An Innovative Approach To Making Ultra Light Weight Wind Turbine Blades

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ABSTRACT

An innovative mould free method for the fabrication of ultimate light weight small wind turbine blades made out of composites has been suggested in this paper. The method has been practically applied with very satisfactory results. The method is low cost and is specifically suitable for individual small wind turbine makers. The airfoils used are simple to shape and possess good C_l/C_d characteristics. The blades are crafted using galvanized iron sheets, aluminum pipes, hard paper and fiberglass. A computer program is included with tip correction features to design the blades at the required power rating, wind speed, tip speed ratio and the chosen constant angle of attack. Results of the program run for designing 250 and 500 watt wind turbine blades at 8 m/s wind speed and tip speed ratios of 5.5 are tabulated. Performance results of the blades thus produced are also discussed.

Key Words: **Wind Energy, Small Wind Turbines, Wind Turbine Blade Manufacturing.**

1. INTRODUCTION

Wind generated energy is the fastest growing energy technology in the world. One of the most popular features of this technology is its commissioning on site, which makes it an ideal source of energy for the dispersed population patches living in both the developing as well as the developed world. The last 14 year's data indicates a 25-30% annual growth rate [1]. USA wind generation capacity grew by nearly 60% in 2008 to currently over 31,000 MW, capable of meeting about 2% of its current total electricity needs, while Spain is meeting more than 11% of its entire electricity needs through the wind resource [2]. The EWEA (European Wind Energy Association) estimates the total EU electricity demand at around 4,400 TWh in 2030. The association has claimed that the wind resources would never be a limiting factor for Europe. There is enough energy over the seas of Europe to meet total European electricity demand several times over. The EWEA envisions the Europe's offshore installed wind power capacity to grow to 40 gigawatts by 2020 from 1.9 GW in 2009, and to 150 GW by 2030 [3]. The EU market for onshore wind grew by an average 32% per year in the 12-year period from 1992-2004. By the end of 2008, the total EU wind energy installed capacity was nearly 65,000 MW [4]. It is expected that similar growth patterns will be maintained in the now pursued, off shore developments.

While most of the new installed capacity in the world appears in the form of giant sized megawatt scale wind turbines, usage of small wind turbines is increasing at a rapid rate, even in countries like USA, due to special government incentives. Small wind turbines can be

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significant power resources that have proven records of performance even in locations with modest winds [5]. The US market for small wind turbines grew by 78% in 2008 adding 17.3 MW to the already installed capacity, while the global market grew by 53%. A large portion (60%) of the US growth was from wind turbines below 10 kW capacity. The industry projects a 30-fold growth in the next five years, for a cumulative US small wind turbine installed capacity of 1,700 MW by the end of 2013 [2].

Small turbines are of special interest to individual home, business and farm owners. Commercially available small wind turbines in the international markets are still expensive for users in the developing countries. There is a growing need to establish not only regional wind power industries but also developing workable windmill plans that could be easily implemented by individual users with reliable results. One of the major challenges associated with making wind turbines is the proper shaping of the blades for maximum energy harnessing. Most of the available techniques require the use of moulds which is not only expensive but makes the job significantly more complicated, especially for non-commercial enthusiasts. Crafting the blades from wood is also expensive and requires special skills. Out of the two major categories, the horizontal axis wind turbines have proven more promising due to their self starting and installation at height capabilities. The work reported in the current paper presents an easy to follow step-by-step, cheap and practical method for the fabrication of very light weight small horizontal axis wind turbine blades, using composites without needing any moulds.

