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Development of vertical axis wind turbines

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Abstract. This paper summarises the work done at the National Aeronautical Laboratory (NAL) between 1975 and 1977 on the development of vertical axis wind turbines based on the Darrieus rotor. On the analytical side, a performance analysis was developed which permits the estimation of the characteristics of such machines. A 5 m high wind turbine using curved wooden blades was designed, fabricated and tested. Both the theory and initial tests confirmed the low starting torque of the turbine. Wind tunnel tests were performed on model Savonius rotors to determine optimum starter bucket configurations. Finally a straight-bladed turbine was designed and constructed. It is concluded from our experience that Darrieus turbines are likely to be useful in large systems used to generate electrical power for the grid; for direct water pumping purposes, however, these turbines are unlikely to be suitable.

Keywords. Wind turbine; Darrieus rotor; vertical axis windmill.

1. Introduction

Vertical axis windmills have a feature that is particularly attractive—they accept wind from any horizontal direction and do not need the complicated head mechanisms of conventional horizontal axis windmills. The resulting mechanical simplification is sufficient to warrant interest in any new vertical axis concept that arises. During the early seventies, South & Rangi (1971, 1972) conducted wind tunnel tests on a novel vertical axis configuration at the National Research Council, Canada, which showed that the device worked efficiently at high tip speed ratios but had poor starting torque. In effect, the new device behaved much like a low solidity horizontal axis machine but was conceptually a great deal simpler. It appears that the configuration was originally discovered and patented by Darrieus (1931). We refer to this configuration as the Darrieus rotor and when used as a turbine as the vertical axis wind turbine (VAWT).

The Darrieus rotor (figure 1a) consists of a number of curved blades rotating about the vertical axis through their ends. Sections of any blade, in planes normal to the slope of the major (lengthwise) axis, are of aerofoil shape with the chords aligned in the azimuthal direction. One can understand how the device works by studying figures 1b and 1c. These figures show elemental sections of a blade at various azimuthal positions ϕ for a given wind speed V_∞ and at a particular blade angular speed Ω. When the local azimuthal speed $r\Omega$ is large compared with the local wind speed V (figure 1b) the blade element is unstalled for all ϕ as the effective angle of attack α is small (note that dD has been exaggerated in the figure for clarity). In this condition the elemental lift dL contributes positively to the torque while the elemental drag dD detracts from it. On the other hand, when $r\Omega < V$ (figure 1c), the effective angle of attack can vary from 0° to ±180° i.e. the blade may be stalled or be in reversed flow over part of its trajectory. In this situation the elemental lift can act to reduce the torque and the elemental drag to add to it over a range of azimuthal angles. Since in the stalled case the net forces are often in opposition and since the

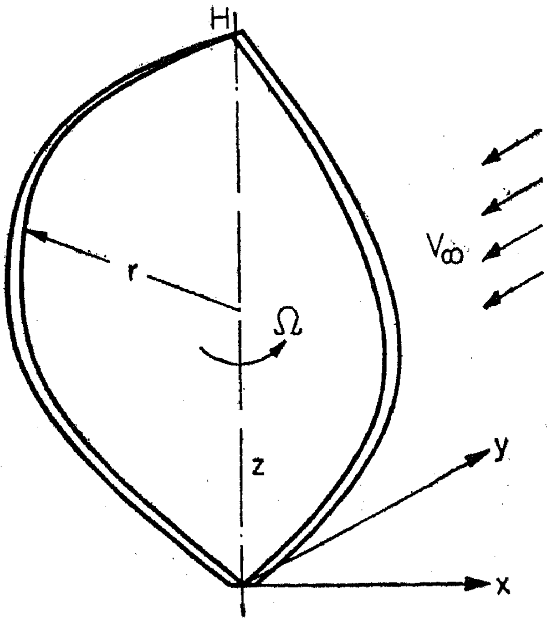

Figure 1a. The rotor geometry. The blades rotate about the vertical axis.

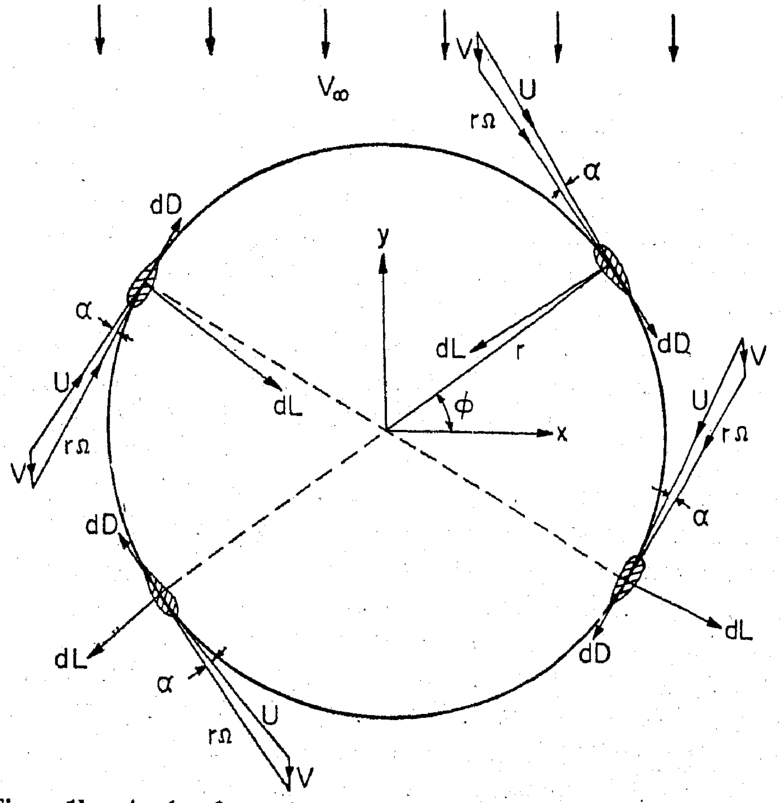

Figure 1b. Angle of attack variations about the azimuth for a blade element whose tip speed $r\Omega$ is large compared to the local wind speed V.

