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EDITORIAL

Growth of Wind Power Industry has been rather slow in 2008 with global economic crisis looming large. Recession is on the path of reversal and several entrepreneurs are re-entering the Indian Market. With the result, India is slowly moving towards an annual market of 5000 MW by 2012. Small Wind Turbine (SWT) and Wind Solar Hybrid System (WSHS) are gaining popularity. In Maharashtra, Goa and Karnataka installations of these systems range from 0.3 kW to 50 kW machines.

The logistic difficulties of Indian Wind Industry such as large rotors for turbine development, evacuation of power in the weak grid and other power quality issues are well known. In a way, such difficulties have had an arresting effect in grid interactive wind energy generation. So, if right incentives like taxation benefits for investments by individuals are extended, the Small Wind Turbines can effectively contribute to meet the peak load demands in urban areas, particularly by erecting roof top Wind Solar Hybrid Systems. A galaxy of (SWT/WSHS) such systems is known by the name Micro Wind Generation. With new technologies of net metering (export/import of grid), micro generation has been gaining momentum in Europe and America. Not to be left alone, India is also catching up with more than 1 MW installations of these small systems. In Pune, a Corporate House is meeting 8% of its energy requirements by installing a cluster of more than 20 SWTs for micro wind generation. Scientific and technical concepts and aesthetics of SWTs keep varying to suit the environment they are installed. Small Wind Turbine Certification Council (SWCC) of US is a special body working on a certification procedure in close co-ordination with manufacturers in US and Europe. Efforts of C-WET have also been contemporary to these world wide developments with ardent hope of quality development of SWTs in India.

The R&D unit has several plans to develop indigenous blades for Wind Turbines, particularly the small ones. A comprehensive survey with the assistance of MNRE and WISE, Pune has been conducted for capacity addition of 5000 MW of wind power by 2012 and for the development of an Indian Market for Small Wind Turbines. Overcoming the issues of infirmity of wind power with varying wind velocities has been a grey area in the sector as a whole. With the latest trends in technology, wind resources are also predictable and can be forecast. A pilot project on such prediction and forecasting has commenced with an industry partner at Kayathar in C-WET's R&D wind farm for validation compared with wind and power generation parameters. Two SWTs have been tested during this windy season and further measurements are going on based on IEC 61400-2. Measurement of Acoustic Noise Emission of wind turbines in India was yet another milestone and its report was presented at an International Conference held in Denmark.

WRA unit is busy all the time on third party wind monitoring, production estimation, site assessment, due diligence, micrositing and wind data acquisition. Ninety wind monitoring stations operating from Twenty States are being maintained actively. Four new Stations have been added in Nagaland and Meghalaya during this period. Wind profile at Dhanushkodi in Rameswaram has been measured with the help of Sodar (Sound Detection and Ranging) technique, unique by non deployment of met-mast in the process.

Testing unit is actively exploring the possibility of establishing test facilities for wind turbine blades in India. Blade instrumentation and power curve measurements kept them busy all through the period apart from Type-Testing. Two provisional Type Certifications have been renewed by the S&C unit. The industry is being helped consistently for getting their models included in the quarterly RLMM list by timely compilation and evaluation of documentation by this unit. ITCS participated in URJA-2009 at Cochin. Sixty Nine participants attended the 7th National Training Programme on "Fundamentals of Wind Energy Technology" organised by ITCS unit.

The Global Wind Day was celebrated in C-WET with a special lecture by Shri V. Subramanian, IAS., former Secretary, MNRE on 15.06.2009 who also inaugurated a comprehensive Display Centre with working Wind Turbine models.

We had the proud privilege of hosting the visit of a dignitary to our Campus on 20-06-2009. Dr. Farooq Abdullah, Hon'ble Minister of New & Renewable Energy, Government of India, paid an official visit to the Campus. He went around the campus, inspected the facilities and provided valuable guidance to the scientists in furthering the cause of Renewable Energy. The Hon'ble Minister reassured his commitment of helping C-WET to attain greater heights of International acclaim in the field of Wind Energy.

With active participation of all stake holders we are confident in moving ahead even in Research & Development of wind power in India. Constructive criticism on our activities and on this publication is welcome. Thank you all for the interest shown in responding to our articles in Pavan.