Success with wind turbines requires not only a profound respect for the power from the wind but also analytical engineering skills and creative experimentation [6]. The first successful attempt to predict the shape of the blade of a HAWT (Horizontal Axis Wind Turbine) in terms of energy equations was made by Glauert [7]. These equations provide the essential relationships for analyzing each blade segment using two-dimensional airfoil data neglecting the effect of drag. The drag was incorporated by Miller, et. al. [8] and Stewart [9] for designing optimal rotors. Wilson, et. al. [10] provided further insight by including the tip correction features of the rotor blades. Wilson [11] also considered the effect of hub fairings on wind turbine rotor performance. Tangler, et. al. [12] provided a study of the airfoils designed especially for wind turbines. The wind-tunnel test data of airfoils designed for aircraft is provided by Abbot, et. al. [13]. Driesen, at. el. [14] have discussed small wind turbines in the built environment and their grid connection issues. White and White, et. al. [15] have discussed a way to improve the efficiency of wind turbines with smart rotor blades that can monitor the physical loads being applied by the wind and then adapt the airfoil for increased energy capture. More recently, a number of other researchers have contributed to the understanding of the effect of various airfoil characteristics on wind turbine rotor performance [16-18].

2. BLADE DESIGNING

The basic equation used for the designing of a wind turbine rotor is based upon the power available in the wind.

$$P = C_p \rho A V^3/2 \qquad (1)$$

Where C_p is the coefficient of performance of the wind turbine with a typical value between 0.25-0.35, and a limiting value of 0.59. ρ is the air density, with a typical value of ρ=1.2 kg/m^3. A is the swept area of the rotor blade and V is the free wind velocity.

Once the power required out of a wind turbine at a particular wind speed and a suitable choice of C_p is decided, the next step is to choose the TSR (Tip Speed Ratio), at which the blade will move cutting the free wind. This is carefully chosen subject to the airfoil properties, with a typical value between 4-8. The C_l/C_d curve of the chosen airfoil is used to select a specific angle of attack , typically, the angle at which the ratio is a maximum. Equation (1) provides the required length of the blade. Although more complex rotors consist of a number of different airfoil types, which attempt to acquire a large value of C_{lmax} near the root and small C_{lmax} near the tip which reduces the tendency to overpower the generator in high winds [8], it may be advisable to go with a single airfoil type in order to keep the fabrication simple.

Out of the more than a dozen theories studied for blade designing, the Linearized Tip Correction Theory, as presented by Vries [19] is chosen as most suitable for the current application, due to its relative ease of application and results very close to those of more complex ones. The theory is summarized by the following set of equations:

$$F = (2/\pi) \cos^{-1}[\exp\{(-B/2)((R_o - r)/r \sin\theta)\}] \qquad (2)$$

$$C_p = 8 \int_{x_{hub}}^{\lambda} F \sin^2 \theta (\cos\theta - X \sin\theta)(\sin\theta + X \cos\theta) \left[1 - \frac{C_d}{C_1} \cot\theta \right] X^2 \frac{dX}{\lambda^2} \qquad (3)$$

$$\theta_{opt} = MAX \left[F \sin^2 \theta (\cos\theta - X \sin\theta)(\sin\theta + X \cos\theta) \left\{ 1 - \frac{C_d}{C_1} \cot\theta \right\} \right] \qquad (4)$$

where λ,X, and C_d/C_l are held constant in the maximization process

$$\left(c \frac{C_1}{R_o} \right)_{opt} = \left[\left(\frac{8\pi}{B} \right) \left(\frac{r}{R_o} \right) F \sin\theta \big(\cos\theta - X \sin\theta\big) / \big(\sin\theta + X \cos\theta\big) \right]_{\theta=\theta opt} \qquad (5)$$

wherein Equations (2-5), F is the tip correction factor, r is the current span-wise position of the blade, R_o is maximum length of the blade, B is the number of blades chosen, θ is the angle between the blade chord and the plane of rotation of the blade, λ is the TSR chosen, X_{hub} is tip speed at the point of root cut, and $X = r\lambda/R_o$ is the local value of the TSR. C_l is the coefficient of lift at the chosen angle of attack, and c is the cord length at span-wise position r of the blade.