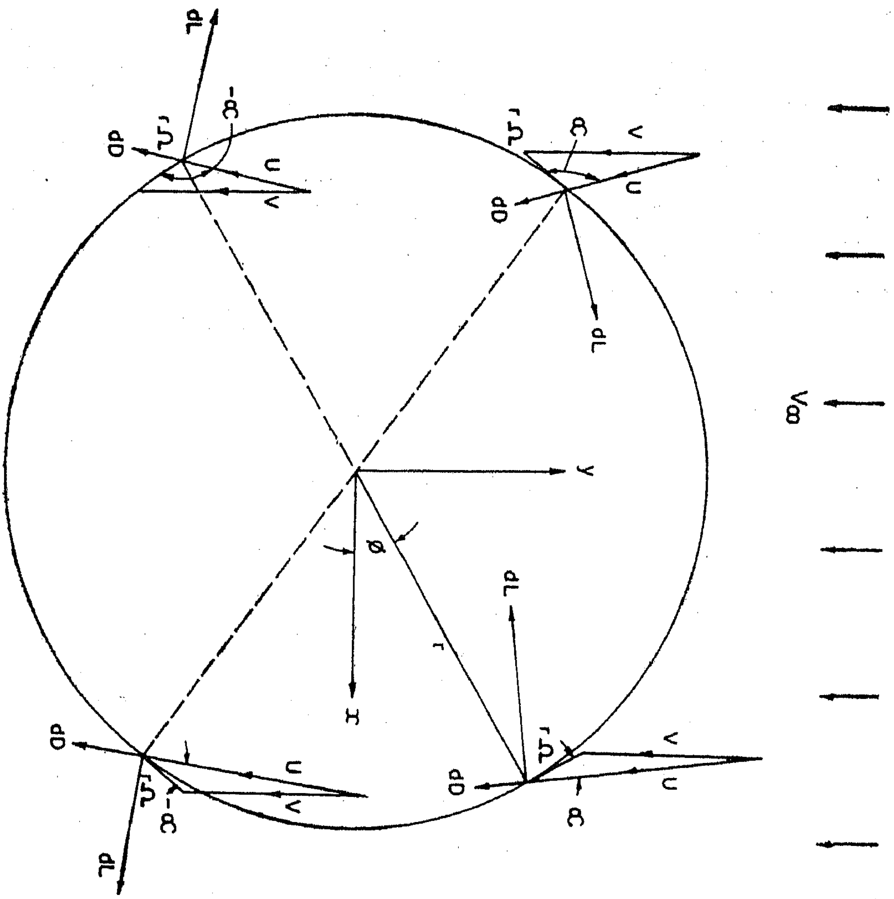

Figure 1c. Angle of attack variations for a blade element whose tip speed is small compared to the local wind speed.

lift-to-drag ratio is normally large in the unstalled case it follows that these machines will operate at high tip speed ratios when at peak power.

Our objective at NAL was to learn and understand the characteristics of Darrieus rotors and to see how feasible they would be in the Indian context. Specific goals were:

(i) to obtain a performance analysis for Darrieus rotors,
(ii) to build a curved bladed machine,
(iii) to study the starting problem, and
(iv) to study the possibility of using straight blades.

The results of our work on these specific tasks are presented in the following sections of this paper.

2. Performance analysis for Darrieus rotors

The Darrieus rotor can be analysed in an elementary way by assuming that each section of a blade behaves as an aerofoil in a two-dimensional flow field. Three-dimensional effects are approximately accounted for by computing the ' induced velocity ' from momentum theory. This simple approximate method gives useful estimates that compare reasonably with available experimental data. The method was first used by Templin (1974); an analysis incorporating non-uniform induced velocity is given in Shankar (1975, 1976a) and in Wilson *et al* (1976).

We first consider the induced flow. When a wind turbine operates in an air stream, the wind speed V at the blades will not be equal to the true upstream wind speed V_∞. In taking energy from the wind, the turbine exerts a decelerating thrust on the air stream. One can estimate the deceleration of the stream to a first approximation by replacing the turbine by an actuator disc (figure 2a) in the plane $y=0$. It is assumed in this approximation that the induced velocity in front and back of the rotor are equal, that it is uniform, that the flow is quasi one-dimensional with well-formed slip streams and that all losses are negligible. Under these assumptions the application of the continuity, momentum and energy equations to a large control volume leads to the result

$$V/V_\infty = (1 + \tfrac{1}{4}C'_T)^{-1}, \tag{1}$$

where C'_T is the thrust coefficient based on the local velocity V:

$$C'_T = T/\tfrac{1}{2}\rho A V^2, \tag{2}$$

and A the frontal area of the wind turbine and ρ the air density.

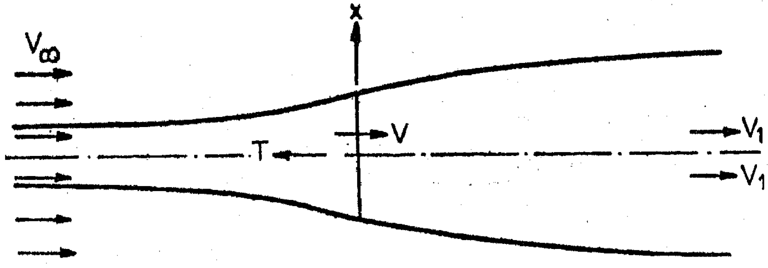

Figure 2a. Actuator disc model of the wind turbine rotor. Here T is the thrust on the wind stream.

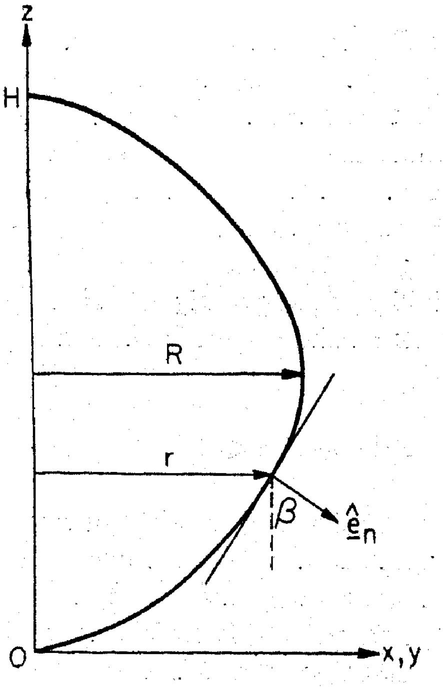

Figure 2b. View of the blade in a direction normal to the plane containing it. $\hat{}_n$. is the unit vector normal to the blade chord and to the span-wise tangent to the bladee