Dr. S. Gomathinayagam
Executive Director

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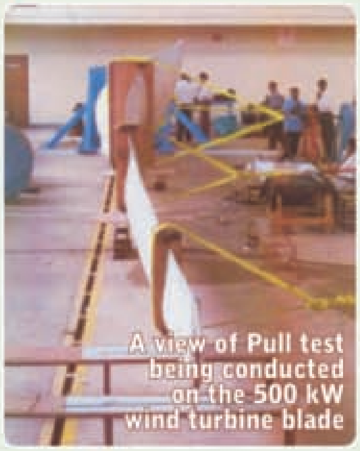
Development and validation of design methodologies and design tools to enable wind turbine rotors / blade to be optimized for low and moderate wind regimes



A view of Pull test being conducted on the 500 kW wind turbine blade

The R&D unit in association with National Aerospace Laboratories, Bangalore has carried out a comprehensive programme for indigenous development and validation of design methodologies and design tools for wind turbine rotors / blades. An effective indigenous design methodology has been evolved. This has been applied to the design and development of a 500 kW NMITLI 2 – bladed, stall-regulated horizontal-axis wind turbine which is fitted with Gurney flaps and which is to be field tested at a wind farm at Kethanur, Coimbatore District during the 2009 wind season.

Wind energy forecasting for the R&D / experimental wind turbine – a technology demonstration project

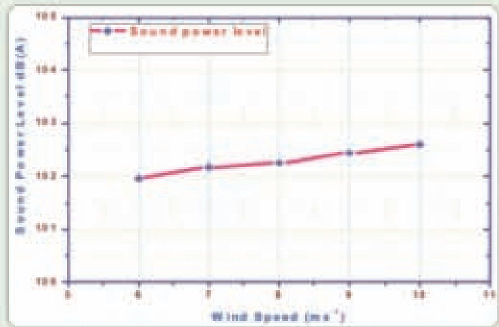
The unit proposes to carry out a project in association with 3-TIER R&D India Pvt. Ltd., Bangalore, to forecast hourly, daily and weekly wind energy power for the R&D/Experimental Wind Farm at Kayathar, Tamil Nadu. The results will help in establishing the reliability of the forecasting system (3-TIERSM) and act as a technology demonstrator to wind energy power generation companies.

Discussion meet on "Wind Solar Hybrid System to be installed in the State of Kerala"

Unit Chief, R&D, participated a discussion meet on "Wind Solar Hybrid System to be installed in the State of Kerala" organized by Agency for Non-Conventional Energy & Rural Technology (ANERT) to create awareness among the selected users as well as prospective beneficiaries. A detailed technical presentation was made on the subject.

Acoustic Noise Emission characteristic study at R&D/experimental wind farm

The unit conducted a study on Acoustic Noise Emission Characteristic of a wind turbine at WTTS, Kayathar. A paper on "Assessment of Acoustic Emissions of a Wind Turbine in India" was presented at Third International Meeting on Wind Turbine Noise at Aalborg, Denmark.



Sound power level Vs Standardized wind speed

Move on in WRA UNIT

During the period of April to June, 4 new Wind Monitoring stations in 2 states (Nagaland & Meghalaya) have been installed. Presently, 90 wind monitoring stations are operational in 20 states and one in Union Territory under various wind monitoring projects funded by the Ministry and other agencies.

Projects on Verification of Procedure for Wind Monitoring at Theni site in Tamilnadu for M/s. Vestas Wind Technology India Private Limited, Chennai, Shiravalli in Satara District of Maharashtra for M/s. Kenersys India Private Limited, Pune, Akal, Jaisalmer District in Rajasthan (Extn.), and Pohra, Jaisalmer District in Rajasthan (Extn.) for M/s. RRB Energy Limited, Chennai and 67 stations in Maharashtra for Maharashtra Energy Development Agency, Pune have been taken up during this period.

Projects on Production Estimation for 20 MW wind farm at Sinnar, Nashik in Maharashtra for M/s. ITC Limited-Hotel Division, Chennai, Energy Generation Estimation for 29.7 MW Wind Energy projects at Arasinagundi and Anabaru in Davanagere District, Karnataka for M/s. Acciona Wind Energy Pvt. Ltd, Bangalore and Micrositing & Annual Generation Estimation for 10 MW wind farm at Kurtkoti Village in Gadag District, Karnataka for M/s. Farmers Wind Power Resources Pvt. Ltd, Bangalore have been taken up during these period. Projects on Wind Resource Assessment Studies at Ambalapuzha IT Park, Kerala for M/s. Infopark, Kochi, Siddavvannadurga site, Chitradurga District, Karnataka for M/s. NSL Power Private limited, Hyderabad and Kukuru region, Betul District, Madhya Pradesh for M/s. Narmada Hydroelectric Development Corporation Ltd, Bhopal have also been taken up during this period.

WRA unit has completed the following projects and submitted reports during this period :

10 Nos. of Verification of Procedure of Wind Monitoring at Sripalvan (Satara District in Maharashtra), Jaibhim & Jambhore (Dhule district in Maharashtra), Vavaniya, (Rajkot district in Gujarat) Nivali & Golbawadi (Barwani district in Madhya Pradesh), Maliya (Rajkot district in Gujarat), Kudre Konda (Shimoga district in Karnataka) Theni 1 (Theni district in Tamil Nadu) and Soda Bandhan (Jaisalmer district in Rajasthan) for different wind farm entrepreneurs.

