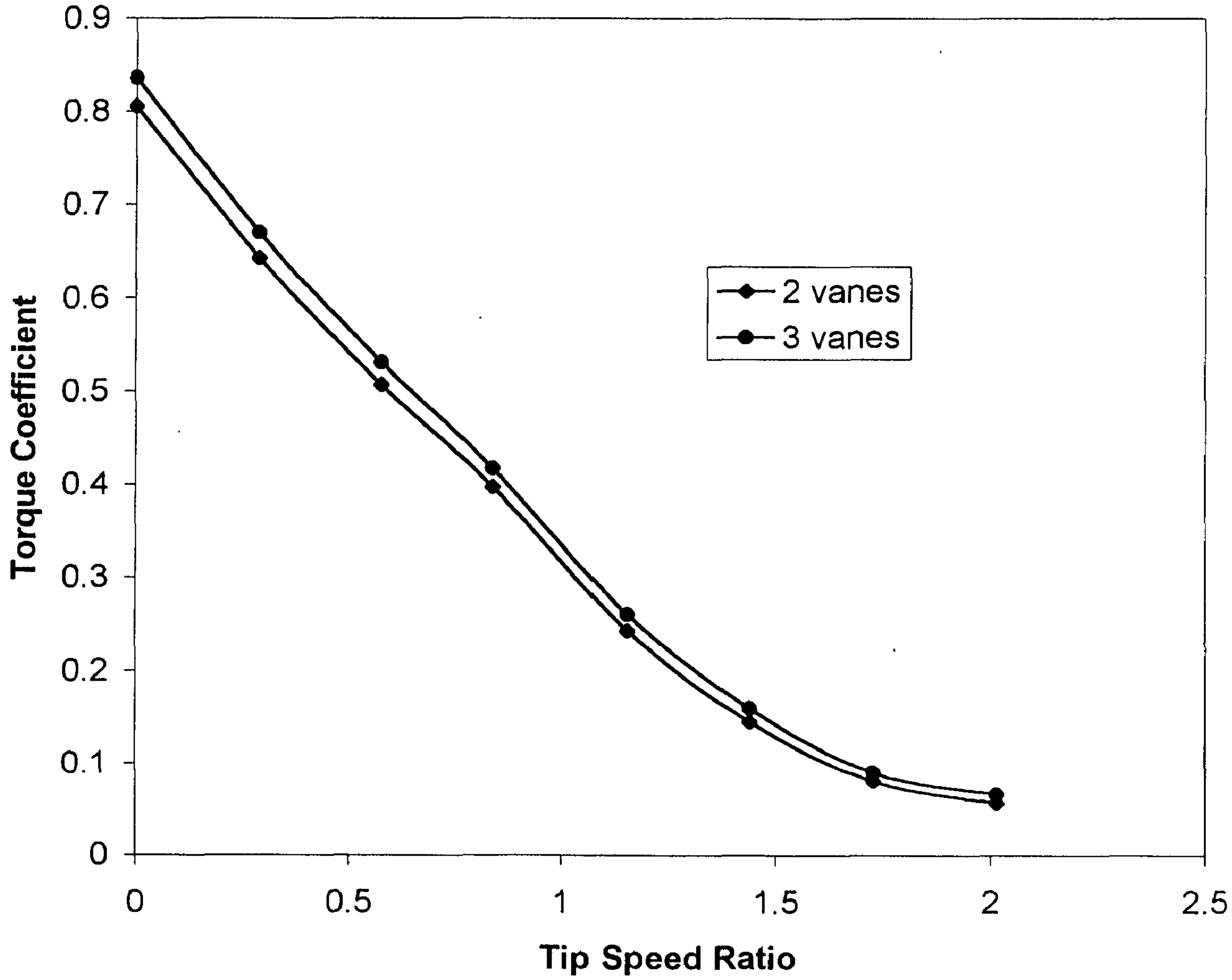

Fig. 4.1 Torque Coefficients at Various Tip Speed Ratios for V_w =2.0m/s

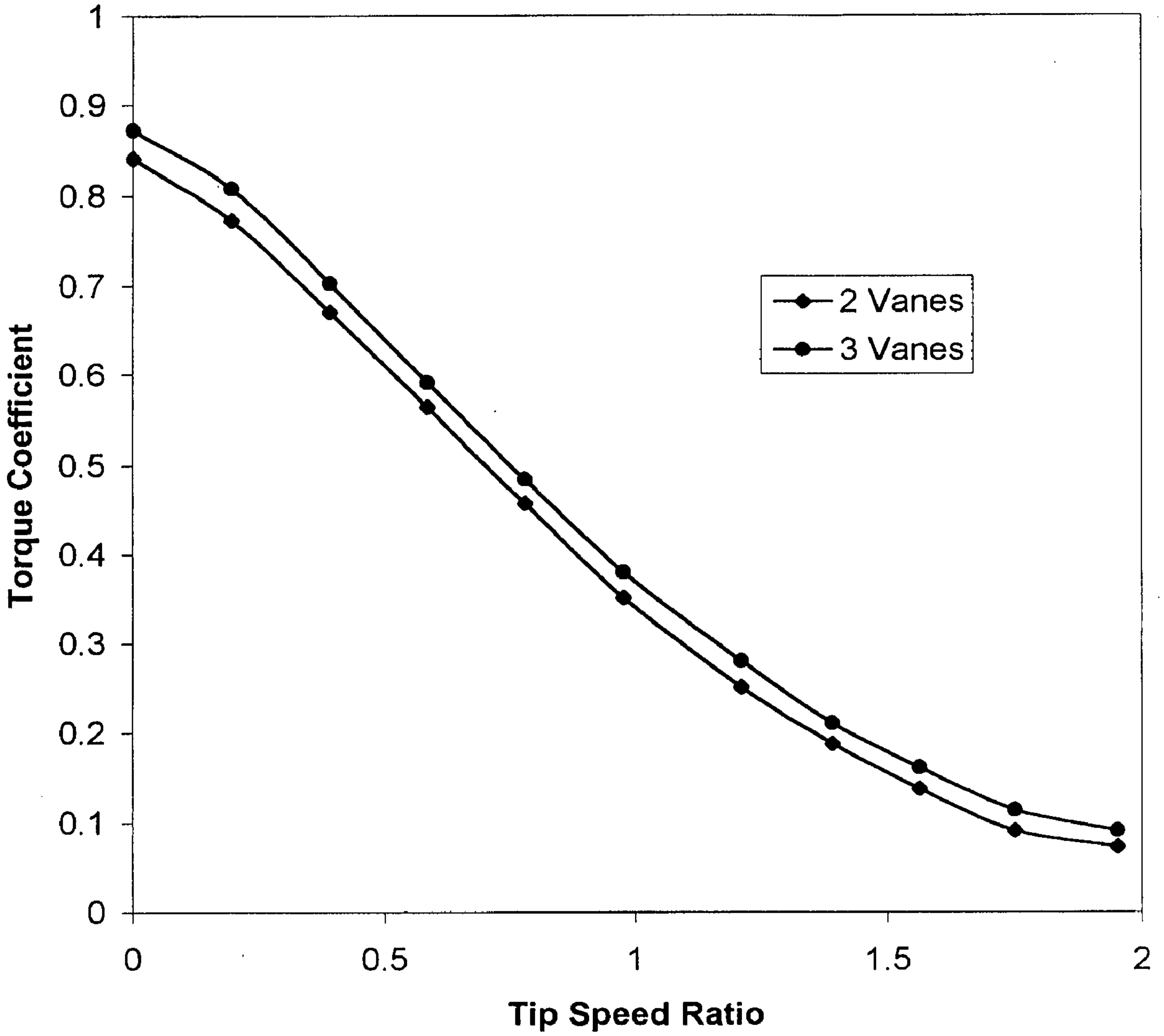

Fig. 4.2 Torque Coefficients at Various Tip Speed Ratios for V_w =3.0m/s

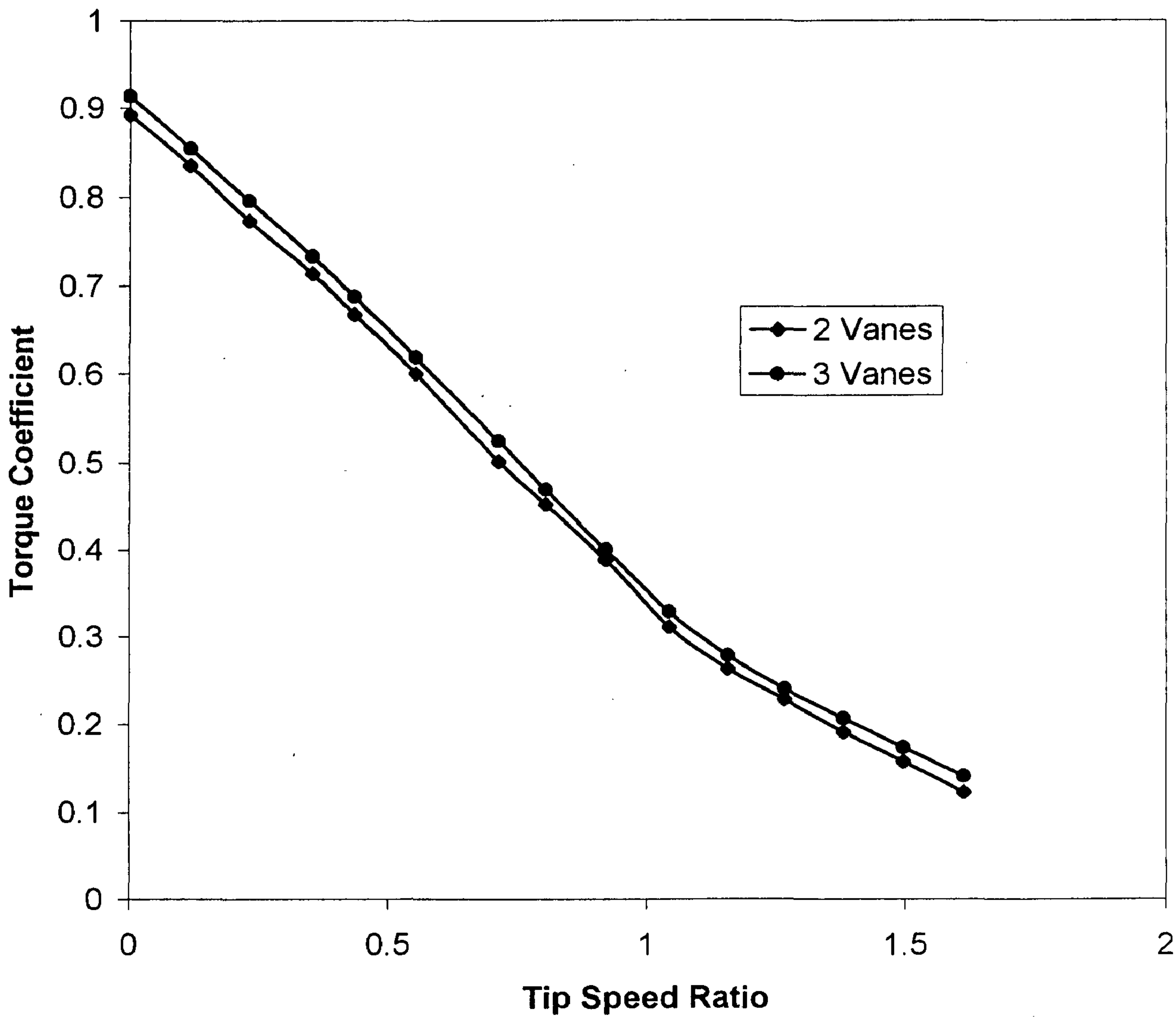

Fig. 4.3 Torque Coefficients at Various Tip Speed Ratios for V_w =5.0m/s

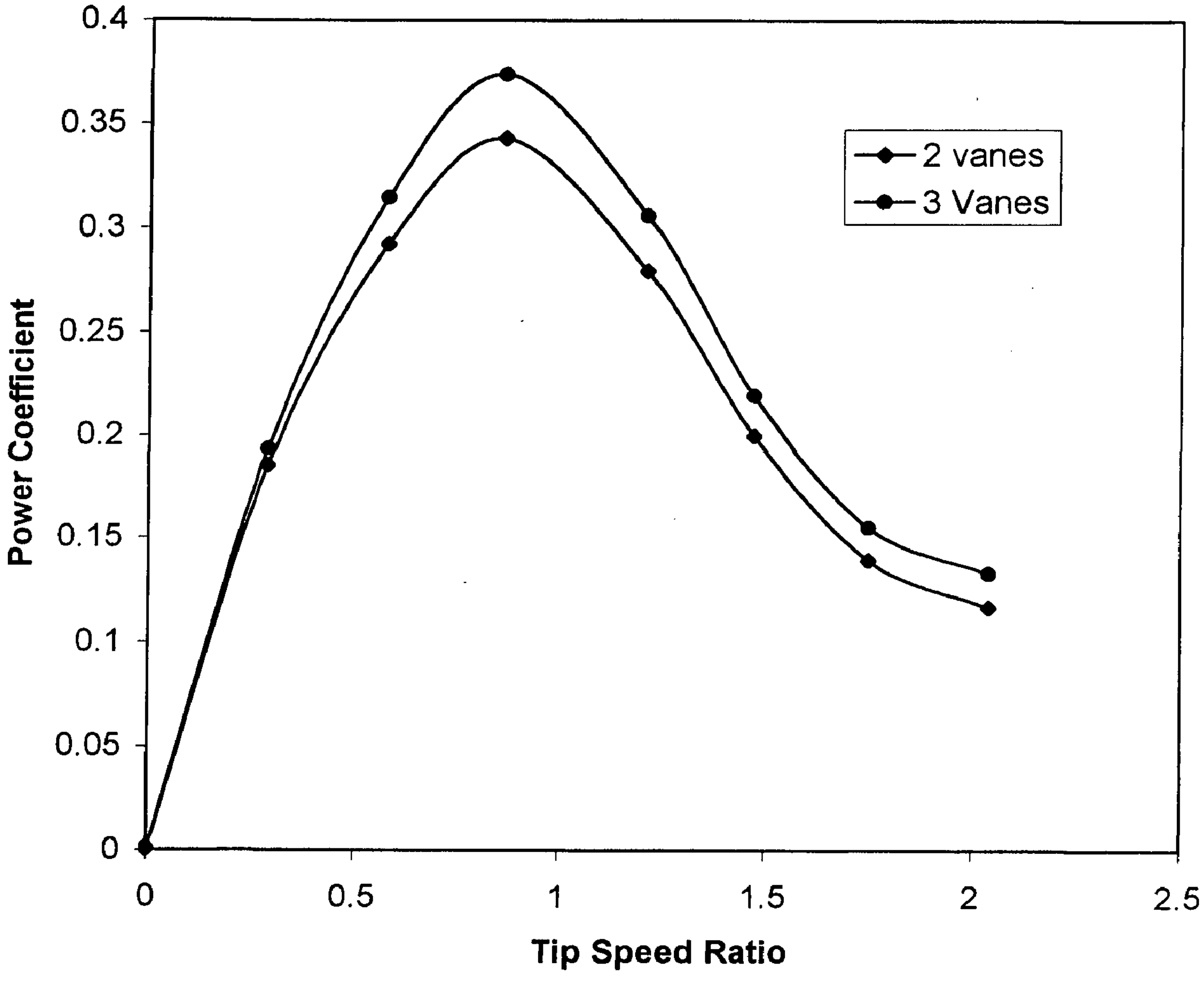

Fig. 4.4 Power Coefficients at Various Tip Speed Ratios for V_w =2.0m/s

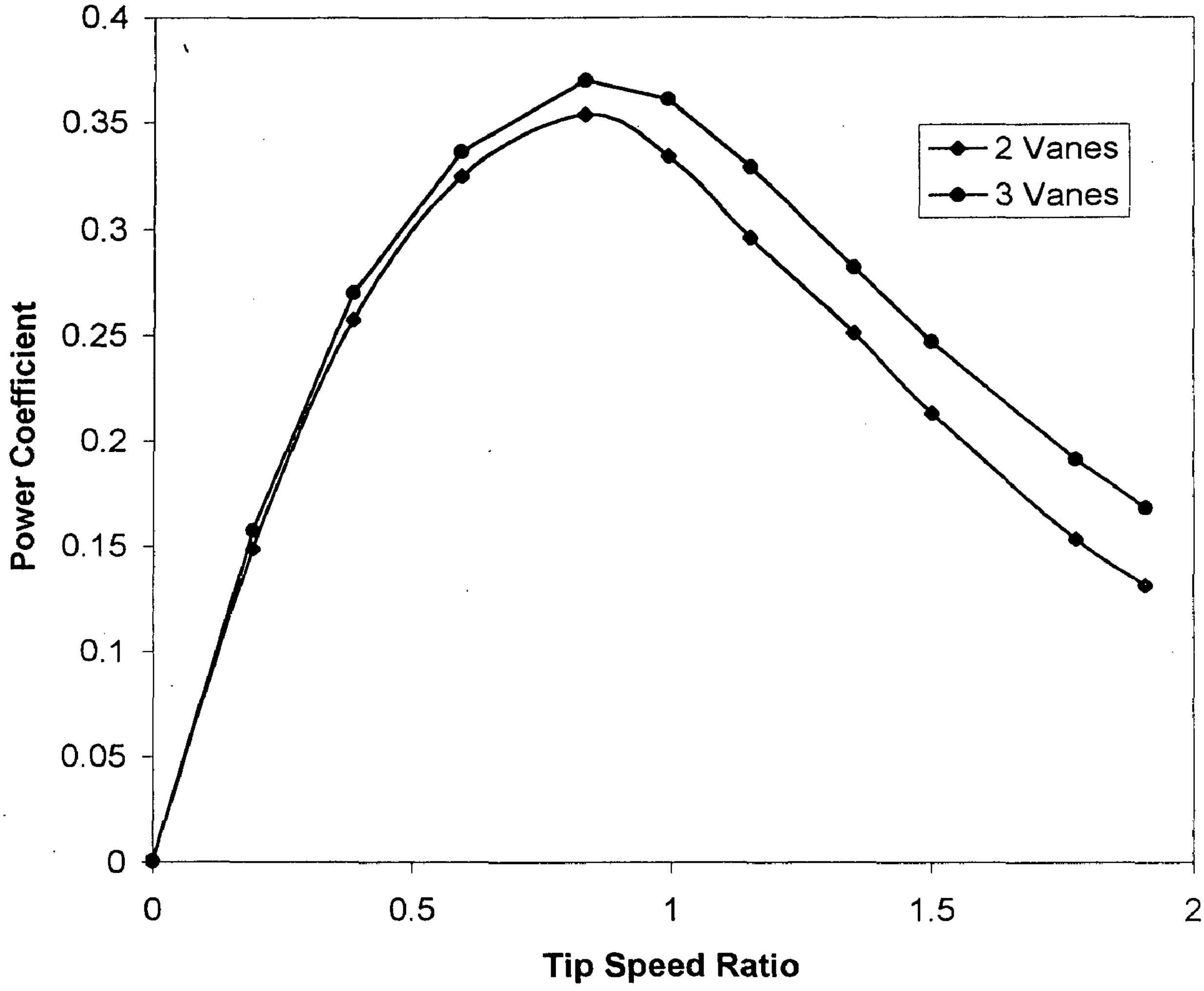