At a blade section distance r from the axis (figure 2b) the effective wind speed U contributing to lift and drag is given by

$$U^2 = (r\Omega + V\cos\phi)^2 + (V\sin\beta\sin\phi)^2, \tag{3}$$

while the effective angle of attack α at the section is determined by

$$\tan\alpha = V\sin\beta\sin\phi/(r\Omega + V\cos\phi). \tag{4}$$

If the blade is of chord c with sectional lift and drag coefficients c_l and c_d, the mean power output P and mean thrust T for an N-bladed turbine are given by

$$P = \frac{N}{2\pi}\int_0^H\int_0^{2\pi} \tfrac{1}{2}\,\rho\, U^2 c c_t \frac{dz\,d\phi}{\sin\beta}, \tag{5a}$$

$$T = \frac{N}{2\pi}\int_0^H\int_0^{2\pi} r\Omega\,\tfrac{1}{2}\,\rho\,\frac{U^2 c}{\sin\beta}\,(\sin\beta\sin\phi\; c_n - \cos\phi\; c_t)\, dz\,d\phi, \tag{5b}$$

where c_t and c_n are the chord-wise and normal force coefficients given by

$$c_t = c_l\sin\alpha - c_d\cos\alpha, \tag{6a}$$

$$c_n = c_l\cos\alpha + c_d\sin\alpha. \tag{6b}$$

If we define the solidity σ, the tip speed ratio μ', power coefficient C'_P and thrust coefficient C'_T based on the local wind speed V as follows:

$$\sigma = \frac{Nc}{\pi R},\ \mu' = \frac{R\Omega}{V},\ C'_P = \frac{P}{k\cdot\frac{1}{2}\rho A V^3},\ C'_T = \frac{T}{\frac{1}{2}\rho A V^2}, \tag{7}$$

where $k=16/27$ and R is a typical radius, and also normalise the rotor frontal area and other lengths by R

$$A = k_1 R^2,\ \bar{r} = r/R,\ \bar{z} = z/R, \tag{8}$$

equations (5a), (5b), (3) and (4) may be rewritten

$$C'_P = \frac{1}{2\pi k k_1}\int_0^{H/R}\int_0^{2\pi} \sigma\,\mu'\,\bar{r}\left(\frac{U}{V}\right)^2 c_t\,\frac{d\bar{z}\,d\phi}{\sin\beta}, \tag{9a}$$

$$C'_T = \frac{1}{2\pi k_1}\int_0^{H/R}\int_0^{2\pi} \sigma\left(\frac{U}{V}\right)^2 \{\sin\phi\sin\beta\cdot c_n - \cos\phi\; c_t\}\,\frac{d\bar{z}\,d\phi}{\sin\beta}, \tag{9b}$$

$$(U/V)^2 = (\bar{r}\,\mu' + \cos\phi)^2 + (\sin\phi\sin\beta)^2, \tag{9c}$$

$$\tan\alpha = \sin\beta\sin\phi/(\bar{r}\mu' + \cos\phi). \tag{9d}$$

In practice we require the tip speed ratio μ, power coefficient C_P and thrust coefficient C_T based on the true wind speed V_∞. By using (1) for the induced velocity we obtain

$$\mu = \mu' V/V_\infty = \mu'(1 + \tfrac{1}{4}C'_T)^{-1}, \tag{10a}$$

$$C_T = C'_T\,(V/V_\infty)^2 = C'_T(1 + \tfrac{1}{4}\,C'_T)^{-2}, \tag{10b}$$

$$C_P = C'_P\,(V/V_\infty)^3 = C'_P\,(1 + \tfrac{1}{4}\,C'_T)^{-3}. \tag{10c}$$

The calculational procedure is then as follows. With the blade and rotor geometry given C'_P and C'_T are computed as functions of μ' by evaluating the integrals (9a) and (9b). Once these have been computed the true tip speed ratio μ, power coefficient C_P and thrust coefficient C_T may be calculated using (10a), (10b) and (10c). A useful linearisation for high tip speed ratios and a method of incorporating non-uniform induced velocity are given in Shankar (1976a). In figures 3a and 3b computations based on the performance analysis are compared with the experimental results of South & Rangi (1972). It may be seen that the agreement is generally satisfactory. Thus, the analysis is a useful tool for the design of Darrieus rotors.

3. Curved bladed turbine

In order to gain direct experience in the design, construction and operation of VAWTs it was decided in 1975 that a turbine be built at NAL. At the outset it was decided that simplicity, availability of materials and speed of fabrication would be the most important considerations. The design did not therefore take into consideration the problems that might arise in mass production; nor was economics considered except in so far as to avoid unnecessary or wasteful expenditure.

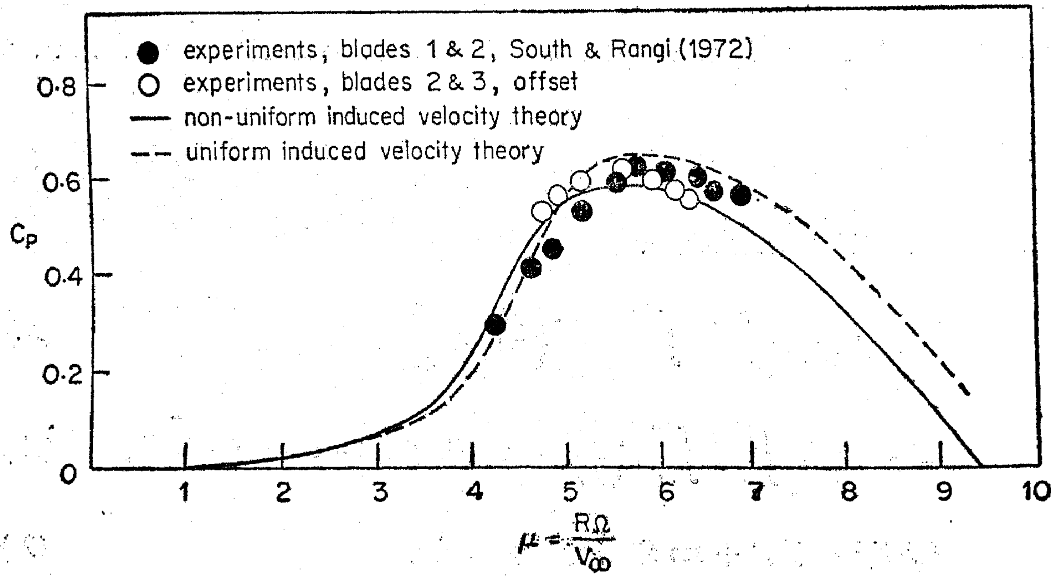

Figure 3a. Comparison of calculations with experimental results for a catenary-shaped rotor with σ=0·143.