- Site assessment for wind monitoring in the Telungana region for M/s. Belum Wind Infrastructure Pvt. Ltd, Hyderabad.
- Site assessment for wind monitoring in the Rayalaseema region of Andhra Pradesh for M/s. Rayalaseema wind Energy Company Pvt. Ltd, Hyderabad.
- Production Estimate of 5 x 1500 kW wind farm at Kappatagudda in Gadag District, Karnataka for M/s. Suzlon Energy Ltd, Pune.
- Production Estimate of 3 x 1500 kW Wind farm at Elkurnahalli in Chitradurga District, Karnataka for M/s. Suzlon Energy Ltd, Pune.
- Site Validation & Generation Estimate of Proposed 50.4 MW Wind Farm Project at Chavaneshwar, Satara District in Maharashtra for M/s. Enercon (India) Limited, Mumbai.
- Micrositing & Generation Estimate of Proposed Wind Farm Project at Kurtkoti village of Gadag District in Karnataka for M/s. Farmers Wind Power Resources Pvt. Ltd, Hulkoti.
- Site Validation & Generation Estimate of Proposed 9.0 MW wind farm project at Sinnar, Nashik District in Maharashtra for M/s. ITC Limited-Hotel Division-HQ, Gurgaon.
- Site Validation & Generation Estimate of 29.7 MW wind farm projects at Anabaru & Arasinagundi sites in Davangere District, Karnataka for M/s. Acciona Wind Energy Pvt. Ltd, Bangalore.

SODAR Project

Wind profile Measurement at Dhanushkodi in Rameshwaram, Ramanathapuram district has been carried out by using SODAR.

Steps forward in TESTING UNIT

- Instrumentation for static blade testing for a blade used in 1 MW Wind Turbines manufactured by M/s. Winwind was carried out at their premises in Vengal during the month of May 2009.
- An agreement has been signed between C-WET and M/s.Winwind for Power Curve Measurements of 1000 kW Wind Turbines erected at Ayyanaruthu near Kayathar.
- Establishment of a Remote Access Provision to data measurement at various sites using MPLS (Multi Protocol Label Switching) has been initiated at C-WET.

Marching ahead in S&C UNIT

Completed Projects/Activities

- The Renewed Provisional Type Certificate has been issued to M/s. Southern Wind Farms Ltd. for GWL 225-225 kW wind turbine model upon successful completion of review of documentation for renewal.
- The Renewed Provisional Type Certificate has been issued to M/s. RRB Energy Ltd. for V 39-500 kW with 47m Rotor wind turbine model upon successful completion of review of documentation for renewal.
- Manufacturing facility of M/s.Winwind Power Energy Private Ltd. has been verified by S&C Engineers for RLMM purpose.
- Revised List of Models and Manufacturers of Wind Electric Generators / Wind Turbine Equipment (RLMM) has been issued on 08.04.2009.
- Documentation / information have been obtained from the wind turbine manufacturers for updating the RLMM. Reviewed the documentation and organized the next RLMM meeting on 18.06.2009.The updated RLMM has been issued on 22.06.2009.

Current Activities

- The certification projects, taken up as per TAPS-2000 (amended) are under progress.
- The continual improvement and maintaining the Quality Management System are ongoing.

Highlights from ITCS UNIT

Participation in Exhibition

C-WET stall has been put up in URJA 2009, a National Exhibition on Energy Efficient & Renewable Energy Products and Technologies during 21st to 25th May 2009 at Town Hall, Ernakulam, Cochin, wherein the information about C-WET's activities and services has been disseminated. The technical explanation at the stall was well appreciated.

National Training Course

ITCS unit had successfully organized the seventh National training course on "Fundamentals of Wind Energy" during 28th & 29th May 2009 to address all aspects of Wind Power starting from Wind Resource Assessment to project implementation and operations & maintenance in a focused manner. The course was attended by 69 participants from academic institutes, industry, State Nodal Agencies, developers and consultants from various part of the country. The training course was inaugurated by Dr. Michael Hogedal, Managing Director & Vice President, Vestas Wind Technology India Private Limited.

Dr. Michael Hogedal delivering inaugural address (Left)
Shri. Raju Manoharan read out the valedictory address (Right)

The following were the issues addressed in the training course : 1. Introduction to wind energy, evolution & developments 2. Government policies and supportive schemes & programme 3. Environmental issues 4. Wind resource assessment 5. Design of carefully vetted wind farming projects 6. Installation & commissioning of wind farms 7. Investment techniques 8. Integration of WE to grid 9. O&M aspects of wind farms 10. Detailed description of success stories and focussed case studies 11. Finance opportunities.