A computer program in FORTRAN to predict the shape of the blade, based upon the above set of equations is included in Appendix-A. The program utilizes an iterative approach for each span-wise position along the blade length, starting from $r=0.2R_o$, at which position the root is cut to avoid excessive twist and high cord values. At each selected value of r, Equation (4) is maximized for the entire range of possible values of θ. The optimized value θ_{opt} is used in Equation (5) to find the optimum chord length c, and in Equation (3) to integrate to the power coefficient C_p. Results of a run, for input values λ=5, R_o=1.86 meters and α=8 degrees are presented in Table l at 4 inches span-wise distances, for C_d, C_l data of NACA 4415 airfoil [20]. Figs. 1-2 show respectively, the basic shapes of NACA 4415 and Flat Airfoils. Angle of twist is obtained by subtracting from opt in each case. Optimized blade shape is plotted in Fig. 3 as predicted by the computer program based upon the above equations. The blade length is deducted for a 8m/s wind speed rating and C_p=0.3 assumption. Figs. 4-5 provide the coefficient of lift and coefficient of drag data respectively, of the NACA 4415 airfoil.

3. BLADE FABRICATION

The method described in this section has been successfully used to translate the designed parameters into a 3 feet long blade, for a 250 watt wind turbine at 8 m/s wind speed. Blade section parameters are listed in Table 1. The whole blade length is divided into 15 sections, 0.05 meters apart. The first section starts at 20% distance from the root to avoid large twist of the blade in that region. The corresponding cord length is 17.2cm, while near the tip (last section) chord length is 3.6cm. The step-by-step procedure is described as:

(i) Three pieces of galvanized iron sheet (22 gauge) are cut 73.8cm long each, such that each piece is 3.1cm wide on one side and is 16.7cm on the other as shown in Fig. 6, leaving a 5mm space along the length for fiberglass extension.

(ii) A 73.8cm long and 2 inches diameter aluminum pipe is cut into four identical pieces along the length, such that arc wise each piece is symmetrically 25mm on one side and 55mm on the other as shown in Fig. 7.

(iii) The whole length of each aluminum piece is to be given a total twist of 22 degrees as listed in Table 1. This is to be done carefully, as the rate of twist is not uniform throughout, it is much more near the root (55mm side) than near the tip.

