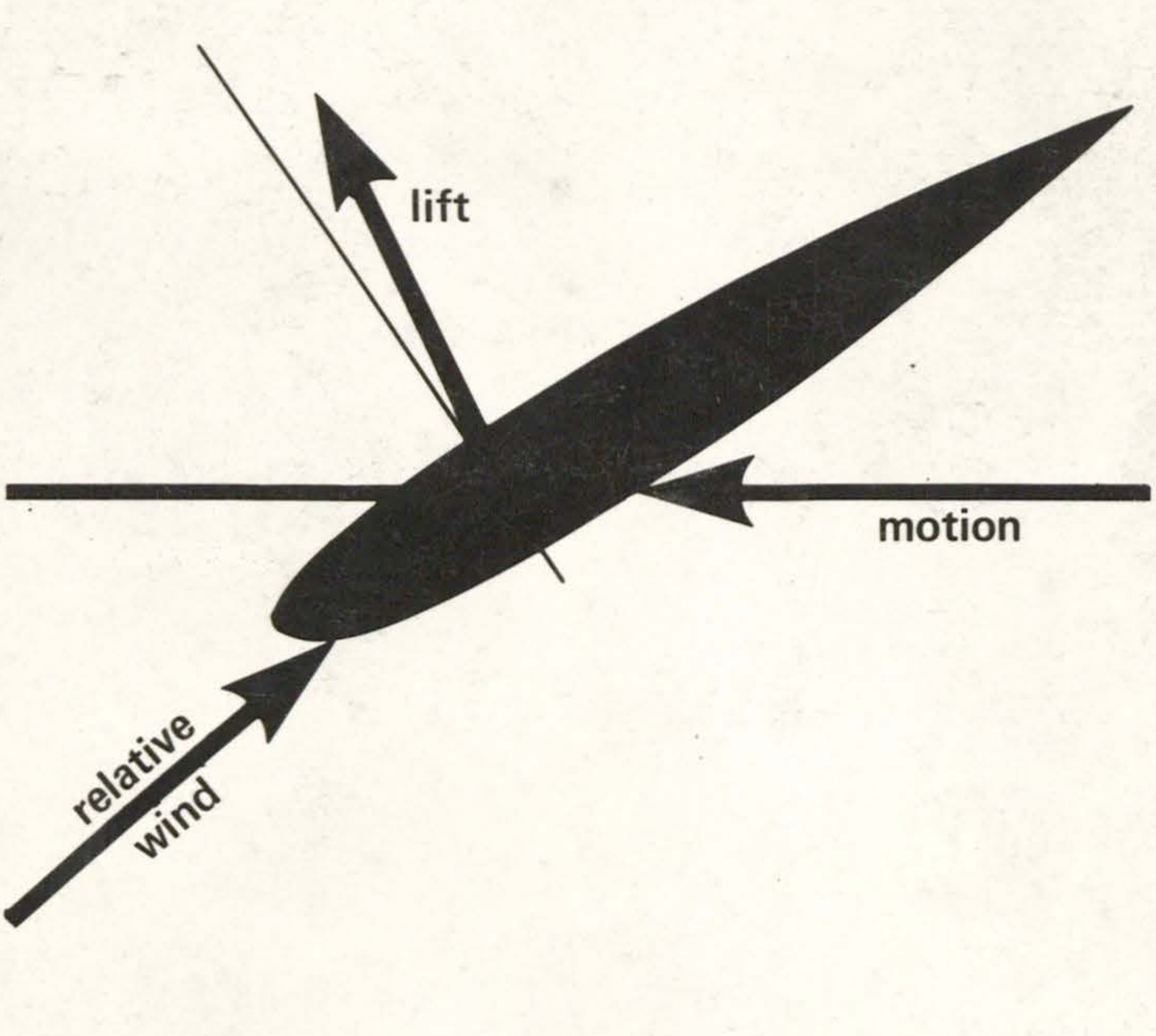
NUMBER 91
MARCH 1979

AYRS

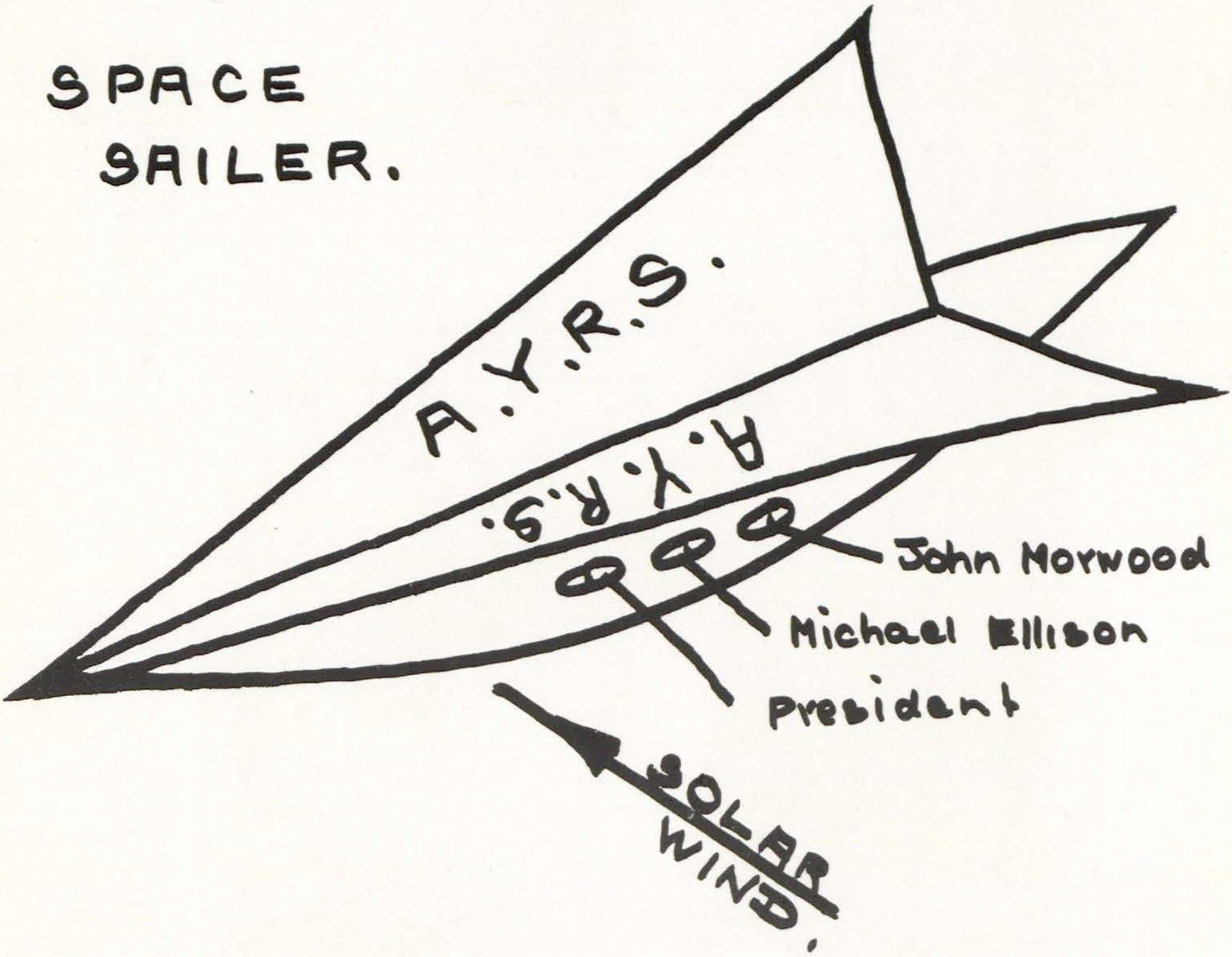
Power from the Wind



Windmills, Boats, Vehicles.

A.Y.R.S.

SPACE
SAILER.



AWAITING DEVELOPMENT GRANT OF
£400,000,000 FOR 'STARTERS'.

HERMITAGE.

THE AMATEUR YACHT RESEARCH SOCIETY

(Founded, June 1955 to encourage Amateur and Individual Yacht Research)

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The Amateur Yacht Research Society is a Limited Company, and a registered educational charity. Membership is open to anyone interested in the improvement of yachts and equipment by the use of research and development.

CONTENTS

INTRODUCTION

oOo

Members of the Amateur Yacht Research Society are interested mainly in sail boats, so use of wind power to provide marine propulsion takes first place in this publication.

There are marine applications for generating auxiliary power from wind. Examples include charging batteries, and providing electricity in isolated coastal sailing club buildings.

Power is derived from the differences in speed between wind and land, or between wind and water. It is just as logical to regard the wind speed as zero and the land or water speed as gale force. Which leads us to study how to get power from water flow past a boat.