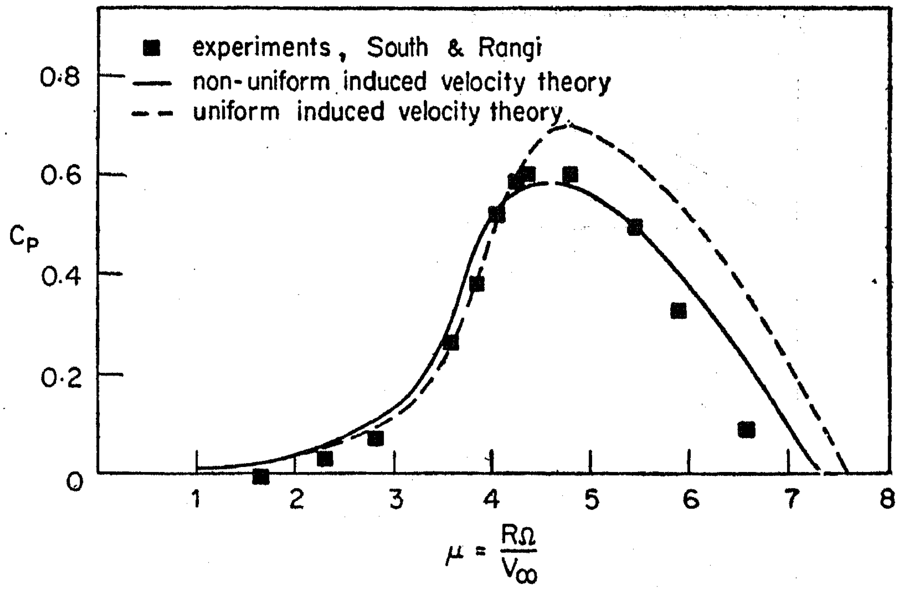

Figure 3b. Comparison of calculations with experimental results for a parabolic rotor with $\sigma=0{\cdot}25$.

Aerodynamic performance calculations led to the following specifications (Shankar 1975).

Power output	1000 W in winds of about 25 km/hr
Rev/min	135 at rated power and wind speed
Frontal area	17·2 m^2
Blade shape	Catenary of diameter 5 m and height 5 m
Number of blades	2
Aerofoil section	NACA 0012 of chord 250 mm
Starters	Two Savonius buckets of height 1 m and diameter 2 m.

Figure 4 shows a sketch of the turbine configuration and support system. The central column is a welded structure made of three 25 mm × 25 mm × 6 mm angles located at the vertices of an equilateral triangle of base 250 mm. The rotor is supported on a four-legged steel table with the table top 2 m above the ground. The central column rotates with the blades, the upper bearing being held in place by three 6 mm guy wires. A simple band brake assembly was used for emergency breaking, the assembly being located below the lower bearing.

The method of construction of the blades was as follows. Two steel tubes, approximately 13 mm in diameter were bent to the shape of the catenary. A wooden former also of the same shape was erected so that the blades could be built on the former. Now wooden pieces, approximately 25 mm thick, were roughly shaped to the aerofoil profile. These pieces had two slots, 13 mm wide, cut out equidistant from the quarter chord point and spaced 52 mm apart. The wooden pieces were assembled on the former, the steel tubes placed in the slots, and the wooden pieces glued together. The outer surfaces were then finished to the aerofoil profile. The blades were then finally finished with fibreglass cloth (for weather protection and extra strength), smoothed with putty and painted.

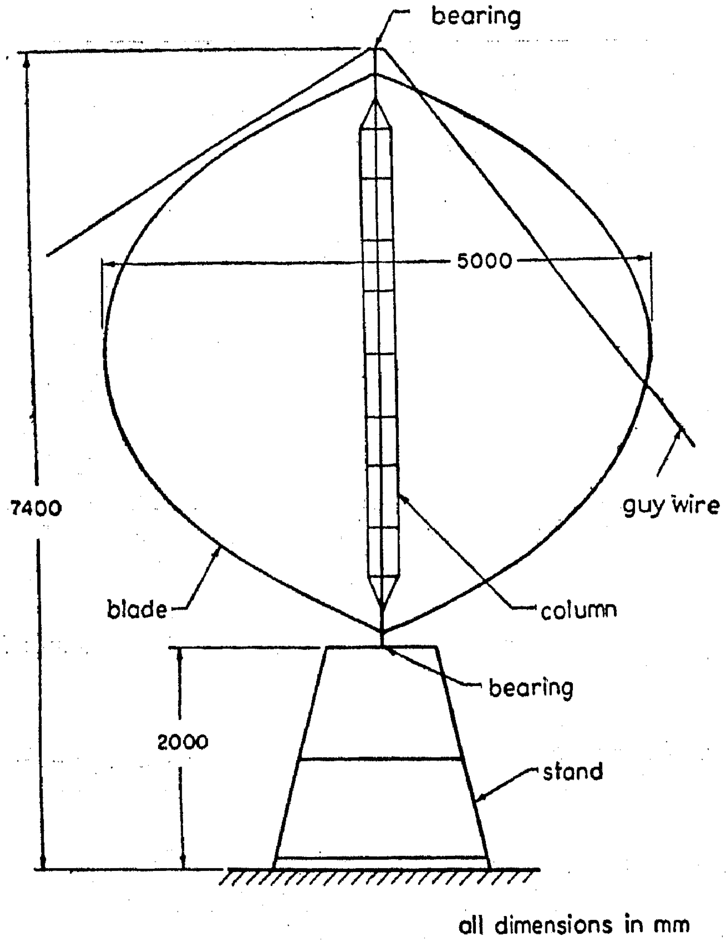

Figure 4. Sketch of the wind turbine configuration and support system.

The turbine was used to drive a commercially available self-priming centrifugal pump rated at 1 h.p. at a shaft speed of 1440 rev/min. A 9·3:1 step-up gear box using chain and sprockets was used for shaft speed matching. The choice of the load was poor as the commercial pump requires high starting torque and is very inefficient In fact a separate d.c. motor was used for on-load starting purposes.

Figure 5 (plate 1) shows a photograph of the VAWT. Details of the findings of the initial tests are given in Shankar (1975). In summary it was found that:

(i) the turbine did generate 1 kW and more in winds of 25 km/hr and above;

(ii) the turbine was not self-starting on load. With the 2 m diameter Savonius buckets, self-starting on no load occurred in winds of about 10 km/hr;

(iii) the turbine-bearing system, which consisted of a 7211 angular contact bearing (55 mm i.d.) at the bottom and a 1205 self-aligning bearing (25 mm i.d.) at the top,had a high starting frictional torque of the order of 1.5 kg. m. The estimated total vertical load in this configuration was between 300 and 400 kg.

(iv) the conventional centrifugal pump is not suitable for this type of turbine.

Following the initial tests various modifications were considered and implemented A configuration having the central column stationary was tried out (figure 6, plate 2). A clutch assembly was designed and fabricated which permitted the rotor blades to be off-load at start and to engage the load only when the rotor rev/min was around 70 The device used the centrifugal load of the blades to lift a friction pad concentric to the shaft; initially the pad was free but at around 70 rev/min its vertical movement forced it to engage the load. This configuration was found to be superior to the initial one used as far as starting characteristics are concerned.

4. Wind tunnel tests of Savonius rotors

The Savonius rotor is a vertical axis device which has a high starting torque and reasonable peak power output. Its use as a windmill has been restricted till now because of the large surface area it employs. However, there has been renewed interest in this device in view of its simplicity. Using cloth-like surfaces it now appears that Savonius windmills may have potential in regions of low mean wind speed for generating small amounts of power for water pumping etc. (see Govindaraju & Narasimha 1977, 1979). At NAL, interest in the Savonius rotor stemmed from its use as a starter for the Darrieus rotor. In view of the negligible amount of reliable data on Savonius rotors it was decided to test a range of configurations in the Boundary Layer Tunnel at NAL.