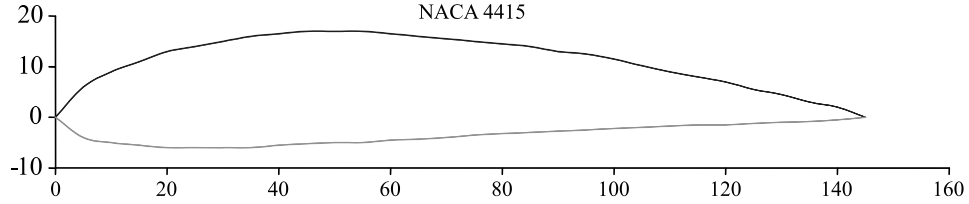


FIG. 1. BASIC SHAPE OF A NACA 4415 AIRFOIL

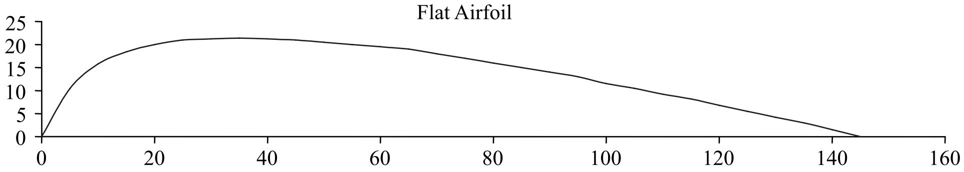


FIG. 2. BASIC SHAPE OF A FLAT AIRFOIL

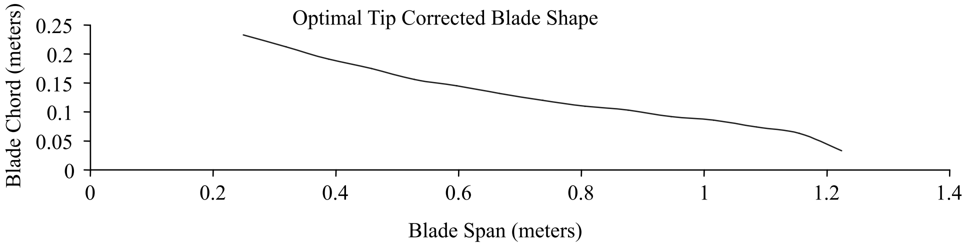


FIG. 3. OPTIMAL SHAPE OF A BLADE WITH TIP CORRECTION FEATURES AS OBTAINED THROUGH THE PROGRAM RUN

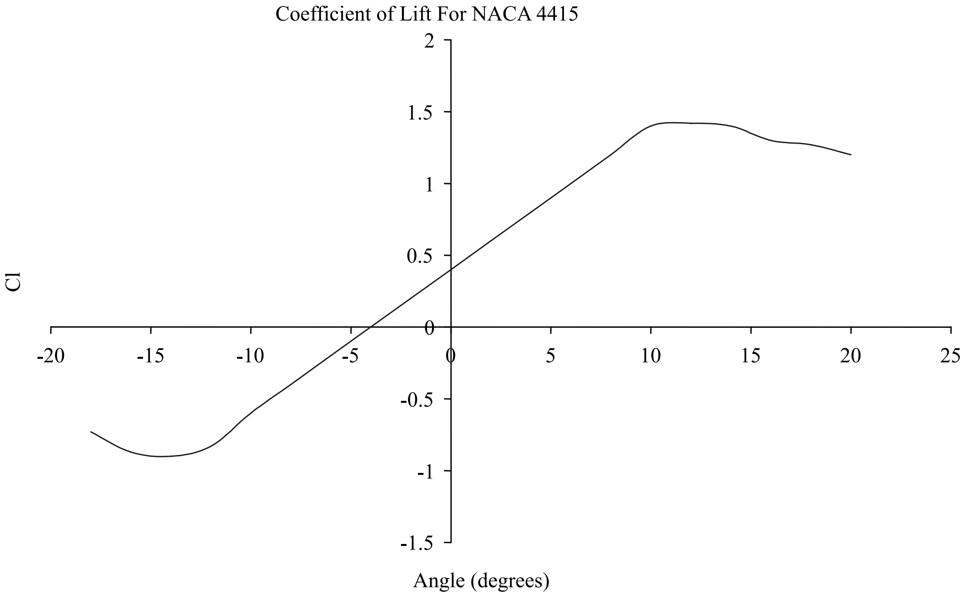


FIG. 4. COEFFICIENT OF LIFT FOR NACA 4415 VERSUS ANGLE OF ATTACK

(iv) According to the NACA 4415 profile, the maximum thickness of the airfoil occurs at 40% distance from the leading edge. The side of the

73.8cm long galvanized iron sheet having right angles at both the ends is to make the leading edge of the blade. Now the twisted piece of the