Fig. 4.5 Power Coefficients at Various Tip Speed Ratios for V_w =3.0m/s

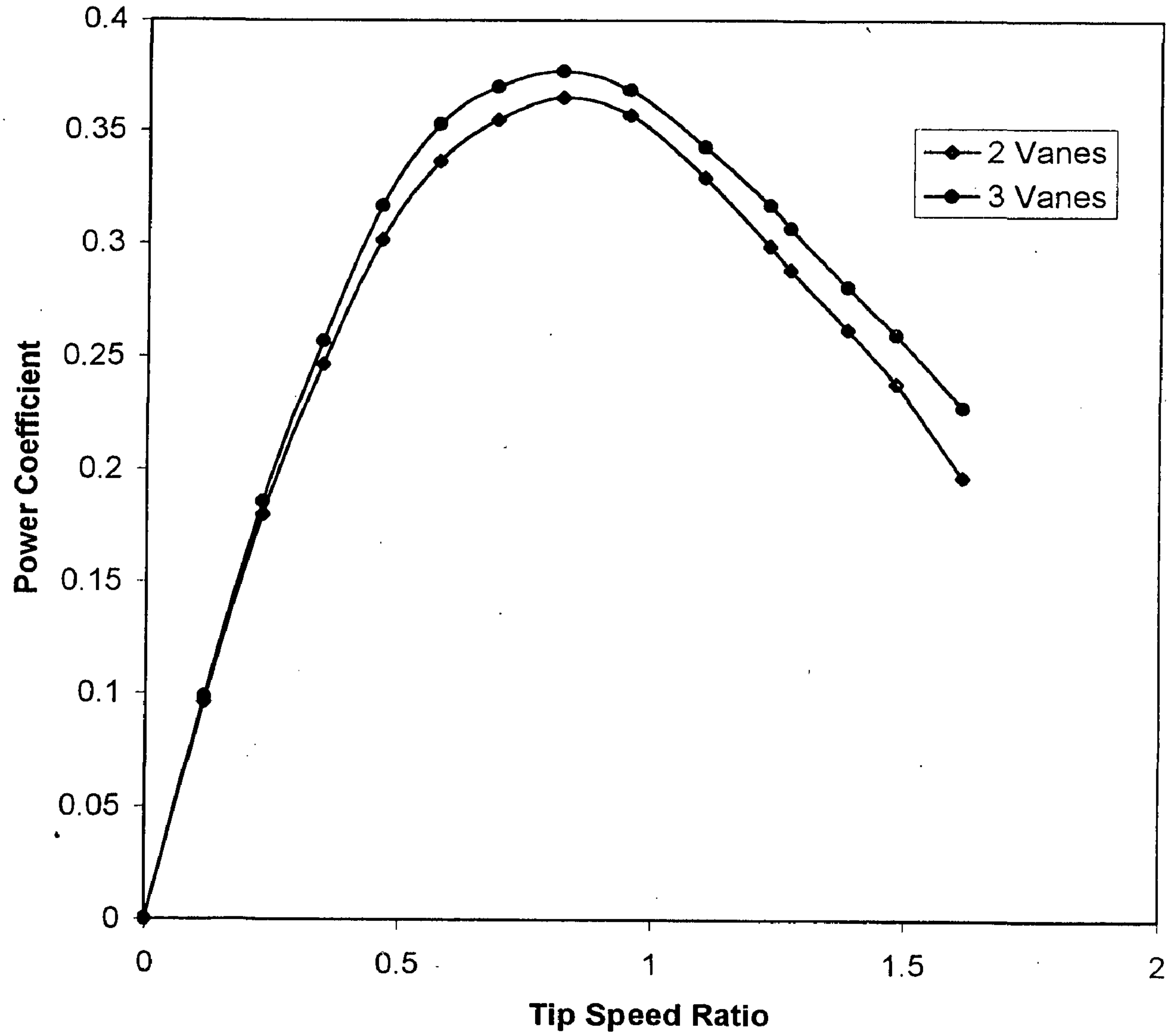

Fig. 4.6 Power Coefficients at Various Tip Speed Ratios for V_w =5.0m/s

Tab.4.7 Average Performance Coefficients for Two Bladed Rotor

S.No	Tip Speed Ratio	Torque Coefficient		Power Coefficient	
		Theoretical	Experimental	Theoretical	Experimental
1	0.001	0.8410	0.770	0.0006	0.0001
2	0.257	0.7408	0.657	0.1915	0.1857
3	0.513	0.6124	0.557	0.3080	0.2890
4	0.769	0.4782	0.443	0.3588	0.3357
5	1.025	0.3254	0.312	0.3321	0.3143
6	1.281	0.2160	0.200	0.2814	0.2571
7	1.537	0.1425	0.114	0.2183	0.1571
8	1.739	0.0827	0.020	0.1475	0.0357

Tab. 4.8 Average Performance Coefficients for a Three Bladed Rotor

S.No	Tip Speed Ratio	Torque Coefficient		Power Coefficient	
		Theoretical	Experimental	Theoretical	Experimental
1	0.001	0.8740	0.830	0.0006	0.0001
2	0.257	0.7760	0.629	0.1912	0.1571
3	0.513	0.6274	0.443	0.3213	0.2285
4	0.769	0.4901	0.242	0.3749	0.2050
5	1.025	0.3440	0.057	0.3505	0.0350
6	1.120	0.3075	0.000	0.3366	0.0000
7	1.281	0.2360	-	0.3131	-
8	1.537	0.1591	-	0.2422	-
9	1.739	0.1038	-	0.1859	-