Shri.Raju Manoharan, Supernatant Engineer, Non-Conventional Energy Sources (NCES), Tamil Nadu Electricity Board (TNEB) has made his presence and read out the valedictory address on behalf of Shri. T. Jayaseelan, Chief Engineer, NCES, TNEB and distributed the course certificate to the participants.

Display Facilities

ITCS unit established display facilities in the Display Hall, which will showcase the activities & services of C-WET and demonstrate the wind turbine technologies. This facility has been established with the aim of disseminating the information about C-WET and the existing wind technologies to the visitor of the campus.

Global Wind Day

C-WET celebrated "Global Wind Day 2009" for the first time in India on 15th June 2009 between 11 am to 1 pm . Shri.V.Subramanian, I.A.S. former Secretary, MNRE delivered a Wind - Day lecture on "Wind Energy: Global Scenario" at C-WET lecture hall.

Various stake holders from State Nodal Agencies, Industries and Association of wind energy sector, including investors in wind energy attended the Wind Day lecture.

Shri. V. Subramanian also inaugurated a Display Facility of C-WET, where the working models of wind turbine and information about C-WET activities and services are described.

Honourable Minister visits C-WET Campus

Honourable Minister of New and Renewable Energy, Government of India, Dr. Farooq Abdullah visited C-WET on 20th June 2009.

Dr. S. Gomathinayagam, Executive Director, C-WET made a brief presentation about C-WET explaining its activities & services.

Honourable Minister visited the newly inaugurated display facilities, library, laboratories & facilities of all the units of C-WET. He had an interesting and insightful discussion with all the unit chiefs and scientists, inspiring them to contribute more in the area of wind energy.

He also planted a sappling in the Centre in commemoration of his visit.

Ms. Gauri Singh, Joint Secretary, MNRE and Mr. K. P. Sukumaran, Advisor, MNRE made their presence to grace the occasion.

AERODYNAMICS OF HORIZONTAL AXIS WIND TURBINES

Prof. S. Soundaranayagam (Retd.), Indian Institute of Science

A horizontal axis wind turbine or windmill is essentially an axial flow machine and its aerodynamics can be described in terms of axial turbo machine theory. The nomenclature used is as listed below :

a	Axial inflow factor
a'	Rotational inflow factor
C	Absolute air velocity
c	Blade chord
P	Power
Q	Torque
R	Radius of windmill rotor
r	Local radius
T	Thrust
u_∞	Free Stream wind speed
u	Air axial velocity
W	Air velocity relative to rotating blade
Z	Blade number
C_P	Power Coefficient $\frac{P}{\pi R^2 \rho u_\infty^3}$
C_Q	Torque Coefficient $\frac{Q}{\pi R^2 \rho u_\infty^2}$
C_T	Thrust Coefficient $\frac{T}{\pi R^2 \rho u_\infty^2}$
C_L	Profile lift Coefficient
C_D	Profile Drag Coefficient
λ	Local blade speed ratio $\frac{\tau\Omega}{u_\infty}$
λ_t	Blade tip speed ratio of rotor $\frac{R\Omega}{u_\infty}$
Ω	Angular velocity

Flow through rotor

As wind approaches a wind mill it would be slowed down due to the resistance offered by the rotor. There would be a drop in pressure after the rotor and the flow which passed through the rotor will continue to slow down further as its pressure rises again to atmospheric pressure far downstream. The flow that passed through the rotor will be contained within a slip stream enclosed by a sheath formed by shed vortices or vortex lines leaving the blade tips. Extrapolating the slip stream upstream the envelope would form an expanding tube with the boundaries being parallel far upstream and downstream as the flow there would be in equilibrium with the surrounding atmosphere. There would be some rotation within the slipstream downstream due to the change in angular momentum suffered in passing through the rotor. This rotation would be accompanied by a radial pressure gradient given by $\frac{dp}{dr} = \frac{\rho C_\theta^2}{r}$ The residual rotation would be small in a lightly loaded windmill and the radial pressure gradient could be ignored. In that event the pressure within the slip stream far upstream and downstream would be atmospheric, the same as in the surrounding airstream.

We treat the windmill rotor as a disc across which these is a sudden change in pressure and angular momentum. Due to reasons of continuity the axial velocity would be continuous across the disc and would have the same value immediately before and after the disc. The velocity 'u1' entering the slipstream would be equal to the free stream velocity u_∞ while the velocity leaving the slip stream far downstream 'u2' would be less than the free stream velocity (Fig. 1).