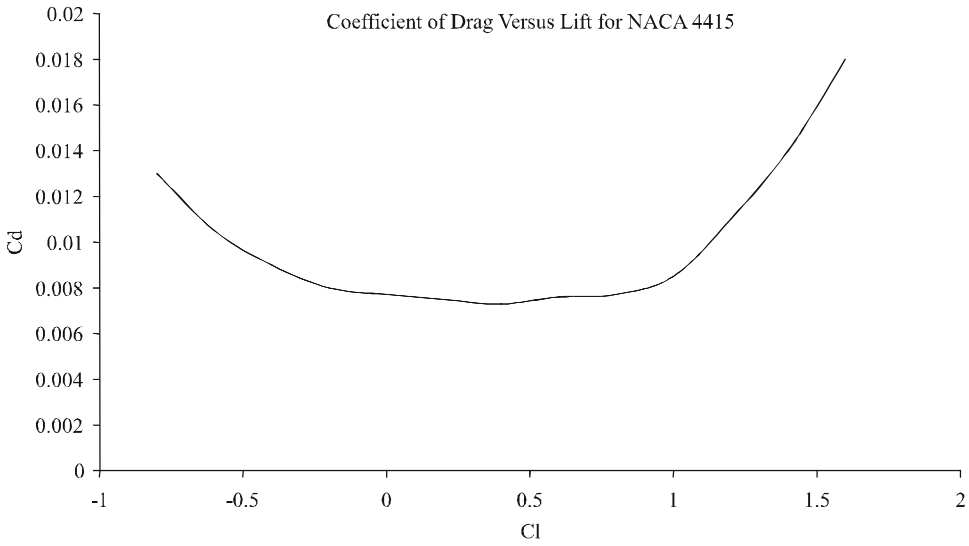


TABLE 1. BLADE DESIGN PARAMETERS AS PREDICTED BY THE LINEARIZED TIP CORRECTION THEORY, FOR 250 AND 500 WATT HAWT, BASED UPON NACA 4415 AIRFOIL, AT A=8, C_D/C_L=0.01, YIELDING C_P=0.47.APPENDIX-A

	500 Watt	250 Watt	Both	Both	500 Watt	250 Watt	Both
Blade Section No.	Radial Position (meters)	Radial Position (meters)	Twist $(q_{opt}-a)$ (Degrees)	$(c\ C_l/R_o)_{opt}$	Cord Length (meters)	Cord Length (meters)	Tip Correc Factor
1.	0.249	0.185	22.0	0.224	0.233	0.172	1.000
2.	0.319	0.235	17.5	0.205	0.212	0.158	1.000
3.	0.388	0.285	14.0	0.184	0.191	0.144	1.000
4.	0.458	0.335	11.0	0.169	0.175	0.130	1.000
5.	0.528	0.385	9.0	0.151	0.156	0.118	0.999
6.	0.597	0.435	7.0	0.139	0.145	0.108	0.999
7.	0.667	0.485	5.5	0.128	0.132	0.098	0.998
8.	0.737	0.535	4.5	0.116	0.120	0.090	0.995
9.	0.806	0.585	3.5	0.106	0.110	0.084	0.989
10.	0.876	0.635	2.5	0.099	0.103	0.077	0.980
11.	0.946	0.685	2.0	0.088	0.092	0.072	0.959
12.	1.015	0.735	1.0	0.083	0.086	0.066	0.928
13.	1.0854	0.785	0.5	0.072	0.074	0.059	0.857
14.	1.155	0.835	-0.5	0.061	0.063	0.050	0.735
15.	1.224	0.885	-0.1	0.032	0.043	0.036	0.403

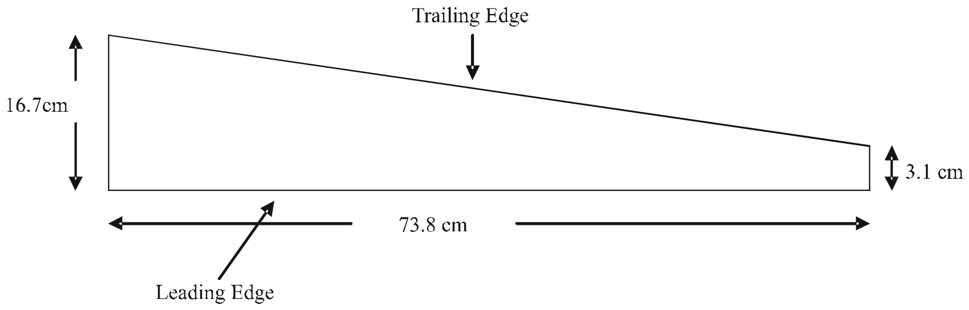
aluminum pipe is placed over this sheet such that the distance of the central line of the piece is 14.4mm from the leading edge on one end and 70mm on the other. The position of the aluminum piece is marked on the sheet drawing straight lines.

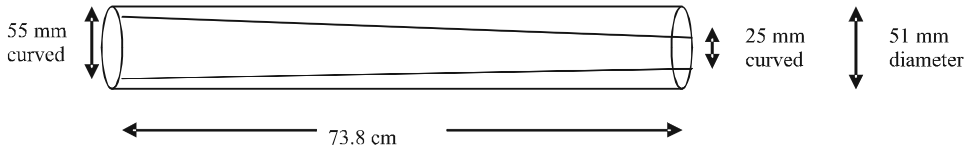
(v) Now 0.5mm holes are drilled on both sides along the length of these lines, as well as along the length of the aluminum piece, at 10mm intervals.