Both two-bladed and three-bladed geometries were tested. Figures 7a and 7b show the configurations that were tested. The models, made of 1 mm aluminium sheets, were of diameter 200 mm and height 70 mm. The models were tested in the open jet of a wind tunnel of rectangular section of dimensions 1·51 m×0·305 m. Thus the blockage of 3% was quite small. Tests were carried out at wind speeds ranging from 7·6 m/s to 15·2 m/s and model rev/min ranged from 0 to 2300.

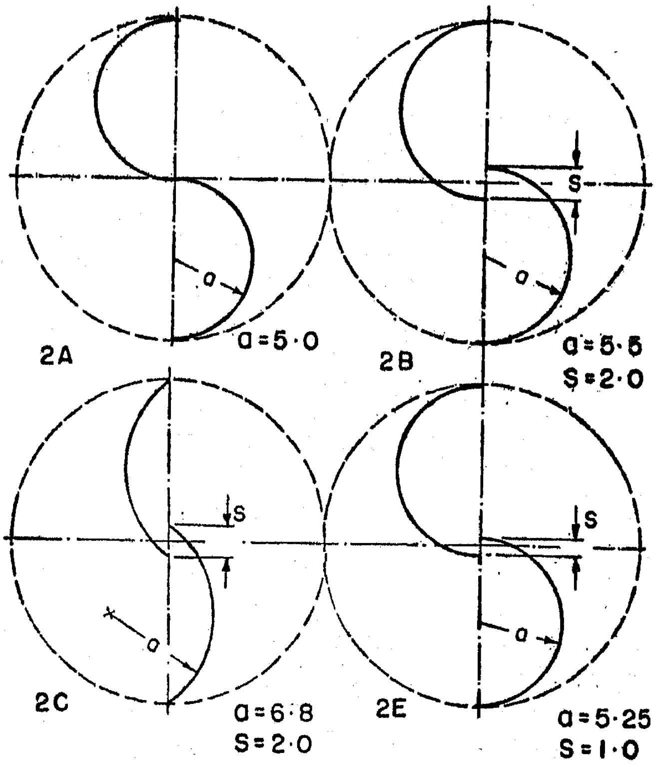

Figure 7a. The geometrical characteristics of two-bladed Savonius rotor models; $d=20$ cm.

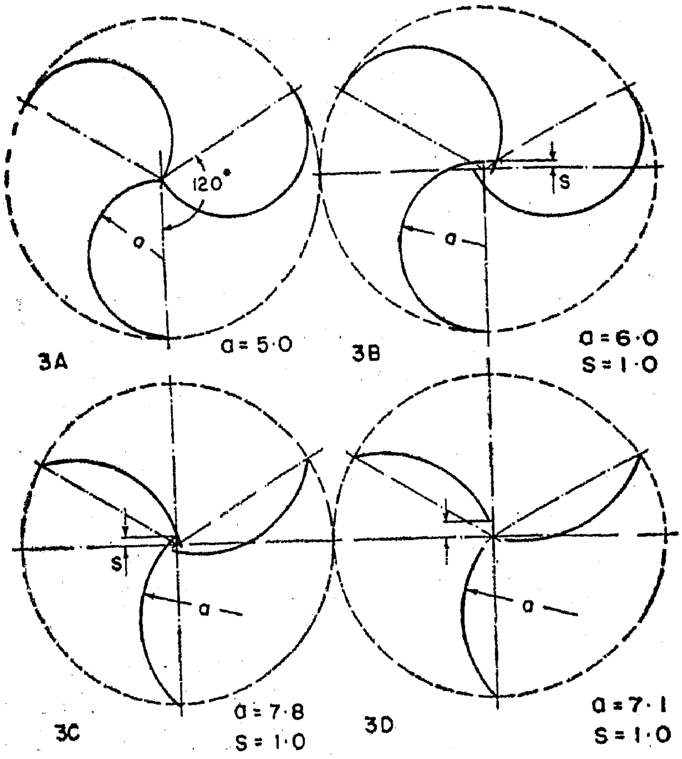

Figure 7b. Geometrical characteristics of three-bladed Savonius rotor models; d=20 cm.

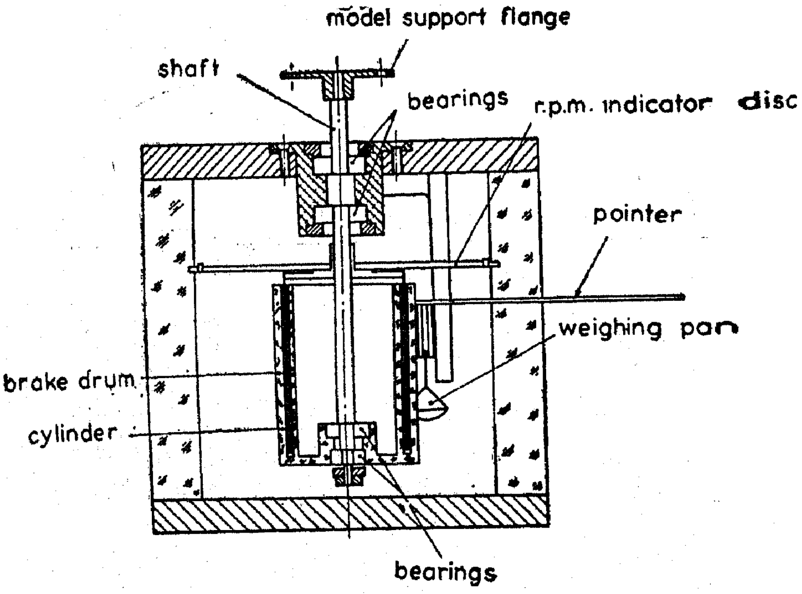

Figure 8. Sketch of the viscous dynamometer used in the wind tunnel experiments.

The balance used was a viscous dynamometer and is sketched in figure 8. Details of the dynamometer are given in Shankar (1976b).