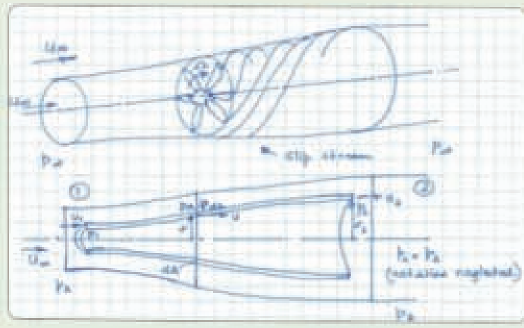


Fig. 1. Stream tube representation of flow past wind mill

Consider an annular ring and the stream tube defined by it. Applying Bernoulli's equation to relate P_{d1} and u to conditions far upstream and P_{d2} and u to conditions far downstream.

$$p_1 + \frac{1}{2}\rho u_1^2 = p_{d1} + \frac{1}{2}\rho u^2$$

$$p_2 + \frac{1}{2}\rho\left[u_2^2 + C_{\theta 2}^2\right] = p_{d2} + \frac{1}{2}\rho\left[u^2 + C_\theta^2\right]$$

Where C_θ is the tangential velocity just after the disc and $C_{\theta 2}$ the tangential velocity downstream. Due to conservation of circulation.

$$rC_\theta = r_2 C_{\theta 2}$$

$$p_2 + \frac{1}{2}\rho u_2^2 + \frac{1}{2}\rho C_{\theta 2}^2 = p_{d2} + \frac{1}{2}\rho u^2 + \frac{1}{2}\rho C_\theta^2$$

The Pressure drop across the disc will be

$$\Delta p = p_{d1} - p_{d2} = (p_1 - p_2) + \frac{1}{2}\rho\left(u_1^2 - u_2^2\right) + \frac{1}{2}\rho C_\theta^2\left[1 - \left(\frac{C_{\theta 2}}{C_\theta}\right)^2\right]$$

Due to conservation of circulation

$$rC_\theta = r_2 C_{\theta 2}$$

$$\frac{C_{\theta 2}}{C_\theta} = \frac{r}{r_2}$$

$$\Delta p = (p_1 - p_2) + \frac{1}{2}\rho(u_1^2 - u_2^2) + \frac{1}{2}\rho C_\theta^2\left[1 - \left[\frac{r}{r_2}\right]^2\right]$$

In a lightly loaded windmill C_θ would be small. Also the enlargement of the slip stream downstream would be small making $\left(\frac{r}{r_2}\right) \rightarrow 0$.

The last term in the equation above would be very small and is neglected. Furthermore p_1 and p_2 would be equal to p_A and $(p_1-p_2)=0$, giving

$$\Delta p = \frac{1}{2}\rho\,(u_1^2-u_2^2) = \frac{1}{2}\rho\,(u_1+u_2)(u_1-u_2)$$

Thrust on the elemental annulus of the disc would be

$$\Delta T = \Delta p \Delta A = \Delta A \frac{1}{2}\rho\,(u_1+u_2)(u_1-u_2) \qquad (1)$$

The thrust can also be estimated from momentum considerations.

Mass flux through the annulus $= \rho \Delta A\, u$

Change in its axial momentum flux $= \rho \Delta A\, u\, [u_1-u_2]$

The force on the air in the annulus causing this change in momentum is the thrust on the disc element plus the pressure force on the full annulus surface. The pressure at stations 1 and 2 is p_A. At very low blade loading the resistance offered by the rotor would be small and the enlargement of the stream tube would be small. In the limit of zero loading the annulus would be a straight cylindrical tube and the integrated axial pressure force would be zero. At low loadings we take the axial force to be due to the disc thrust alone.

$$\Delta T = \rho \Delta A\, u\, [u_1-u_2] \qquad (2)$$

Comparing equations 1 and 2 we get

$$u = \frac{1}{2}[u_1+u_2] \qquad (3)$$

that is, the axial velocity at the rotor disc is the mean of the axial velocities far upstream and downstream.

Recognizing that the inlet velocity u_1 is the same as the wind velocity u_∞, we can write

$$u = u_\infty (1-a) \qquad (4)$$

Where 'a' is the axial inflow factor.

The rotor does not see the full wind speed u_∞. It sees an effective wind speed $(1-a)u_\infty$. The change in axial velocity (u_1-u_2), from far upstream to far downstream is

Change in axial velocity $(u_1-u_2) = 2au_\infty$.

The elemental thrust is now

$dT = 2\pi r\, dr\, \rho\, u\, [u_1-u_2]$

$$\text{or } \frac{dT}{dr} = 4\pi . r . \rho . u_\infty^2 . (1-a) . a \qquad (5)$$