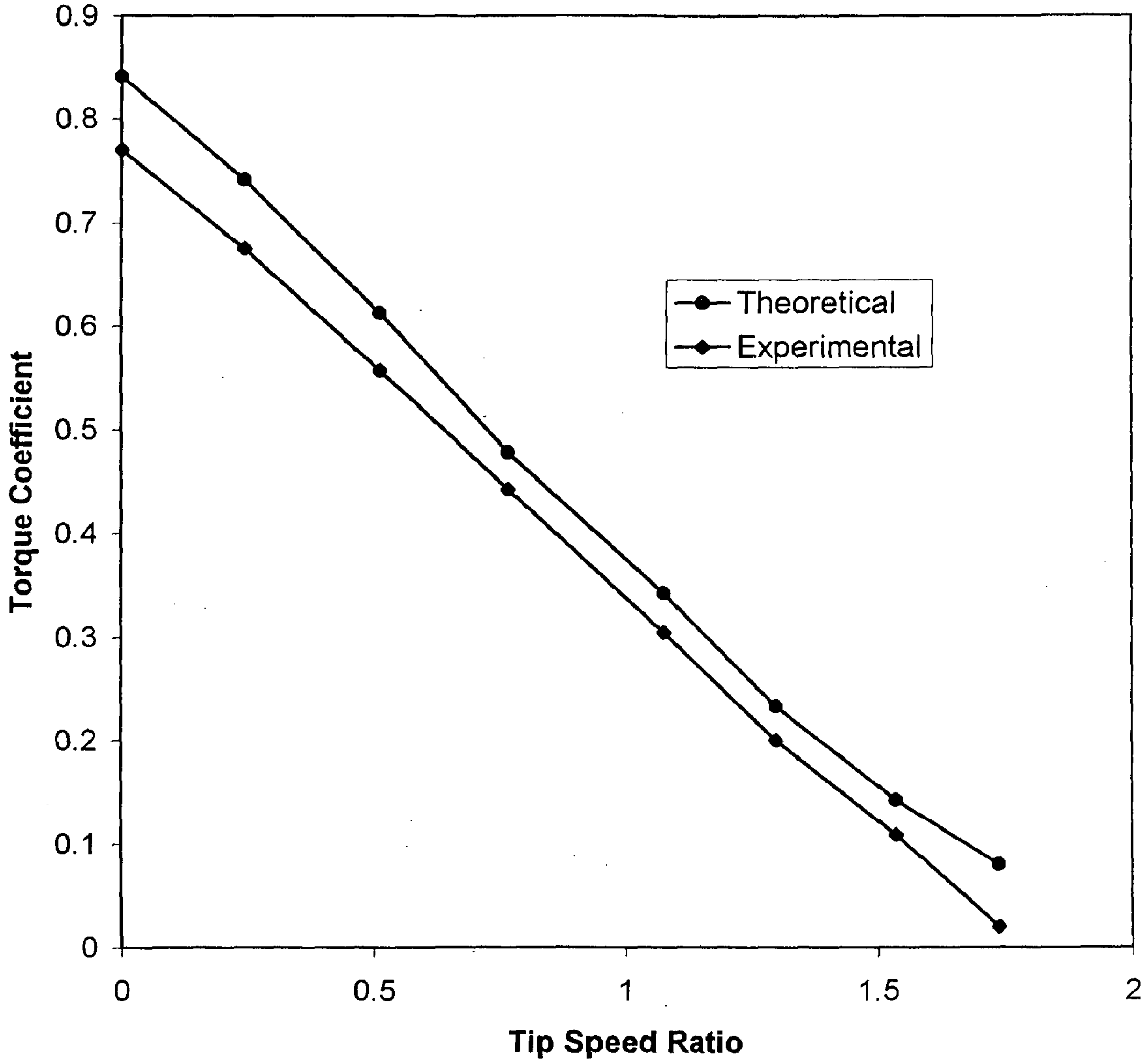

Fig. 4.7 Comparison of Torque Coefficients for 2 bladed rotor

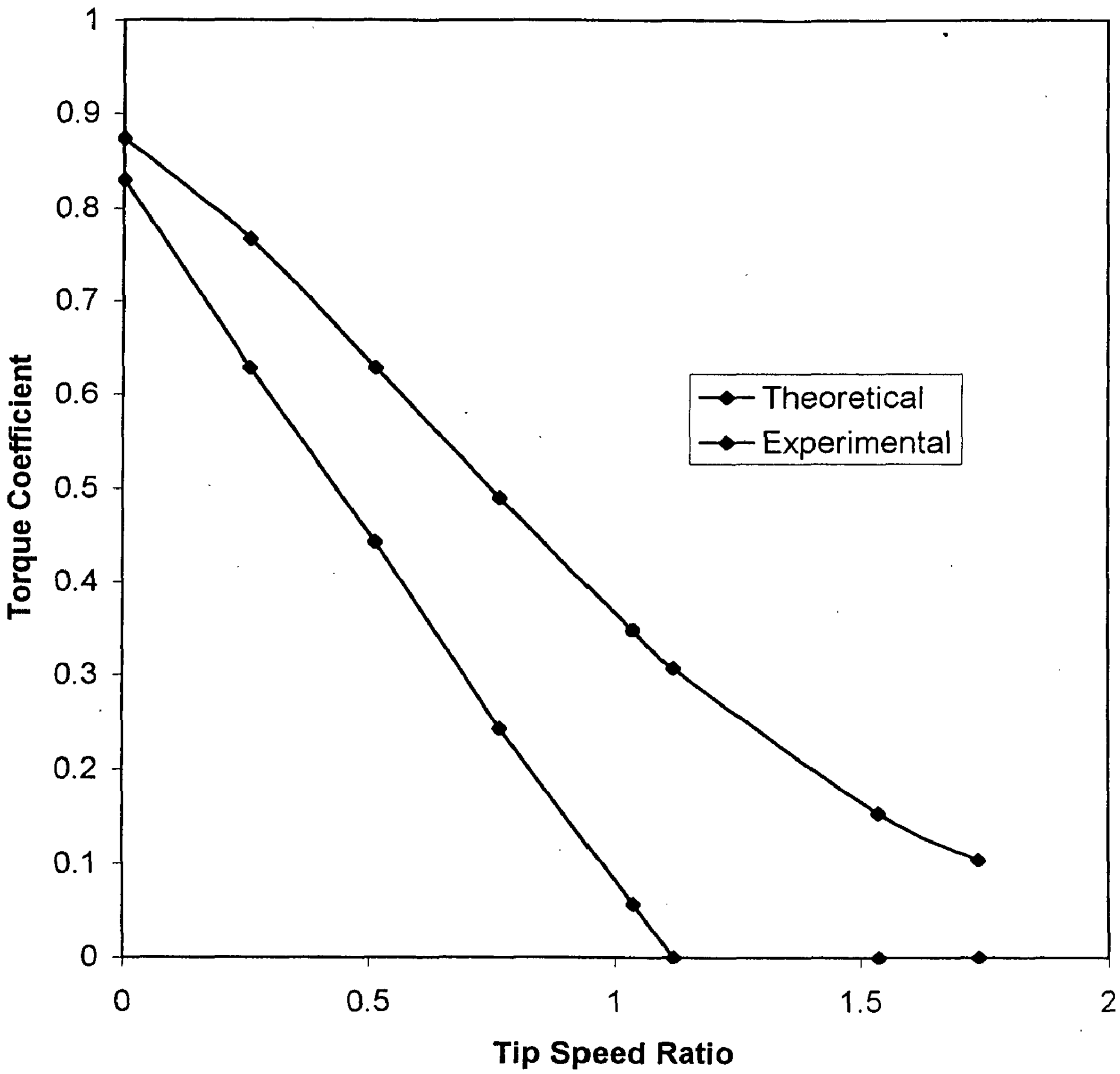

Fig. 4.8 Comparison of Torque Coefficients for 3 bladed rotor

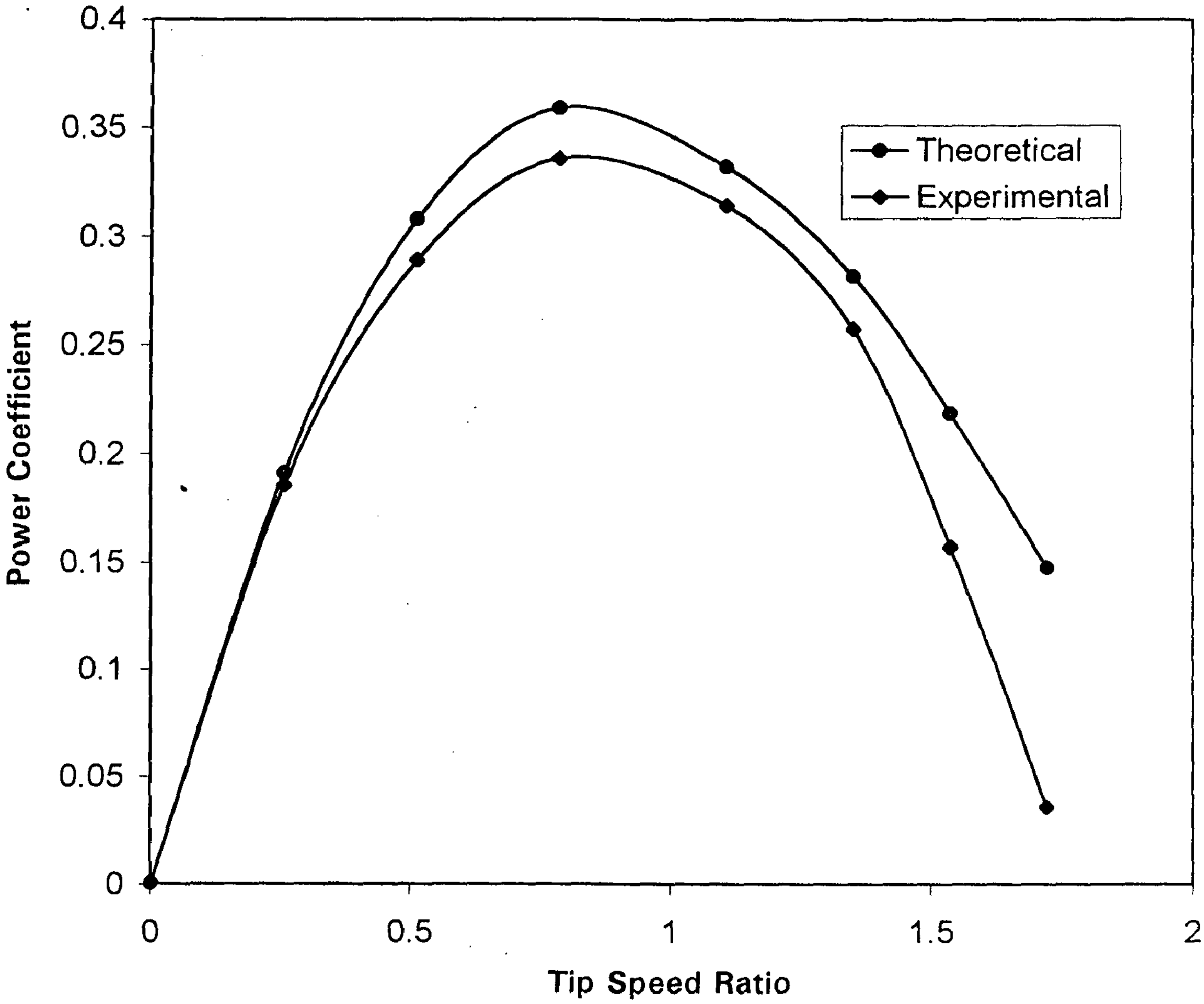

Fig. 4.9 Comparison of Power Coefficient for 2 bladed rotor

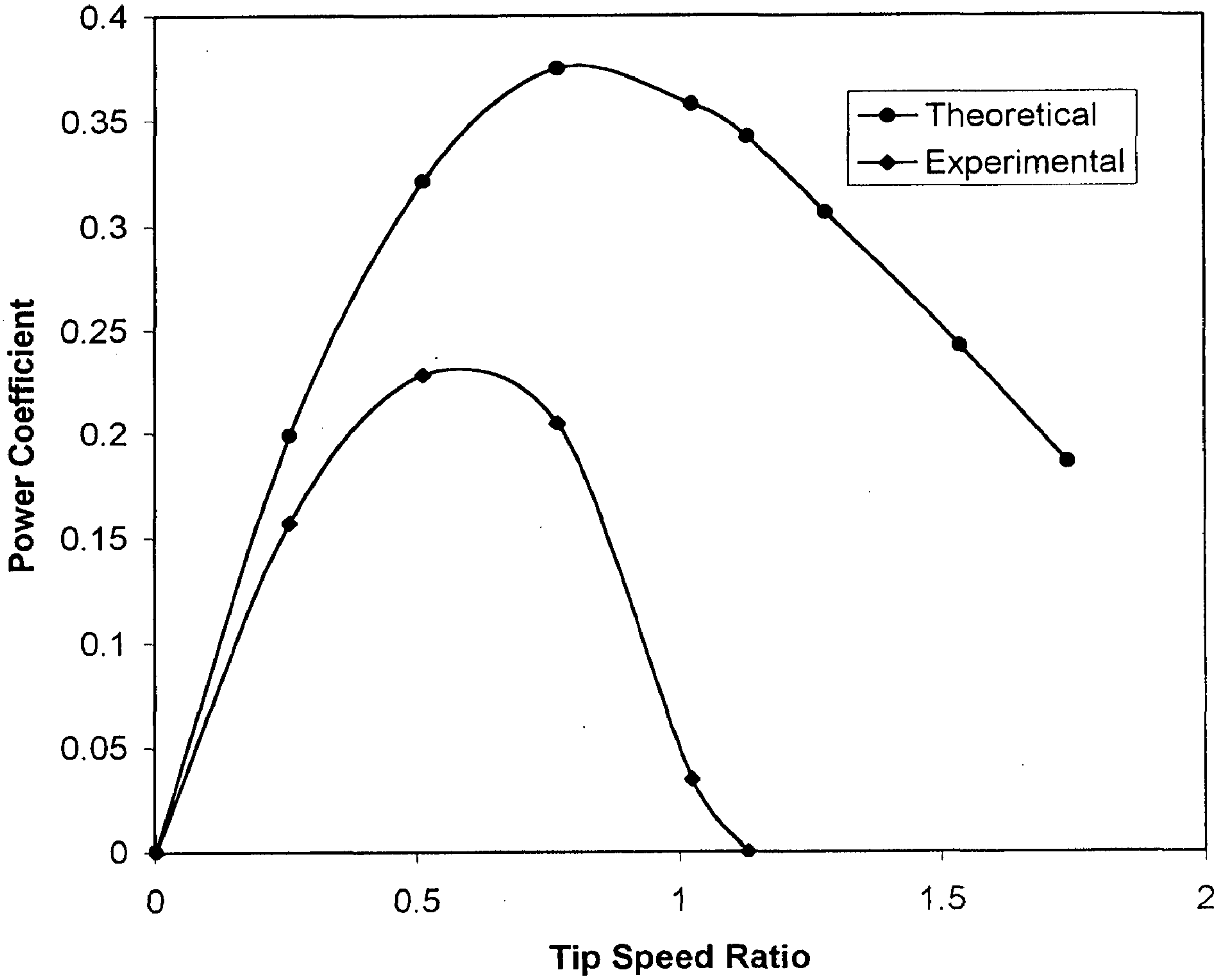

Fig. 4.10 Comparison of Power Coefficient for 3 bladed rotor

theoretical results are not coming to zero but the power coefficients are decreasing with increasing tip speed ratios and the decrease is less as tip speed ratio is increased.

At high angular velocities the wake effects are high, due to which the power coefficients of the rotor actually decreases and become zero at low tip speed ratios when compared to theoretical results. For three bladed rotors performance coefficients reduces to zero at very low tip speed ratios than the two bladed rotors, as the wake effects are predominant in the case of three bladed rotor as the wind does not flow freely on the other side of the axis which is intercepted by the vanes, due to which performance decreases to a great extent.

4.3 *Effect of Number of Blades on the Performance Coefficients:*

The power coefficient differs for rotor with two and three blades. The experimental results show that two bladed rotor have better performance coefficients when compared to three bladed rotor (fig 4.7 to 4.10), but theoretical results show that three bladed rotor has better performance coefficients when compared to two bladed rotor. The assumption that is taken in theoretical analysis, that on one side of the rotor axis there is no force on the vane that is the vane is in open position all the time, plays an important role. This is almost true for two bladed-rotor in actual case also and only on one side of axis wind is intercepted.

For the case of three bladed-rotor in actual case, the blades will intercept the wind on both sides of the axis, so the intercepting area increases and torque acts in the opposite directions and the blades intercept the wind behind the rotor axis, so wake increases and so the power and torque coefficients are very less when compared to theoretical results.

4.4 *Variation of Torque With Blade Angle:*

From the fig. 4.11, it is clear that as the blade angle (θ) increases torque also increases up to a certain angle and then decreases and becomes zero at an angle just below 180°. This angle at which torque becomes zero will depend on the tip speed ratio. The torque again increases at angle just greater than 180° and the trend will be same as between 0 to 180°. This will be due to the another vane of the rotor. From the figure it is observed that torque will be zero initially up to a certain angle. This angle is denoted as θ_s. This angle again depends on the tip speed ratio. The variation of this angle with tip speed ratio is shown in fig. 4.12. It is seen from the figure that θ_s increases with increase in tip speed ratio.