Figures 9a and 9b show the measured variation of power coefficient C_p with tip speed ratio μ for the two-bladed and three-bladed models. It is clear that the two-bladed rotors generally have much higher peak power output than the three-bladed rotors. The significant findings of the tests were

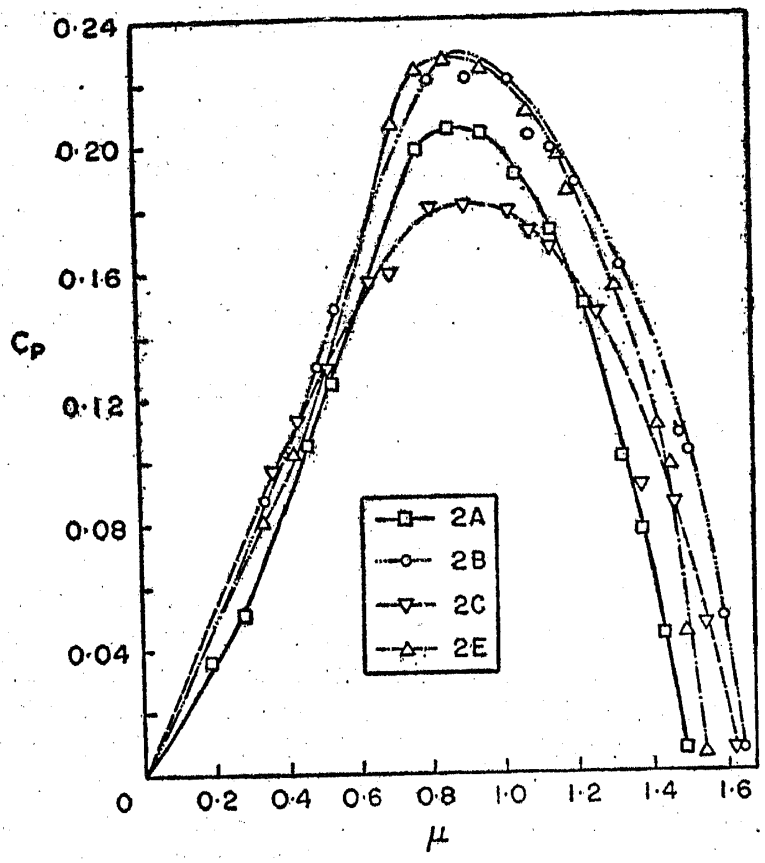

Figure 9a. Power coefficient for two-bucket models at a Reynolds Number of $1{\cdot}96\times10^5$.

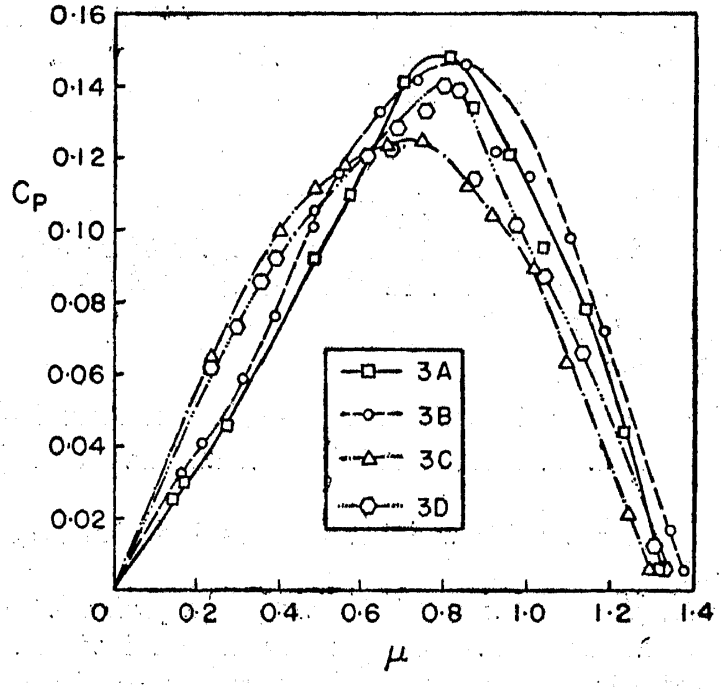

Figure 9b. Power coefficient for three bucket models at a Reynolds Number of $1{\cdot}96\times10^5$.

(i) in the range of Reynolds Numbers tested, the performance of all Savonius type rotors improved with Reynolds Number;

(ii) two-bladed Savonius rotors have almost 50% higher peak power output than the three-bladed rotors;

(iii) three-bladed rotors have smaller regions of negative starting torque but the torque coefficient at start is not significantly larger than that for two-bladed models;

(iv) while gap size is of some significance for the two-bladed models it is not of much significance for three-bladed models;

(v) shallow bucketed models have higher torque at low tip speed ratios but have worse peak performance;

(vi) a support rod at the centre of a Savonius rotor with a gap does not significantly affect its performance.

Most of the above findings have been confirmed in tests done at the Sandia Laboratories by Blackwell *et al* (1977).

5. The straight bladed turbine

A great disadvantage of the Darrieus rotor is the complication inherent in the fabrication of the curved blades. The large curved blades also pose a problem in handling, transportation and assembly. The main reasons for using curved blades are structural. The curved blade minimises bending stresses and the attachments to the top and bottom of the central shaft help to minimise vibrations. However, the possibility of using straight blades has remained an intriguing one over the years.

At NAL, a decision was made to try out a turbine using straight blades. At the outset it was decided that, in order to limit bending stresses and centrifugal loads, the upper rev/min would be strictly limited. The blades too would be of minimum weight.

Figures 10a (plate 3) and 10b (plate 4) show photographs of two- and three-bladed versions of the straight-bladed turbine. The blades were fabricated out of aircraft quality aluminium sheets with internal stiffeners. The specifications of the turbine were as follows.

Power output	1 kW in winds of speed 25 km/hr
Shaft speed	80 rev/min for the two-bladed and 70 rev/min for the three-bladed version at rated power and wind speed
Frontal area	17 m^2
Blade length	2·44 m
Blade profile	Conforming to NACA 0024 section of chord 0·44 m
Starters	2 Savonius rotors of height 1 m and diameter 2 m

The 24% thick section and the large chord were used to minimise bending stresses in the sheet metal.

While the turbine pick-up, starting friction and general performance were found to be satisfactory it was found that the support system was inadequate especially at revolutions greater than 100 rev/min. It has been our experience both with the straight-bladed turbine and the curved-bladed one that guy wire supports are really not adequate. In any practical system the upper bearing must be housed in a rigid structure.

6. Conclusions

The development work done at NAL gave us experience in the design, fabrication and field testing of Darrieus turbines. There is no doubt that the Darrieus rotor is a high speed device of efficiency comparable to horizontal axis windmills. It seems likely that this device will find use in the conversion of wind energy to electric power especially if used on a large scale in conjunction with the grid. In fact a 200 kW turbine driving a generator is at present being tested in Canada. With such large devices it is quite feasible to have adequate control systems for starting and controlling the system. In India, however, the mean wind speeds are generally so low that it is unlikely that wind power can be economically converted to electric power for grid augmentation. The most practical use for wind power is likely to be direct water pumping for drinking water and minor irrigation purposes. The water pumping application generally implies high starting torque and low control costs. Hence it appears, at least from the NAL experience, that Darrieus turbines are not likely to be of much use in the Indian context.