The torque on the blading can be estimated by calculating the change in angular momentum of the air in passing through the rotor. At an annular cross-section of the blading the profiles can be laid out to form a linear cascade. The blades see an axial velocity $(1-a)\,u_\infty$ which when combined with the blade tangential velocity $r\,\Omega$ gives a relative flow velocity W_1. The relative velocity W1 is deflected (Fig.2) in passing through the rotor to give an exit relative velocity W_2 (and an absolute exist velocity C_2). The change in tangential velocity is ΔW_θ. The change in absolute tangential velocity is ΔC_θ

$$\Delta W_\theta = \Delta C_\theta$$

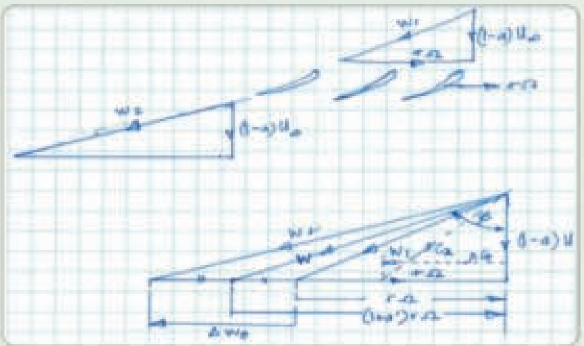


Fig.2. Relative flow velocity past a rotor-blade's airfoil cross section

The free stream velocity that the blade sees is the vector mean of W_1 and W_2. This effective velocity W is the free stream velocity associated with the Kutta-Joukowski theorem and gives the blade forces in conjunction with C_L and C_D.

The tangential component of the relative velocity that the blade sees is larger that $r\,\Omega$.

$W \sin\phi = (1+a')\, r\Omega$

Where a' is the rotary inflow factor.

It is easily seen that

$$\Delta W\theta = 2a' r\Omega \qquad (6)$$

$$\tan\phi = \frac{(1+a')\, r\Omega}{(1-a)\, u_\infty} = \frac{\lambda\,(1+a')}{(1-a)}$$

$$\text{or} \quad \tan\phi = \lambda_t . \frac{(1+a')}{(1-a)} \frac{r}{R} \qquad (7)$$

The torque on the fluid in the elemental annulus would be

$$\Delta Q = 2\pi r\, \Delta r\, \rho u\, \Delta W_\theta r$$
$$= 2\pi r\, \rho (1-a)\, u_\infty 2\, a'\, r\Omega r\, \Delta r$$
$$= 4\pi r\, \rho (1-a) a'\, u_\infty r^3\, \Omega\, \Delta r$$

$$\frac{dQ}{dr} = 4\pi\, \rho r^3\, u_\infty\, \Omega\, (1-a) a' \qquad (8)$$

The work $\Delta T.u$ done by the air goes into the rotor work $\Delta Q.\Omega$ and the kinetic energy of the rotational air velocity ΔW_θ

$$\Delta T\, u_\infty (1-a) = \Delta Q . \Omega + \frac{1}{2} 2\pi r . \Delta r . \rho (1-a) u_\infty . (2a' r\Omega)^2$$

↑ the work done by air ↑ rotor work ↑ KE in ΔW_θ

$$4.\pi.r.\rho.u_\infty^2 (1-a).a.u_\infty (1-a).\Delta r = 4.\pi.r^3.\rho.u_\infty \Omega^2 .(1-a).a'.\Delta r + 4.\pi.r^3.\rho.\Omega^2.u_\infty.a'^2 (1-a).\Delta r$$

$$(1-a)^2.a.u_\infty^2 = r^2\ \Omega^2.(1-a).a' + r^2.\Omega^2 (1-a).a'^2$$

$$(1-a)^2.a = \frac{r^2\Omega^2}{u_\infty^2}[(1-a).a' + (1-a).a'^2]$$

$$(1-a).a = \lambda^2 [(1+a').a'] \qquad (9)$$

The power developed by the elemental annulus would be

$$\Delta P = \Delta Q.\Omega$$

The rotor power is then

$$P = \int_0^R 4.\pi.r^3.\rho.u_\infty.\Omega^2.(1-a).a'.dr$$

Putting it in terms of a non-dimensional power coefficient

$$C_P = \frac{P}{\pi.R^2.\rho.u_\infty^3} = \frac{1}{R^2}\int_0^R \frac{4.r^3.\Omega^3}{u_\infty^3}(1-a).a'.\frac{u_\infty}{\Omega}.dr$$

Now, with $\lambda = \frac{r\Omega}{u_\infty}$ $\quad dr = \frac{u_\infty}{\Omega}d\lambda$

$$C_P = \frac{1}{R^2}\int_0^{\lambda_t} 4.\lambda^3.(1-a).a'.\frac{u_\infty^2}{\Omega^2}.d\lambda$$

$$C_P = \frac{1}{\lambda_t^2}\int_0^{\lambda_t} 4.\lambda^3.(1-a).a'.d\lambda \qquad (10)$$

λ, the local blade speed ratio $\frac{r\Omega}{u_\infty}$ can be treated as a non-dimensional radius along the blade.

For a windmill of given tip speed ratio λ_t the power would be a maximum if (1-a).a′ is a maximum.

$$\text{i.e } (1-a).\frac{da'}{da} + a'.\frac{d}{da}(1-a) = 0$$

$$(1-a).\frac{da'}{da} = a'$$

Differentiating with respect to 'a' instead of 'a' would give the same result.