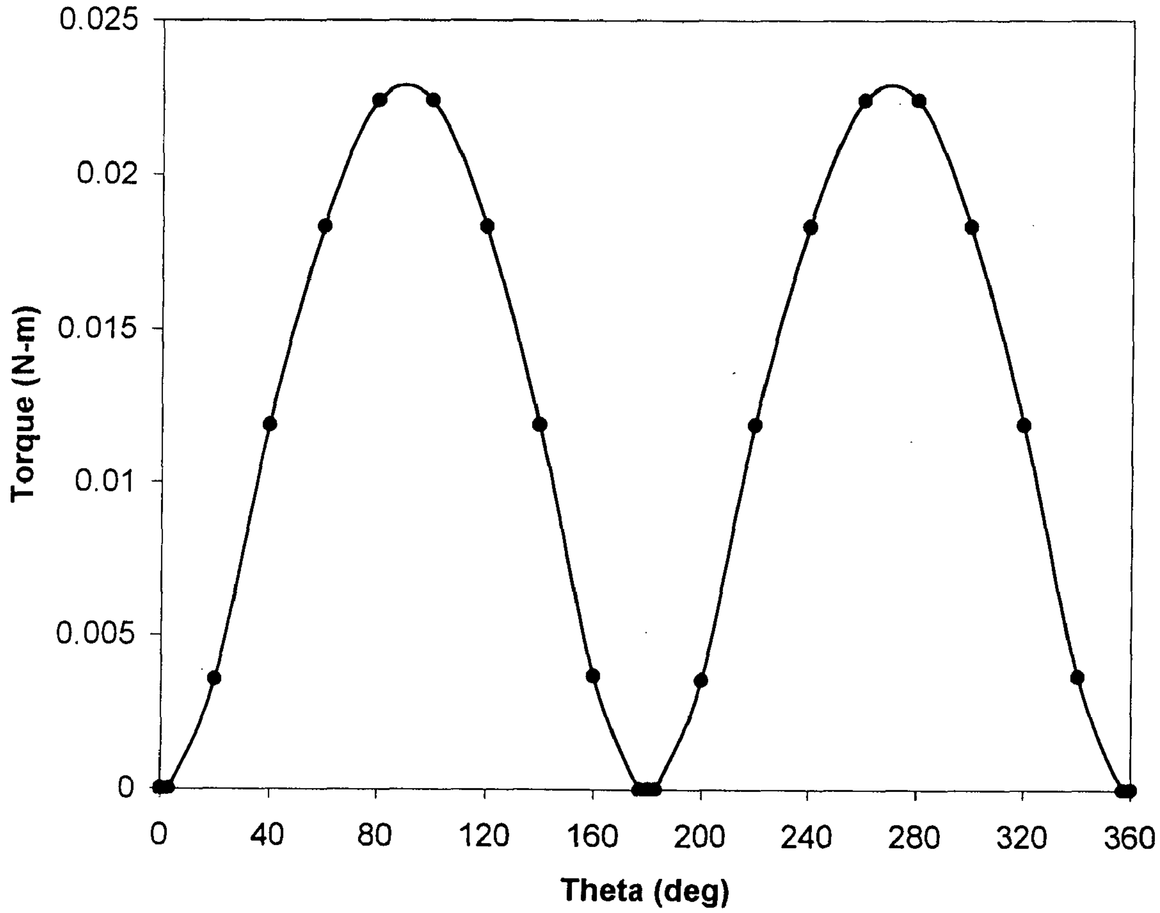

Fig.4.11 Typical Torque Versus Theta Curve for a Two Bladed Rotor

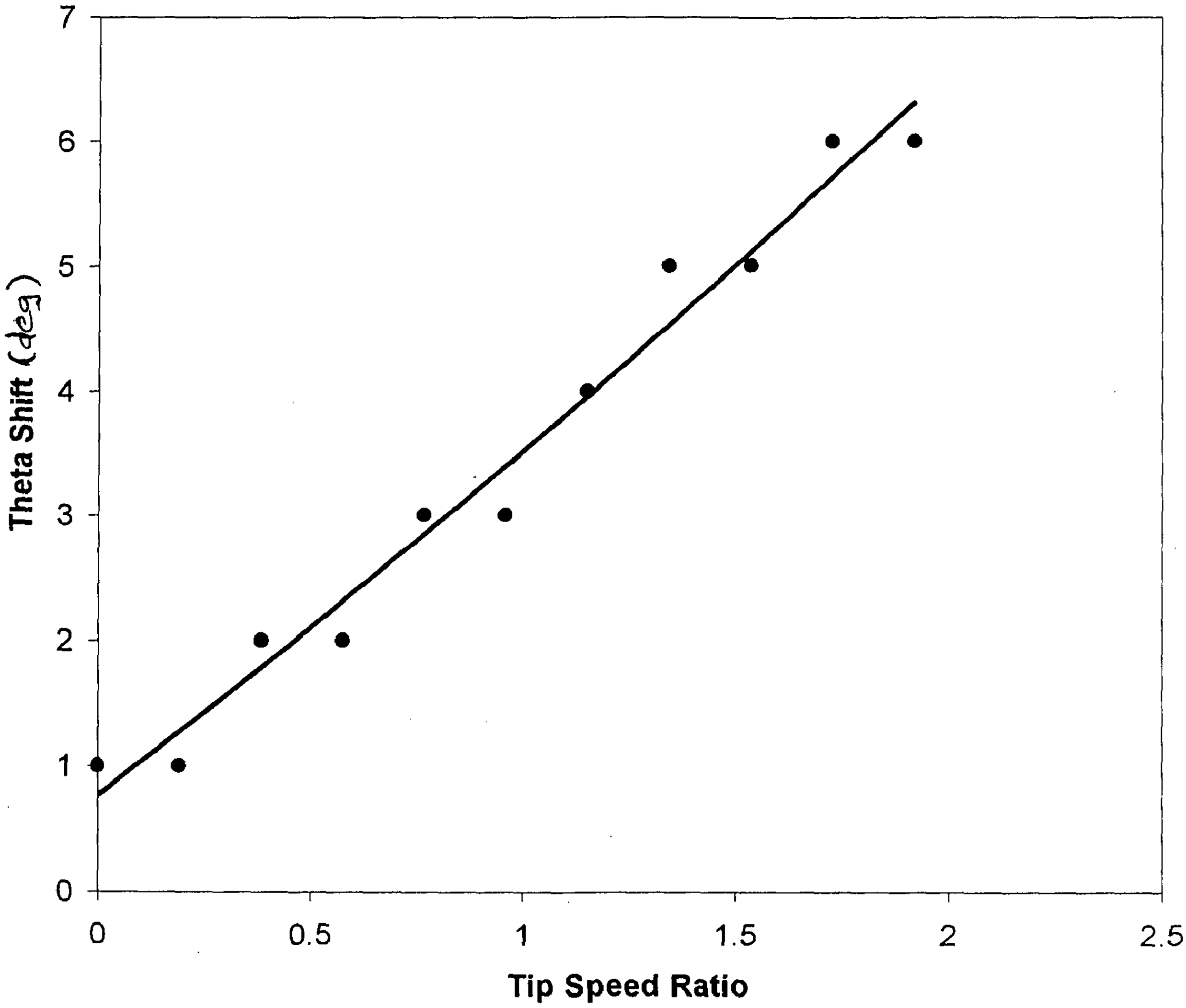

Fig.4.12 Variation of θ_s with Tip Speed Ratio

Chapter 5

CONCLUSIONS AND SCOPE OF FUTUTRE WORK

Conclusions:

A new design of a vertical axis wind rotor using two and three flat swinging vanes has been analysed for the performance coefficients in this work and the results are compared with the available experimental results. On the basis of results obtained and comparison with experimental results the following conclusions are drawn:

1. This wind mill is self starting.
2. This swinging vane wind rotor works even at a low wind velocity.
3. From the comparison curves, it is concluded that the rotor with two vanes is superior to that with three vanes. This is also desirable as the cost of two-vane rotor will be less than three vane rotor.

Scope of Future Work:

The present work has been carried out by neglecting the effects of wake. The work can be extended by considering the effects of wake.

REFERENCES

1. Barnes W. McCormick (1979), "Aerodynamics, Aeronautics and Flight Mechanics", Newyork, JohnWiley and Sons, Inc.
2. Durand. W.F (Editor in Chief) (1935), "Aerodynamic Theory Vol4", Dover Publications, Inc.
3. Frank R. Eldridge (1980), "Wind Machines", Van Nostrand Reinhold Co.
4. Gangil.D. (2000), "Performance of a Swinging Vanes Vertical Axis Small Wind Mill – A Dissertation" MIED Dept, University of Roorkee,Roorkee
5. Gipe,P (1995), "Wind Energy Comes of Age", Newyork, John Wiley and Sons, Inc.
6. Golding. E.W. (1976), "The Generation of Electricity by Wind Power", John Wiley and Sons, Inc.
7. John J. Bertin and Michael L. Smith (1979), "Aerodynamics for Engineers", Prentice-Hall, Inc.,
8. Nicholas P. Cheremisinoff (1978), "Fundamentals of Wind Energy", Ann Arbor Science.
9. P.N. Modi and S.M. Seth (1991),10^{th} ed "Hydraulics and Fluid mechanics", Standard Book House, Delhi
10. Schultz. R.R and Cole.R. (1979). "Uncertainty Analysis in Boiling Nucleates", Alcha, Symp. Series No. 189, Vol.75, pp 32-39.
11. Seigfried Heier (1998), "Grid Integration of Wind Energy Conversion Systems", John Wiley and Sons, Inc.
12. Warne. D. F. (1983), "Wind Power Equipment", E. & F. N. Spon Ltd.

APPENDIX A

Velocity Measurement:

Velocity is measured with Pitot Static tube, which is connected to an inclined manometer with methyl alcohol as fluid.

A Pitot tube is a simple device used for measuring the velocity of flow. The basic principle used in this device is that if the velocity of flow at a particular point is reduced to zero, which is known as stagnation point, the pressure there is increased due to the conversion of the kinetic energy into pressure energy and by measuring the increase in the pressure energy at this point the velocity of flow may be determined [9] .

Velocities at Different Positions :

S.No	Distance (mm)	Manometer difference,h (mm)	Velocity V_w(m/s)
1	0	8	4.235
2	5	9	4.492
3	10	10	4.735
4	15	12	5.187
5	20	14	5.6
6	25	16	5.989
7	30	22	7.023
8	35	14	5.6
9	40	16.5	6.08
10	45	15	5.799
11	50	16	5.989
12	55	20	6.69

Average velocity V_w =5.618 m/s

Sample Calculations:

Velocity is given by the following formula

$$V_w = \sqrt{2gh \sin\phi \,[(S_m/S) - 1]}$$

S_m = Specific gravity of methyl alcohol =0.78

S = Specific gravity of air

ϕ = manometer inclination =10°

g = acceleration due to gravity =9.81 m/s^2

Substituting all the values, the equation takes the form

$$V_w = 47.35\sqrt{h \times 10^{-3}}$$

Where h is manometric head in mm

At h =14 mm, V_w = 5.6 m/s

APPENDIX B

Experimental Results

Blade Angle	Elastic 1 (mm) Δx	Δy	Δz	res	Elastic 2 (mm) Δx	Δy	Δz	res	Elastic 3 (mm) Δx	Δy	Δz	res	Elastic 4 (mm) Δx	Δy	Δz	Res
0	1.0	65.0	214.5	224.1	0.5	67.5	215.5	225.8	0.0	68.5	103.0	123.7	0.5	69.0	105.5	126.0
5	3.5	64.5	215.5	224.9	8.0	66.5	215.0	225.2	7.5	67.0	104.5	124.4	4.5	70.5	103.5	125.3
10	9.0	64.0	215.5	224.9	17.5	63.0	215.0	224.7	12.5	66.0	103.5	123.4	6.0	71.5	103.0	125.5
15	12.5	66.5	213.5	223.9	18	60.0	215.0	223.9	16.0	63.0	103.0	121.8	7.5	69.5	106.0	127.0
20	17.5	64.5	213.5	223.7	25.5	55.0	215.5	223.8	20.5	58.5	104.0	121.0	16.5	67.5	106.5	127.2
25	23.0	67.0	214.5	225.9	29.0	53.5	215.5	223.9	22.0	56.0	104.5	120.6	17.0	64.0	106.0	125.0
30	29.0	66.0	214.5	226.3	32.0	52.0	215.5	224.0	27.0	56.0	99.5	117.3	23.0	66.0	103.5	124.8
35	29.5	66.0	214.0	225.8	38.0	50.0	216.0	225.0	32.0	53.0	105.0	121.9	28.5	65.5	104.0	126.2
40	26.5	53.5	212.0	220.2	37.0	47.5	214.0	223.3	31.5	49.0	103.0	118.3	26.5	65.0	105.5	126.7

Angle of Attack (α)	ψ_1 (deg) 1	2	3	4	ψ_2 (deg) 1	2	3	4	Drag Force (N) 1	2	3	4	Total	Lift Force (N) 1	2	3	4	Total	C_D	C_L
90	73.1	72.6	56.4	56.8	0.9	0.42	0	0.4	0.094	0.099	0.147	0.107	0.4474	0.001	0.0007	0	0.0007	0.003	1.284	0.0085
85	73.3	72.7	57.2	55.7	3.1	6.8	6.38	3.65	0.095	0.096	0.148	0.102	0.4415	0.005	0.011	0.016	0.006	0.04	1.267	0.114
80	73.3	73.0	57.0	55.1	8.0	15.5	10.7	4.8	0.094	0.09	0.14	0.106	0.43	0.013	0.025	0.026	0.009	0.074	1.236	0.212
75	72.2	73.7	57.7	56.6	10.6	16.7	14.2	6.16	0.096	0.085	0.125	0.116	0.421	0.018	0.025	0.032	0.013	0.087	1.209	0.2515
70	72.6	74.3	59.2	56.8	15.2	24.9	19.3	13.7	0.093	0.077	0.111	0.114	0.396	0.025	0.036	0.039	0.027	0.128	1.136	0.368
65	71.7	74.2	60.1	58.0	19.0	28.5	21.4	14.9	0.099	0.075	0.104	0.09	0.37	0.034	0.041	0.041	0.024	0.14	1.062	0.4024
60	71.4	74.1	58	55.9	23.7	31.6	25.7	19.2	0.098	0.074	0.085	0.092	0.35	0.043	0.045	0.041	0.032	0.162	1.004	0.4646
55	71.3	73.8	59.5	55.5	24.1	37.2	31.1	23.5	0.098	0.072	0.105	0.103	0.38	0.044	0.055	0.064	0.045	0.207	1.085	0.594
50	74.3	74.3	60.5	56.3	26.3	37.9	32.7	22.2	0.072	0.065	0.08	0.106	0.324	0.036	0.05	0.051	0.043	0.181	0.93	0.5199

Initial Lengths (IL)	**Thread Lengths (TL)**
Elastic 1 : 80mm	104mm
Elastic 2 : 84mm	103mm
Elastic 3 : 49mm	58mm
Elastic 4 : 48mm	69mm

x_1, y_1, z_1 are coordinates referring frame in mm

x_2, y_2, z_2 are coordinates referring the vane in mm

Sample Calculations:

$$\psi_1 = \cos^{-1}[(\sqrt{\Delta x^2 + \Delta y^2}) / (\sqrt{\Delta x^2 + \Delta y^2 + \Delta z^2})]$$

$$\psi_2 = \cos^{-1}[(\Delta y) / (\sqrt{\Delta x^2 + \Delta y^2})]$$

$$\text{Resultant Lengths} = \sqrt{\Delta x^2 + \Delta y^2 + \Delta z^2} - TL$$

F is the net force corresponding to the length from the calibration curves after removing the force due to initial expansion (Fig 3.4a-d)

Drag Force (F_D) = $[F\cos\psi_1]\cos\psi_2$

Lift Force (F_L) = $[F\cos\psi_1]\sin\psi_2$

Total drag force and lift forces are sum of all drag and lift forces respectively.

C_D =Total Drag Force/$(0.5\rho A_v V_w^2)$

C_L = Total Lift Force/$(0.5\rho A_v V_w^2)$

$A_v = 12 \times 16\ cm^2$ $\quad$ $V_w = 5.618$ m/s

Sample calculation are given for $\alpha = 70°$

Elastic 1

$\Delta x = 17.5mm$

$\Delta y = 64.5mm$

$\Delta z = 213.5mm$

$\psi_1 = 72.6°$

$\psi_2 = 15.2°$

$F = 0.3211N$

$F_{D1} = 0.093N$

$F_{L1} = 0.025N$

Elastic 2

$\Delta x = 25.5mm$

$\Delta y = 55.0mm$

$\Delta z = 215.5mm$

$\psi_1 = 74.3°$

$\psi_2 = 24.9°$

$F = 0.3162N$

$F_{D2} = 0.077N$

$F_{L2} = 0.036N$

Elastic 3

$\Delta x = 20.5mm$

$\Delta y = 58.5mm$

$\Delta z = 104.0mm$

$\psi_1 = 59.2°$

$\psi_2 = 19.3°$

$F = 0.2313N$

$F_{D3} = 0.111N$

$F_{L3} = 0.039N$

Elastic 4

$\Delta x = 16.5mm$

$\Delta y = 67.5mm$

$\Delta z = 106.5mm$

$\psi_1 = 56.8°$

$\psi_2 = 13.7°$

$F = 0.215N$

$F_{D4} = 0.114N$

$F_{L4} = 0.027N$

Total Drag Force $= F_{D1} + F_{D2} + F_{D3} + F_{D4}$

$= 0.396N$

Total Lift Force $= F_{D1} + F_{D2} + F_{D3} + F_{D4}$

$= 0.128N$

$C_D = 1.136$

$C_L = 0.368$

UNCERTAINTY ANALYSIS

Schultz and Cole[10] suggested the following method of analysing the efect of uncertainty in each variable of the uncertainty of the result:

$$E_R = \left[\sum_{i=1}^{n} \left(\frac{\partial R}{\partial y_i} Ey_i \right)^2 \right]^{1/2}$$

Where E_R is the estimate of the uncertainty in the calculated value of the desired variable R, due to the independent uncertainty E_{yi} in the primary measurements of n number of variables, Y_i, affecting the results.

Here R= C_D and C_L

Uncertainty analysis is carried out for the above sample calculations.

Considering an error of ±1mm in Δx Δy and Δz

$C_D = F_D/(0.5\rho A_v V_w^2)$

$C_L = F_L/(0.5\rho A_v V_w^2)$

Error in C_D is calculated by calculating the individual errors in elongation and V_w.

Error in elongation is calculated by calculating the individual errors in Δx, Δy and Δz .

$\partial e/\partial \Delta x = \Delta x/(\sqrt{\Delta x^2+\Delta y^2+\Delta z^2})$

This is for one elastic and for Δx and this is repeated for four elastics and for Δy and Δz

Elongations

Elastic 1: 39.715

Elastic 2: 36.816

Elastic 3: 14.07

Elastic 4: 10.06

Error due to Δx is

Elastic1: error= 0.078

Elastic 2: error=0.1

Elastic 3 : error=0.169

Elastic 4: error=0.129

Error due to Δy is

Elastic1: error= 0.288

Elastic 2: error=0.245

Elastic 3 : error=0.484

Elastic 4: error=0.53

Error due to Δz is

Elastic1: error= 0.954

Elastic 2: error=0.96

Elastic 3 : error=0.86

Elastic 4: error=0.837

Total error in elongation in elastic 1 is sum of squares of due to errors in 3 co ordinates.

Elastic.No	Total error	%error
1	1.0	1.0×100/39.715=2.5%
2	0.995	0.995×100/36.86 =2.7%
3	1.0	1×100/14.07 =7.1%
4	1.0	1×100/14.07 =9.8%

Same errors can be accounted in the drag and lift forces.

Now error in C_D and C_L is calculated by calculating the individual errors due to forces and velocity.