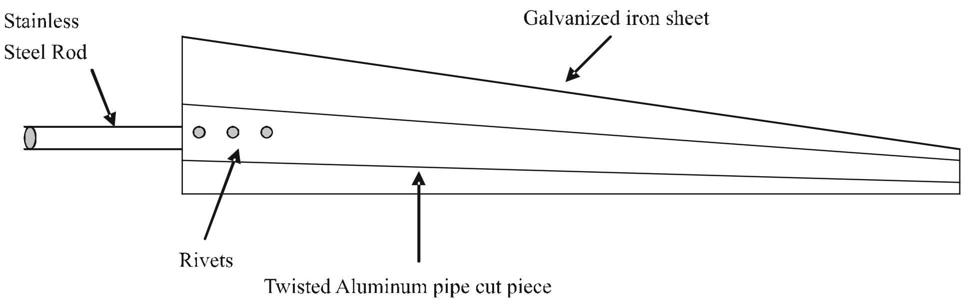
(vi) In the next stage, fishing cord is used to stitch the aluminum piece with the galvanized iron sheet. The galvanized sheet will thus acquire the desired twist and the aluminum pipe will give it not only bending strength, but also determine the shape of the desired airfoil (NACA 4415 in this case).

(vii) Now a piece of seven inches long 12mm diameter stainless steel pipe is inserted up to 2 inches, between the wider ends of the sheet and the aluminum pipe. Three holes are drilled from the top and riveted as shown in Fig. 8.

(viii) Now 25cm wide each, pieces of three cardboards are glued around the sheet, one after the other to impart the whole blade an airfoil shape. This is dried and then cut along the trailing edge of the blade.







(ix) Finally, two to three layers of fiberglass are applied onto this surface. Sandpaper is applied to smooth the surface, which is then polished and painted.

(x) After preparing all the three blades this way, a 50mm thick piece of wood is cut into a circular shape with 150mm diameter. Three holes, 120 degrees apart and 12mm diameter are drilled up to 50mm depth on to the periphery of this disc in the radial direction.

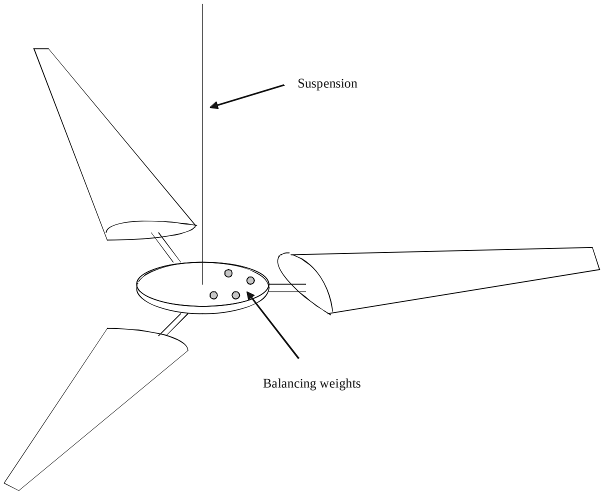
(xi) The root rods of the blades are inserted into the above holes. Care is to be exercised that the tips of all the three blades are held parallel to the plane of rotation of the rotor. Now the drill is applied from the top of the wooden disc, making holes through the stainless steel rods and then screws are inserted so that each blade gets tightly fixed at its position.

(xii) The next stage is to balance the rotor. This can be achieved by drilling a small hole in the center of the wooden disc, and then horizontally suspending the whole rotor using a rope passing through this hole. If the rotor shows any trend of tilting on any one side, counter weights (usually made out of 5mm diameter cylindrical lead shots or iron pieces) are placed on the opposite side of the wooden disc, until the tips of all the three blades acquire same distance from the ground - meaning that the whole rotor becomes perfectly horizontal as shown in Fig. 9.