$\frac{da'}{da}$ can be obtained by using equation (9)

$$\frac{d}{da}(a-a^2) = \lambda^2.\frac{d}{da}(a' + a'^2)$$

$$(1-2a) = \lambda^2(1+2a').\frac{da'}{da}$$

$$\frac{da'}{da} = \frac{1-2a}{\lambda^2(1+2a')}$$

Substituting in previous step

$$\frac{(1-a)(1-2a)}{\lambda^2(1+2a')} = a'$$

$$\lambda^2(1+2a')a' = (1-a)(1-2a)$$

Equation (9) is $\lambda^2(1+a')a' = (1-a)a$

Dividing, we get $\frac{(1+2a')}{(1+a')} = \frac{(1-2a)}{a}$

$(1+2a')a = (1+a')(1-2a)$

$a + 2.a.a' = 1 - 2a + a' - 2aa'$

$4.a.a' - a' = 1 - 3a$

$$\text{i.e} \quad a' = \frac{1-3a}{4a-1} \qquad (11)$$

We can put this in the form

$$(1+a') = 1 + \frac{(1-3a)}{(4a-1)} = \frac{a}{(4a-1)}$$

Substituting in equation (9)

$$\lambda^2 a' = \frac{(1-a)a(4a-1)}{a}$$

$$\lambda^2 = \frac{(1-a)(4a-1)^2}{(1-3a)} \qquad (12)$$

The inflow factors a and a′ and the non dimensional radial position co-ordinate $\lambda = \frac{r\Omega}{U_\infty}$ are linked together through equations (11) & (12) for a wind turbine configured for maximum power. Equation (11) gives the value of 'a′' for a chosen value of 'a' and equation (12) gives the value of λ linked to this pair of values 'a' and 'a′'. This can be done for a series of values of a, giving an universal table of a, a' and applicable for all windmills configuration for maximum power. The variation of 'a' and 'a′' along the non-dimensional radial position $\frac{r\Omega}{U_\infty}$ for an optimized wind mill is given in Fig. 3. The axial inflow factor a varies within very narrow limits and approaches the idealized value of $\frac{1}{3}$ (see appendix) as the blade velocity ratio λ increases. At this condition the rotational inflow factor a' approaches zero confirming that at large velocity ratios the flow through the windmill approaches the simple model discussed in the appendix. At small blade velocity ratios the value of a′ rises very rapidly leading to rapid changes in the value of ϕ which is related to blade twist.

The power co-efficient for wind mills configured for maximum power for a given tip speed ratio λ_t can be computed from equation 10 by numerical integration using the optimum values for a, a' and λ obtained from equations 11 and 12. The variation of maximum power co-efficient for windmills of different tip speed ratios is illustrated in Fig.4. The ideal value of Cp max of 0.296 (the Betz limit. see Appendix) is reached at very large values of λ_t. C_p max falls of very rapidly at low values of tip speed ratio. The choice of design tip speed ratio depends on the requirements, the higher tip speed ratios having larger Cp max and lower residual rotational energy giving better

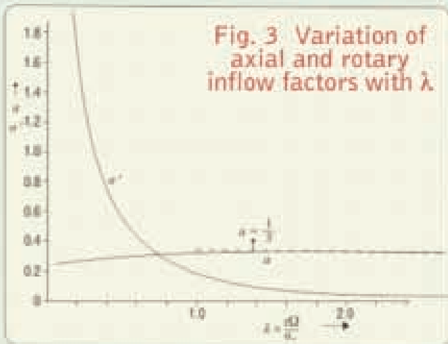


Fig. 3 Variation of axial and rotary inflow factors with λ

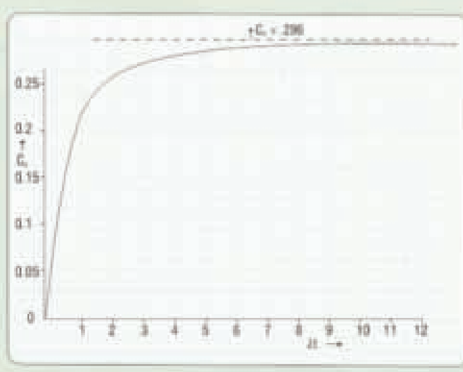


Fig. 4 Variation of maximum power coefficient with tip-speed ratio

efficiency or lower tip speed ratios giving greater torque but with lower power extraction from the wind.