$0.5\rho A_v V_w^2 = 0.35N$

5% error is considered in velocity measurement

Error in drag coefficient $= \sqrt{((dF_{D1} + dF_{D2} + dF_{D3} + dF_{D4})/0.35)^2 + (2F_D d(V_w)/(0.35V_w))^2}$

$= \sqrt{(0.023/0.35)^2 + (/1.966)^2}$

$= 0.1306$

% error in drag Coefficient =0.136x100/1.136=11.5%

Error in lift coefficient $= \sqrt{((dF_{L1} + dF_{L2} + dF_{L3} + dF_{L4})/0.35)^2 + (2F_L d(V_w)/(0.35V_w))^2}$

$= \sqrt{(0.007/0.35)^2 + (0.071/1.966)^2}$

$=0.0413$

% error in lift Coefficient =0.0413x100/0.368 = 11.2%

APPENDIX C

Program 1

```
#include<stdio.h>
#include<conio.h>
#include<math.h>
#define pi 3.14159
FILE *fp1,*fp2;
void main()
{
 int i;
 double alpha,rf,drag,lift,Tdrag,Tlift,den,R,H,Vw,CD,CL,cons;
 double dx,dy,dz,res,res1,rlen,fr1,il,tl,psi1,psi2,a,b,c1,c2;

 fp1=fopen("c:\\turboc3\\rajini\\expin.dat","r");
 fp2=fopen("c:\\turboc3\\rajini\\expout.dat","w");
 fprintf(fp2,"\t alpha \t\t  cd \t\t  cl\n\n");
 clrscr();
  /* Density of air, Vane dimensions and wind velocity
     are input to the program */

 printf("enter den, R, H and Vw\n");
 scanf("%lf %lf %lf %lf",&den,&R,&H,&Vw);
 printf("\nalpha\t\t cd \t\t cl\n\n");

 for(alpha=90.0;alpha>=50;alpha=alpha-5.0)
 {
   printf("%lf\t",alpha);
   Tdrag=0.0;
   Tlift=0.0;
  for(i=1;i<=4;i++)
   {
   /* data gets from the input file every time
         the for loop is called */
   fscanf(fp1, "%lf %lf %lf", &dx,&dy,&dz);
   /* resultant lenghts are calculated */
   res=sqrt(pow(dx,2)+pow(dy,2)+pow(dz,2));
   res1=sqrt(pow(dx,2)+pow(dy,2));
   /* angles are calculated */
   psi1=acos(res1/res)*180/pi;
   psi2=acos(dy/res1)*180/pi;

   /*Resultant Force are Calculated at every corner
     using Switch */

  switch(i)
   {
    case 1:
          tl=104.0;
          il=80.0;
          rlen=res-tl;
          a=0.0071;
          b=-0.0769;
          c1=46.329-rlen;
```

```
            c2=46.329-il;
    fr1=((-b+sqrt(b*b-4*a*c1))/(2*a)-(-b+sqrt(b*b-4*a*c2))/(2*a));
     break;
     case 2:
            il=84;
            tl=103;
            rlen=res-tl;
            a=0.0054;
            b=-0.001;
            c1=40.46-rlen;
            c2=40.46-il;
    fr1=((-b+sqrt(b*b-4*a*c1))/(2*a)-(-b+sqrt(b*b-4*a*c2))/(2*a));
     break;
     case 3:
            il=49;
            tl=58;
            rlen=res-tl;
            a=0.0052;
            b=-0.018;
            c1=38.203-rlen;
            c2=38.203-il;
    fr1=((-b+sqrt(b*b-4*a*c1))/(2*a)-(-b+sqrt(b*b-4*a*c2))/(2*a));
     break;
     case 4:
            il=48;
            tl=69;
            rlen=res-tl;
            a=0.0053;
            b=-0.0081;
            c1=42.301-rlen;
            c2=42.301-il;
    fr1=((-b+sqrt(b*b-4*a*c1))/(2*a)-(-b+sqrt(b*b-4*a*c2))/(2*a));
     break;
   }
     rf=fr1*0.00981*cos(psi1*pi/180);
     drag=rf*cos(psi2*pi/180);
     lift=rf*sin(psi2*pi/180);
     Tdrag=Tdrag+drag;
     Tlift=Tlift+lift;
   }
      cons=0.5*den*R*H*Vw*Vw;
      CD=Tdrag/cons;
      CL=Tlift/cons;
      printf("%lf\t %lf\n",CD,CL);

     /* output is sent to the output file */
      fprintf(fp2,"\t %lf \t %lf \t %lf\n",alpha,CD,CL);
  }
  fclose(fp1);
  fclose(fp2);
  getch();
 }
```

APPENDIX D

Program 2

```
#include<stdio.h>
#include<conio.h>
#include<math.h>
#define pi 3.14159
FILE *fp;
void main()
{
 float Vw,Vb,Vr,angvel,torque,Ttorque,power,Cd,Cl,Ct,Cp;
 float mass,r,R,H,dr,x,den=1.16,avmax,A,theta1,lamda;
 float Nforce,TNforce,moment,Tmoment,Atorque,dtheta,con;
 double alpha,theta,arg,thetamax=180.0,count,m,k;
 int B;

 clrscr();
 fp=fopen("CpCt.dat","w");

 /* R and H are vane dimensions */
 printf("enter vane dimensions R and H \n");
 scanf("%f %f",&R,&H);

 /* Vw, Vb and Vr are free stream wind velocity, blade velocity
  and relative velocity respectively */
 printf("enter free stream wind velocity Vw\n");
 scanf("%f",&Vw);

 /* B is number of blades */
 printf("enter no of vanes B \n");
 scanf("%d",&B);

 /* dr is width of section */
 printf("enter division of plate dr \n");
 scanf("%f",&dr);

 /* dtheta is angular divison */
 printf("enter dtheta\n");
 scanf("%f",&dtheta);

 if(B==2)
 {
 avmax=60.0;

 /* A is intercepting area */
 A=R*H;
 m=0.5*den*A*Vw*Vw*0.192;
 k=0.5*den*A*Vw*Vw*Vw;
 }
 else
 {
 avmax=40.0;
 A=R*H;
 m=0.5*den*A*Vw*Vw*0.192;
```

```
k=0.5*den*A*Vw*Vw*Vw;
}
fprintf(fp,"tipspeed ratio\tTtorque (N-m) \t power (W) \t Ct \tCp\n\n");
printf("tip speed ratio \t Ttorque(N-m) \t power(W) \t Ct \t\t Cp\n\n");

/* outer loop starts */
for(angvel=0.01;angvel<=avmax;angvel=angvel+3)
{
 count=0.0;
 lamda=(angvel*0.192)/Vw;
 torque=0.0;Ttorque=0.0;power=0.0;Ct=0.0;

 /* middle loop starts */
 for(theta=0.0;theta<thetamax;theta=theta+dtheta)
 {
  TNforce=0.0;Nforce=0.0;
  Tmoment=0.0;moment=0.0;

  /* inner loop starts */
  for(r=0.0;r<=R;r=r+dr)
  {
   Vb=angvel*r;
  if(theta>=0.0 && theta<=90.0)
   theta1=90-theta;
   else if(theta>90 && theta<180)
   theta1=(theta-90);

   Vr=(Vw-Vb*cos(theta1*pi/180.0));

   if(Vw>(Vb*cos(theta1*pi/180)))
   {

    if(theta>=0.0 && theta<90.0)
    {
     arg=(Vw-Vb*cos(theta1*pi/180))/(Vb*sin(theta1*pi/180));
     alpha=(atan(arg)*180/pi)-theta1;
    }
    else if(theta==90)
    alpha=90;
    else if(theta>90.0 && theta<=180)
    {
    arg=(Vw-Vb*cos(theta1*pi/180.0))/(Vb*sin(theta1*pi/180.0));
    alpha=(atan(arg)*180/pi)-theta1;
    }

   if(alpha>=0 && alpha<=20.0)
   {
    Cd=(0.0002*pow(alpha,2)+0.012*alpha+0.0027);
    Cl=(-0.0027*pow(alpha,2)+0.0864*alpha+0.0432);
   }
   else if(alpha>20 && alpha<=90)
   {
    Cd=(-0.00005*pow(alpha,2)+0.015*alpha+0.3172)*1.8;
    Cl=(-0.0002*pow(alpha,2)+0.0143*alpha+0.3384);
   }
   else if(alpha<0.0)
   {
   Nforce=0.0;
```

```
  }
 if(alpha>=0.0)
 {
   con=0.5*den*H*dr*Vr*Vr;
   Nforce=(Cl*cos(alpha*pi/180)+Cd*sin(alpha*pi/180))*con;
   moment=Nforce*r;
   TNforce=TNforce+Nforce;
   Tmoment=Tmoment+moment;

  }
 } /*closing of outer if */

 else
  {
   Nforce=0.0;
   break;
  }

 } /*closing of inner for loop */

 if(B==3 && TNforce==0.0)
 count++;
  else
  {
  if(B==3)
  {
  thetamax=count+120.0;

  }
  else
  {
  thetamax=180.0;
  }

  x=Tmoment/TNforce;
  torque=TNforce*(x+0.024);
  torque=torque*dtheta;
  Ttorque=Ttorque+torque;
  }

}/*closing of middle for loop */

 Atorque=Ttorque*B/360.0;
 Ct=Atorque/m;
 power=Atorque*angvel;
 Cp=power/k;

fprintf(fp,"%f \t %f \t %f \t %f \t %f\n",lamda,Atorque,power,Ct,Cp);
printf("%f \t\t %f \t %f \t %f \t %3.4f\n",lamda,Atorque,power,Ct,Cp);
} /*closing of outer for loop */

fclose(fp);
getch();
}
```