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Plate 1

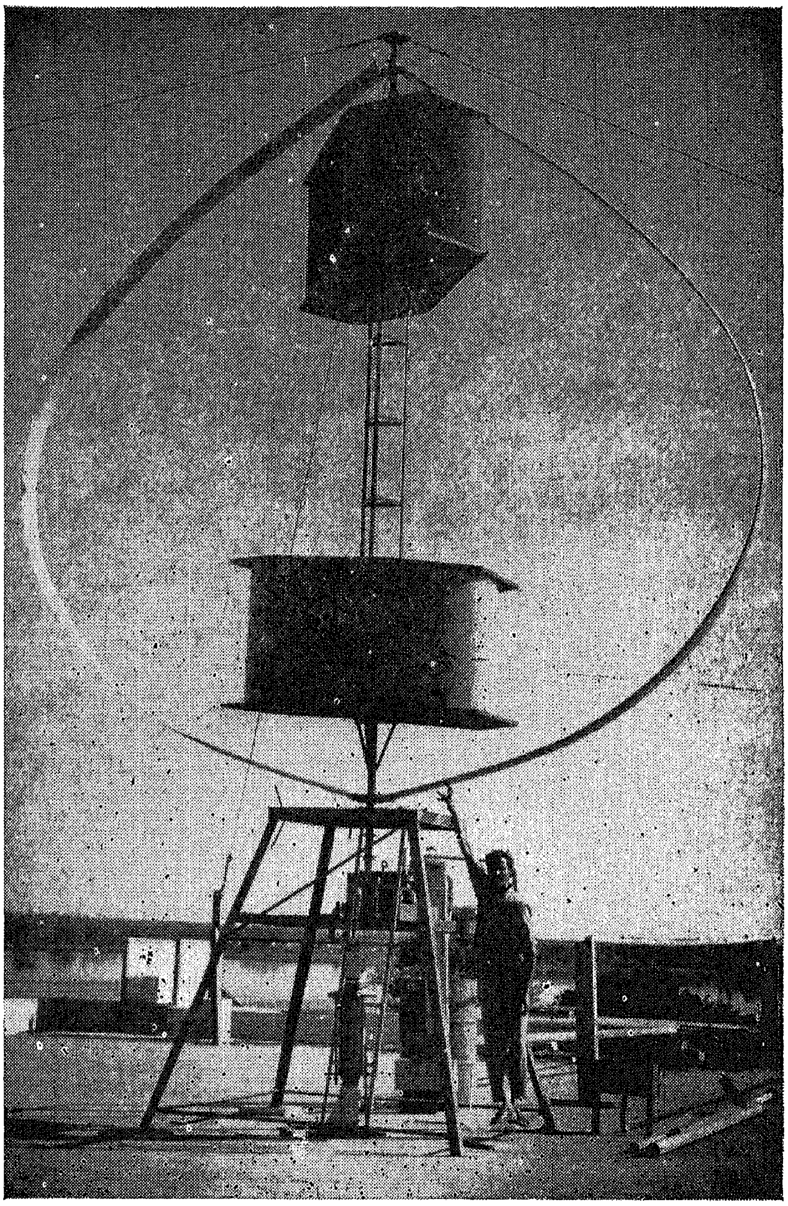

Figure 5. Photograph of curved bladed VAWT with two blades.

Plate 2

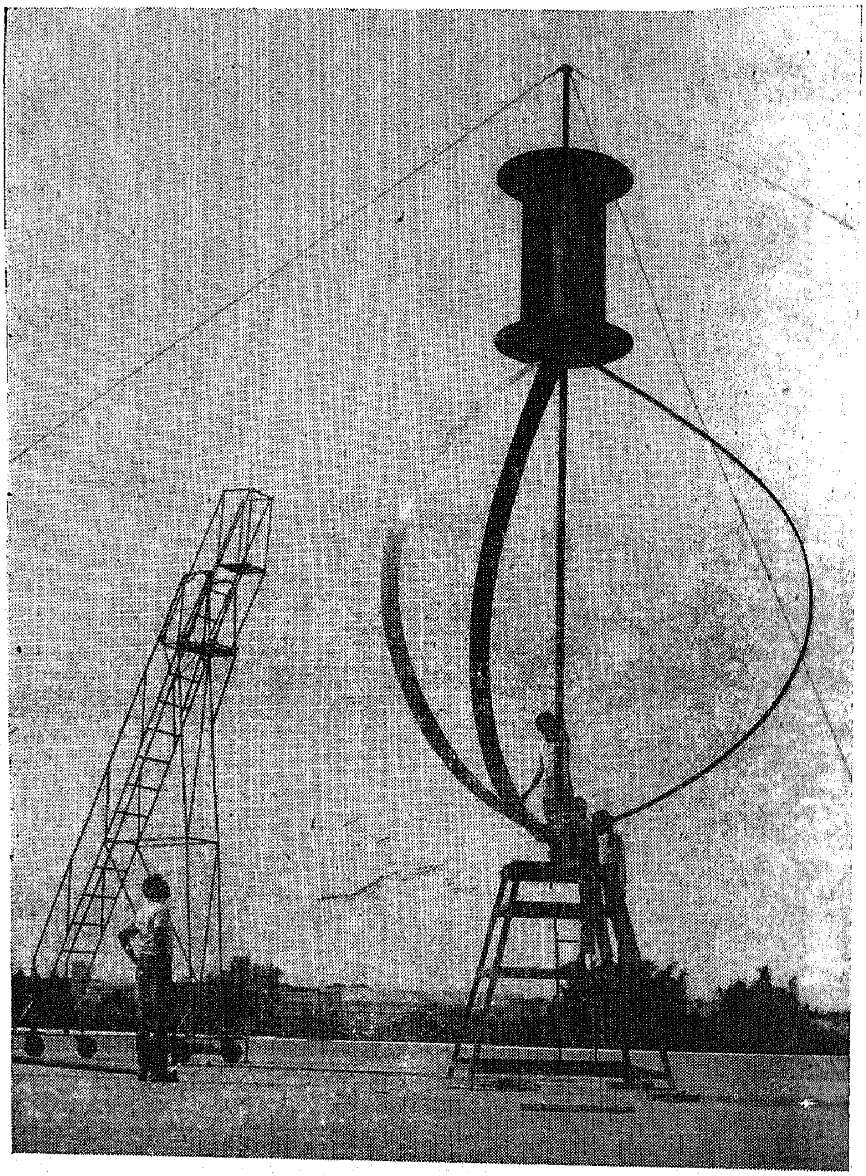

Figure 6. Photograph of three-bladed turbine using a stationary central column and with clutch assembly at the base.