(xiii) The lead shots are then hammered into the wooden disc at their respective positions after drilling tight holes at the spots. The rotor is now ready for mounting onto a hub or nacelle of the wind turbine (Fig. 10).

4. CONCLUSIONS

A simple to follow and inexpensive step by step approach for the designing and fabrication of ultra light weight blades for small HAWT is presented in this paper. The designing is based upon linearized tip correction



theory, which is translated into a FORTRAN program. The program requires the blade length, tip speed ratio, number of blades and the C_d and C_l data of the respective airfoil as the input parameters, and gives the local twist angle and cord length at different span-wise sections as the output. Program inputs and outputs for a 250 watt and a 500 watt wind turbine are tabulated. A mould-free method is proposed for translating the design into actual product. The method is most suitable for individual wind turbine makers. The raw materials to be used are galvanized iron sheet, aluminum pipe, fishing cord, cardboard, stainless steel pipe, fiberglass and wood. The method has been practically applied at the Pakistan Navy Engineering College, Karachi, for the fabrication of wind turbines. For the 250 watt wind turbine, six feet diameter three bladed rotor with wooden

APPENDIX-A

PROGRAM TO DETERMINE THE TWIST & TAPER OF H-AXIS WIND TURBINES *
SUHAIL ZAKI FAROOQUI-JUNE, 2009

PROGRAM BLADE

```
LENGTH      = BLADE LENGTH
NUMBER      = NUMBER OF BLADES IN THE ROTOR
RAD         = CURRENT WORKING RADIUS
CORD        = CORD LENGTH AT THE GIVEN RAD
FIND        = INDUCTION FACTOR IN THE WIND DIRECTION
PFIND       = INDUCTION FACTOR PERPENDICULAR TO THE WIND DIRECTION
PHI         = ANGLE OF RELATIVE WIND W.R.T. PLANE OF ROTATION
THETA       = ANGLE OF THE CHORD W.R.T. PLANE OF ROTATION
ALPHA       = ANGLE OF RELATIVE WIND W.R.T. CHORD
TSR         = TIP SPEED RATIO
TSR2        = 2ND TIP SPEED RATIO FOR TWO POINT OPTIMIZATION
VELCTY      = VELOCITY OF THE WIND
CL          = COEFFICIENT OF LIFT
CD          = COEFFICIENT OF DRAG
SOLID       = SOLIDITY RATIO OF THE TURBINE

COMMON /VARIALS/CD,CL,LENGTH,VELCTY,FIND,PFIND,TSR,PI,ALPHA,NUMBER
REAL CD(-12:12), CL(-12:12), LENGTH, VELCTY, FIND, PFIND, TSR,
1             PI
INTEGER ALPHA, NUMBER

WRITE(*,*)'ENTER BLADE LENGTH AND WIND VELOCITY'
READ(*,*)LENGTH,VELCTY
WRITE(*,*)'ENTER THE TWO INDUCTION FACTORS'
READ(*,*)FIND,PFIND
WRITE(*,*)'ENTER THE TIP SPEED RATIO AND NUMBER OF BLADES'
READ(*,*)TSR,NUMBER

WRITE(*,*)'ENTER THE REQUIRED ANGLE OF ATTACK'
READ(*,*)ALPHA

OPEN(UNIT = 20, FILE = 'NACA4415', STATUS = 'OLD')
OPEN(UNIT = 21, FILE = 'BLADE', STATUS = 'OLD')
PI = 3.141592654

WRITE(21,13)'FIND = ',FIND,' PFIND = ',PFIND
WRITE(21,13)'LENGTH = ',LENGTH,' VELCTY = ',VELCTY
WRITE(21,14)'ALPHA = ',ALPHA,' TSR = ',TSR
WRITE(21,12)'RADIUS','PHI ','THETA ','CORD ','FIND ','    PFIND'
WRITE(21,12)'------','--- ',' ----- ',' ---- ','---- ','    -----'
12    FORMAT(4(2X,A7),2(2X,A9))
13    FORMAT(2(2X,A10,2X,F6.3))
14    FORMAT(4X,A8,I2,1X,A8,F5.2,/)

CALL TIPCOR
STOP
END
```