The device used by man, and by many birds, animals and insects, to derive power from wind and water, is a foil – an aerofoil (or airfoil), and a hydrofoil. Since the term 'fluid' includes both gas and liquid, we can generalise and talk of fluidfoils. Fluidfoils can be very efficient, but as soon as the foil action ceases, that is, after the foil stalls, then propulsion is by drag, and that is not efficient.

A vehicle or boat or ship can use airfoils to move at angles to the wind, tacking up or down wind. It uses drag to go directly down wind. It cannot go directly into the wind, UNLESS we can devise a way to make the foils move across the wind whilst the boat is moving in the wind direction, either with the wind, or against it. One arrangement of foils to do this is the horizontal axis windmill, and the horizontal axis water turbine, which looks like a boat propeller. Alternatively, the foils can be rotated about vertical axes as vertical axis windmills or 'watermills.' They will generate auxiliary power, and propel boats and ships, with some restrictions explained later.

Vehicles and boats can use non-rotating airfoils (sails), and store energy in electric storage batteries, generated by drive from road wheels or from towed water turbines, and use this energy to move directly against the wind, and during lulls. A 'Windmobile' is reported with very interesting performance data.

In the marine field, some members of the A.Y.R.S. have experimented with model and full size windmill propelled boats, and since anyone intending to experiment will find a dearth of information, we include some explanations.

On behalf of the Amateur Yacht Research Society members and staff, I would like to express our appreciation and thanks to contributors, who have been most generous and public spirited in providing reports and data about their experimental work. W.R.F.

EXPERIMENTS WITH MODEL VERTICAL AXIS WINDMILLS

by

Simon H. Sanderson
Mistletoe Cottage, Brancaster Staithe, King's Lynn, Norfolk.

Rotosail Mark 1. (Figure A1)

The vertical 'sails' are shown with one moving at 90 degrees to the real wind on port tack, the opposite 'sail' on starboard tack, whilst another 'sail' is moving directly towards the wind, whilst the fourth is moving downwind.

These 'sails' are free to pivot about vertical axes, placed relative to the centres of pressure so that when pushed over one way or the other, the 'sail' stays there. A cross arm above the rotor carries four wires, and the rotor cross arms carry stops. The 'sails' flip over from side to side, Figure A2 illustrates the movements.