Plate 3

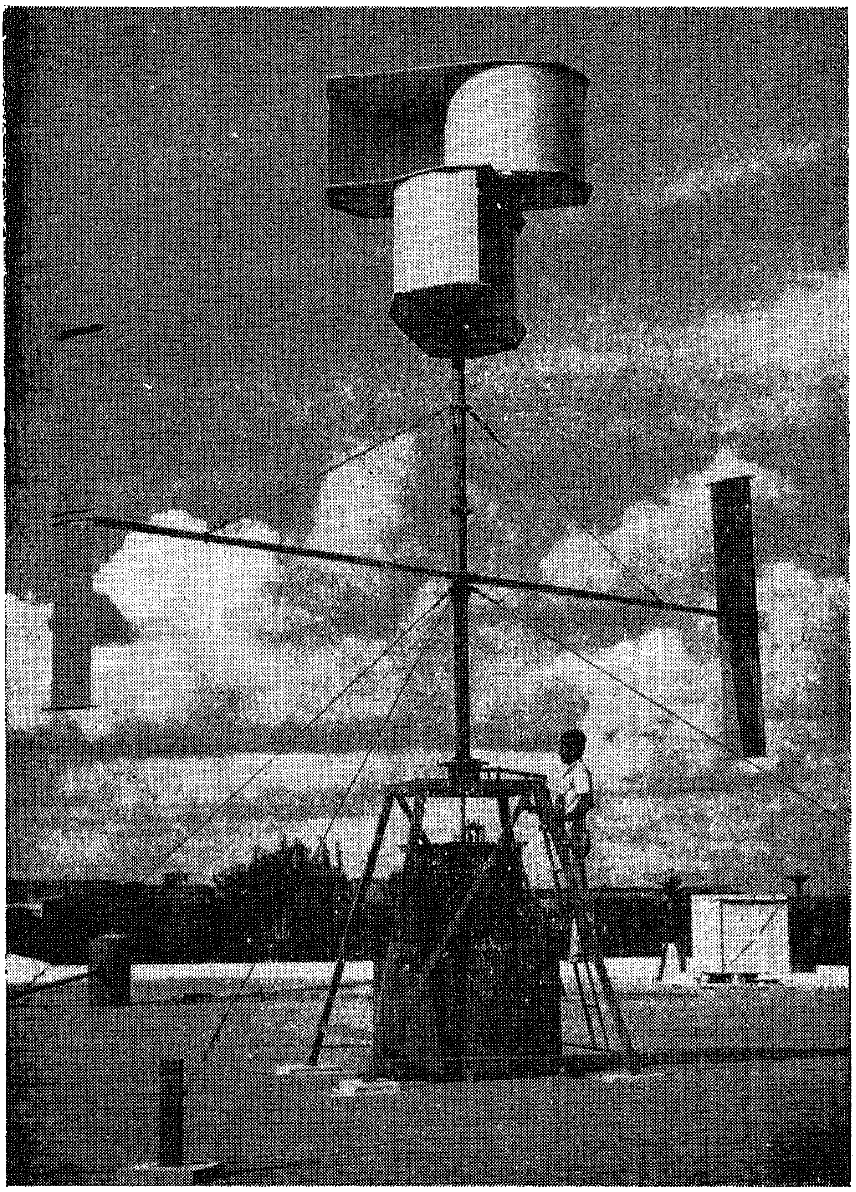

Figure 10a. Photograph of the straight-bladed turbine with two blades.

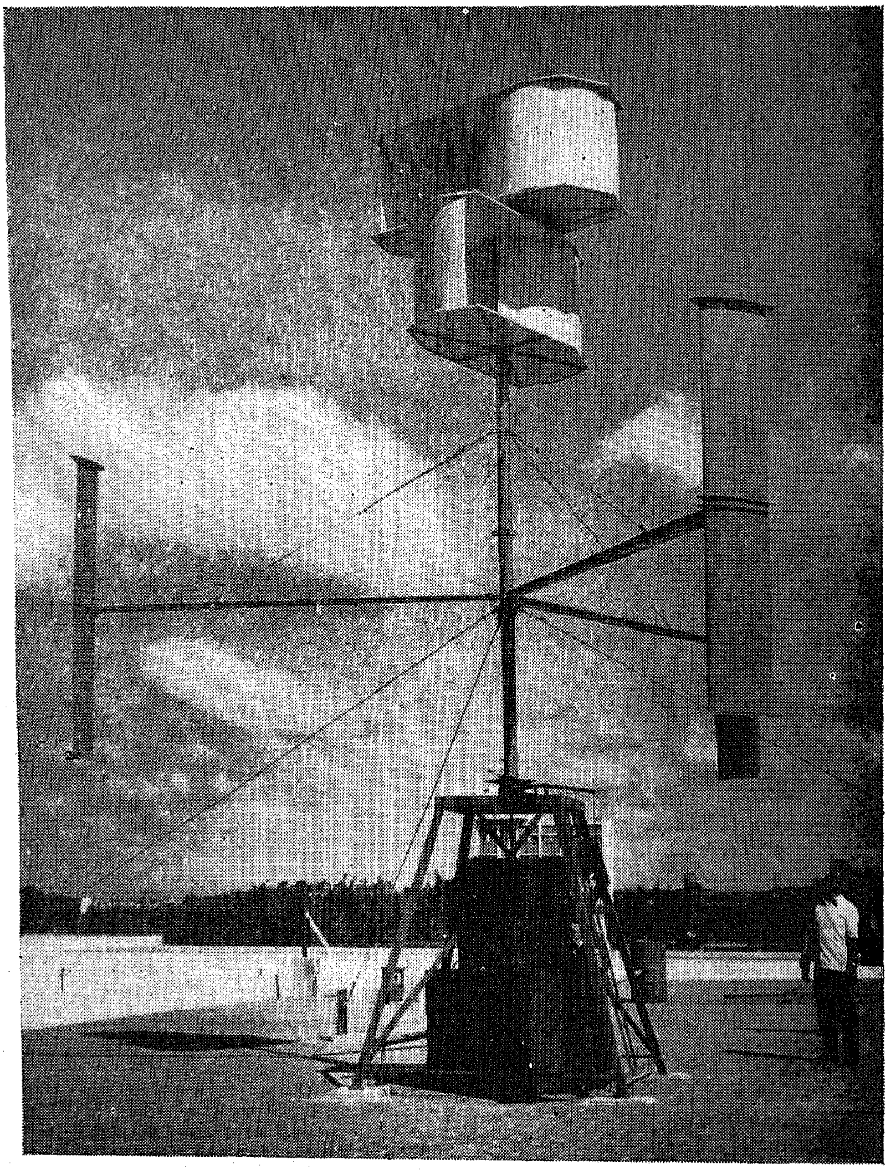

Figure 10b. Photograph of the straight-bladed turbine with 3 blades.