Blade geometry related to aerodynamic parameters

The profile lift co-efficient at any radius can be estimated from the Kutta-Joukowsky theorem $L = \rho W \Gamma$

Where Γ is the blade circulation $\Gamma = \Delta W_\theta . s$

Where S is the blade spacing

$$s = \frac{2\pi r}{Z}$$

$$C_L = \frac{\rho W \Gamma}{\frac{1}{2}\rho W^2 c} = \frac{2\Gamma}{W c}$$

$$= \frac{2 \Delta W_\theta s}{W.c}$$

$$= 2\,\frac{s}{c}.\,\frac{2a' r \Omega}{W}$$

Now $\cos\phi = \frac{(1-a)\,u_\infty}{W}$

and $\frac{r\Omega}{W} = \frac{r\Omega}{u_\infty}\,\frac{u_\infty}{W} = \frac{\lambda\cos\phi}{(1-a)}$

C_L becomes $C_L = 4.\frac{s}{c}\,a'.\frac{\lambda\cos\phi}{(1-a)}$

The inverse of the space to chord ratio (s/c) is the solidity σ

$$\sigma = \frac{c}{s} = \frac{CZ}{2\pi r}$$

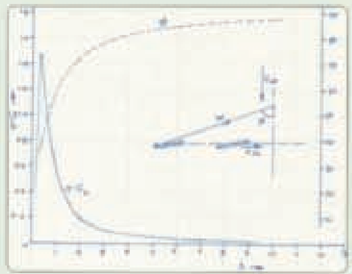
$$\sigma C_L = 4\lambda\cos\phi\,\frac{a'}{(1-a)} \qquad (13)$$

Equation 13 is a general result applicable to all wind mill blade rows, but it will give the variation of lift co-efficient C_L along the blade configured for maximum work extraction if the appropriate values of a, a' and λ are inserted into the equation.

The variation of σ CL along the non-dimensional radius $\frac{r\Omega}{W}$ is plotted in Fig. 5 for the optimum wind mill. This result is applicable to wind mills of any size and speed. If the wind mill is designed for a tip speed ratio of 6, the graph of Fig. 5 will be applicable from the origin $\lambda=0$ to $\lambda=6$.

The graph gives the variation of σ CL, i.e., $\frac{Z c C_L}{2\pi r}$ as $f(\lambda) = f\left(\frac{r\Omega}{U_\infty}\right)$

For a given blade number Z, the c C_L variation determines the variation of CL if the variation of c is fixed by the designer or alternatively the variation of c if the C_L variation is fixed. The blade tapers towards the tip except at low λ near the root where the chord can increase along the radius. Fig. 5 shows the rapid change in the angle Φ as λ decreases and the consequent change in blade setting angle. The blade setting angle β depends on the angle of attack needed to generate the local value of the lift coefficient. (Fig.6).



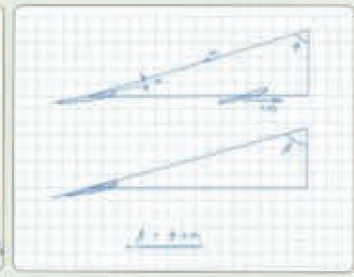


Fig.5. Variation of Φ and σ C_L along non-dimensional radius λ

Fig.6. Blade setting angle : Definition

Appendix

On the basis of limiting low loading when the swirl downstream of the wind mill is vanishingly small the thrust on the rotor in the elemental annulus was shown to bez

$$dT = 4\pi r\rho u_\infty^2(1-a)\;a \qquad (1A)$$

The use of equation 10 to calculate the maximum value of the power co-efficient C_p is difficult as then $a' \rightarrow 0$ and $\lambda \rightarrow \infty$. Equation (1A) for dT can be used for estimating the maximum value of C_p.

The elemental power is $dP = 4\pi r\rho u_\infty^2(1-a)\;a.u$

$$= 4\pi r\rho u_\infty^3(1-a)^2 a$$

For maximum power $(1-a)^2$ a should be a maximum

i.e. $(1-a)^2 - 2a(1-a) = 0$

$$(1\text{-}a) = 2a \qquad \text{or } a = \frac{1}{3} \qquad (2A)$$

Max power would be when $a = \frac{1}{3}$ all over the rotor disc

$$\text{Max power} = \int_0^R 4\pi u_\infty^3 \rho \frac{4}{27}\, r\,dr = \frac{8}{27}\pi R^2 \rho u_\infty^3 \qquad (3A)$$

$$\text{Max } C_p = \frac{\text{Max.Power}}{\pi R^2 \rho u_\infty^3} = \frac{8}{27} = 0.296 \qquad (4A)$$

The mass flow through a disc the same size of the wind mill would be $\pi R^2 \rho u_\infty$. It would have a Kinetic energy ½ $\pi R^2 \rho u_\infty^3$.

Comparing this with equation (3A) it is seen that the maximum possible power that a wind mill could extract from the air would be $\frac{8/27}{1/2} = \frac{16}{27} = 0.5925$ of the K.E flux through a free disc of the same size. This is known as Betz's limit.

New Recruitment

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