LINEARIZED TIP CORRECTION THEORY

```
SUBROUTINE TIPCOR

COMMON /VARIALS/CD,CL,LENGTH,VELCTY,FIND,PFIND,TSR,PI,ALPHA,NUMBER
REAL CD(-12:12), CL(-12:12), LENGTH, VELCTY, FIND, PFIND, TSR, PI
INTEGER ALPHA,NUMBER

WRITE(*,*)" PROVIDE THE CHOSEN Cl, Cd/Cl RATIO AND STEP SIZE"
READ(*,*)CLIFT, CDCL, DELTA
WRITE(21,*)
WRITE(21,8)CLIFT,CDCL,DELTA
8     FORMAT(2X,"CLIFT=",F5.3," Cd/Cl = ",F5.3," STEP SIZE = ",F5.3,/) WRITE(21,9)
9     FORMAT(5X,'LINEARIZED TIP CORRECTION THEORY',/) WRITE(21,10)
10    FORMAT(3X,'RADIUS',4X,'TWIST',5X,'CCl/Ro',3X,'CORD',3X,'TIPFAC')
      WRITE(21,11)
11    FORMAT(3X,'------',4X,'-----',5X,'------',2X,'------',2X,'------')
DO 90 RAD     = 0.2*LENGTH, LENGTH, DELTA

TEMPO         = 0.
COFPR         = 0.
TSRL          = RAD * TSR / LENGTH

DO 80 THETA = 1.,50.,0.5
THET          = THETA * PI / 180
RATIO         = (LENGTH - RAD)/(RAD*SIN(THET))
TIPFAC        = 2./ PI * ACOS(EXP(-NUMBER*RATIO/2.))
OPTANG        = TIPFAC * (SIN(THET))**2*(COS(THET)-TSRL*SIN(THET))
OPTANG        = OPTANG * (SIN(THET) + TSRL*COS(THET))
OPTANG        = OPTANG * (1. - CDCL * COS(THET)/SIN(THET))
                IF(OPTANG.GT.TEMPO)THEN
TEMPO         = OPTANG
ANGMX         = THET
COFPR         = TEMPO * TSRL**2

ENDIF

80    CONTINUE

RATIO         = (LENGTH - RAD)/(RAD*SIN(ANGMX))
TIPFAC        = 2./ PI * ACOS(EXP(-NUMBER*RATIO/2.))
COORD         = (COS(ANGMX)-TSRL*SIN(ANGMX)) (SIN(ANGMX)+TSRL*COS(ANGMX))
COORD         = COORD * TIPFAC * SIN(ANGMX) * RAD/LENGTH * 8. * PI/NUMBER
CORD          = COORD * LENGTH / CLIFT
ANGMX         = ANGMX * 180. / PI - ALPHA
COFPER        = COFPER + COFPR * DELTA * TSRL / RAD
                WRITE(21,91)RAD,ANGMX,COORD,CORD,TIPFAC

90    CONTINUE

COFPER        = COFPER * 8. / TSR**2
WRITE(21,*)
WRITE(21,*)"COEFFICIENT OF PERFORMANCE = ",COFPER

91    FORMAT(5(3X,F6.3))

RETURN
END
```

disc weighed less than 1.8 kilograms. The rated wind speed for the turbine was 8m/s. At the rated wind speed the rotor was supposed to turn at about 455 RPM, with a tip speed ratio of 5.5. The measured RPM at this wind speed was about 450, in very good agreement with the prediction. The rotor operated quite smoothly at this RPM without showing any signs of vibration or unexpected noise. The above outlined step-by-step procedure may be accordingly modified for any blade length. It is expected that the expertise gained and technology developed at the Institute will help bring down the costs in setting up local wind turbine manufacturing industries, as well as encourage the individuals to develop their own wind power systems.

ACKNOWLEDEGMENT

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