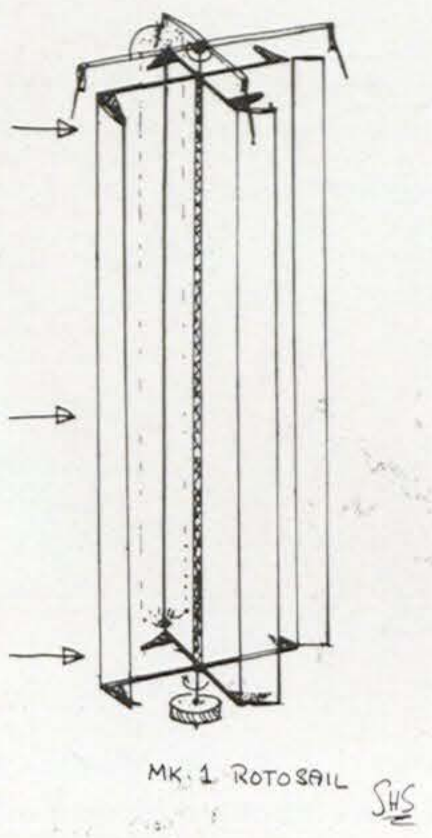


Fig. A1

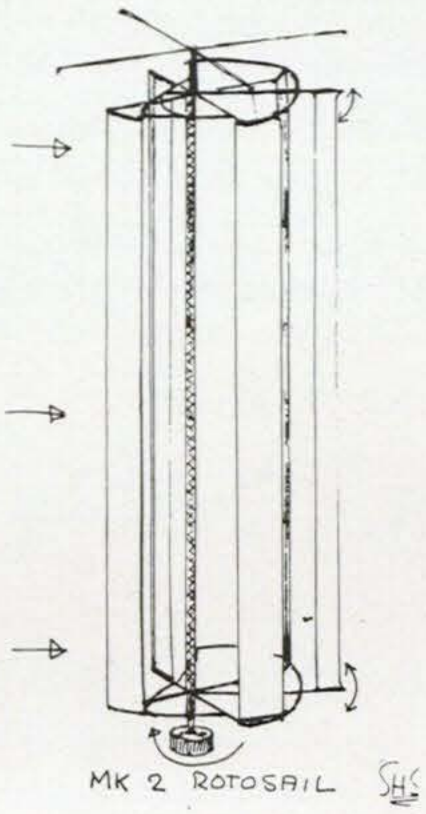


Fig. A2

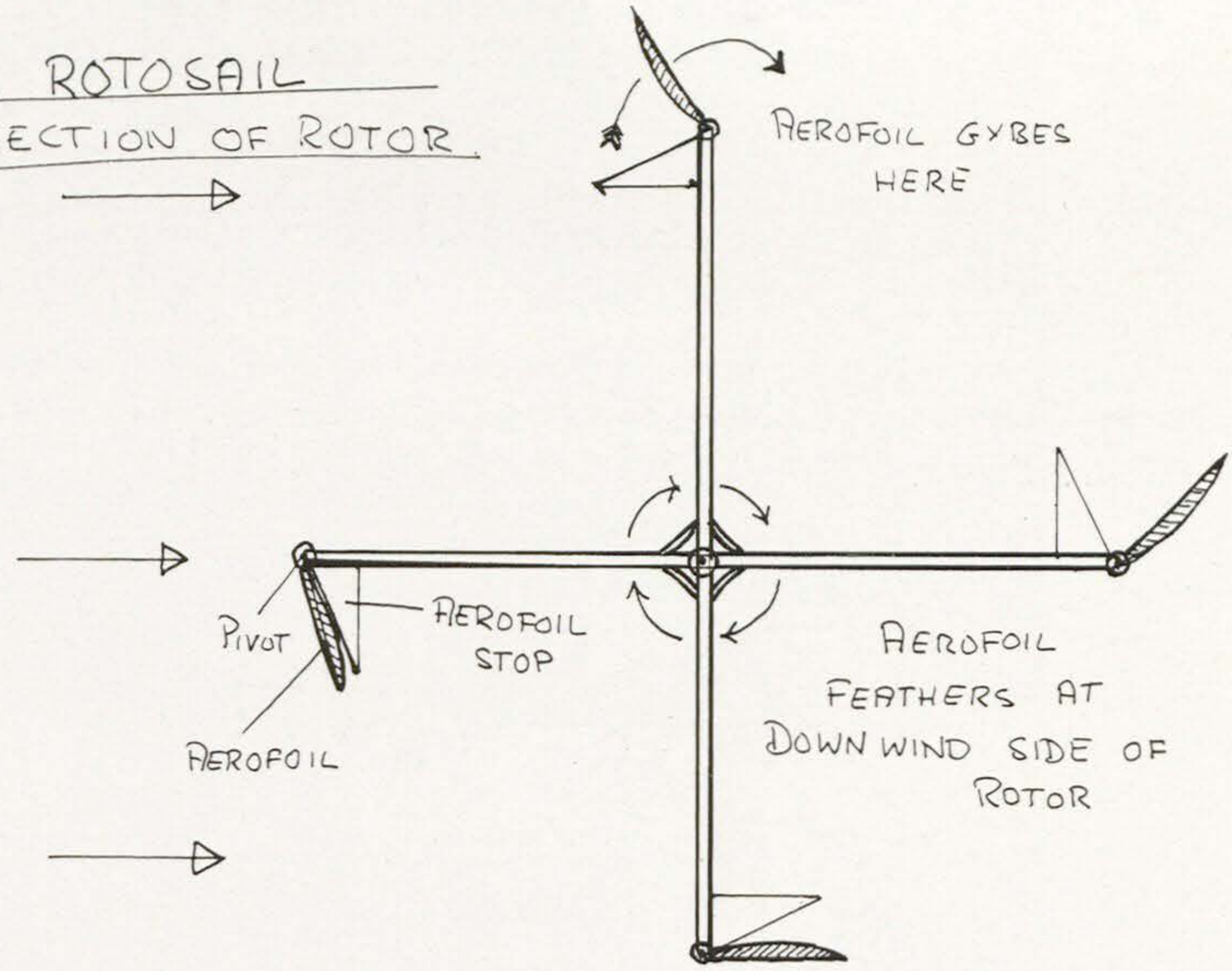
Rotosail Mark 2.

Compared with the mark 1 model, a length of wire curved to a shape found most effective by experiment, acts as a controlling cam. Figure A3 explains how the arrangement works.

These cams were made from coat hangers, rollers were turned from nylon rod. Sail battens were used for cross arms.

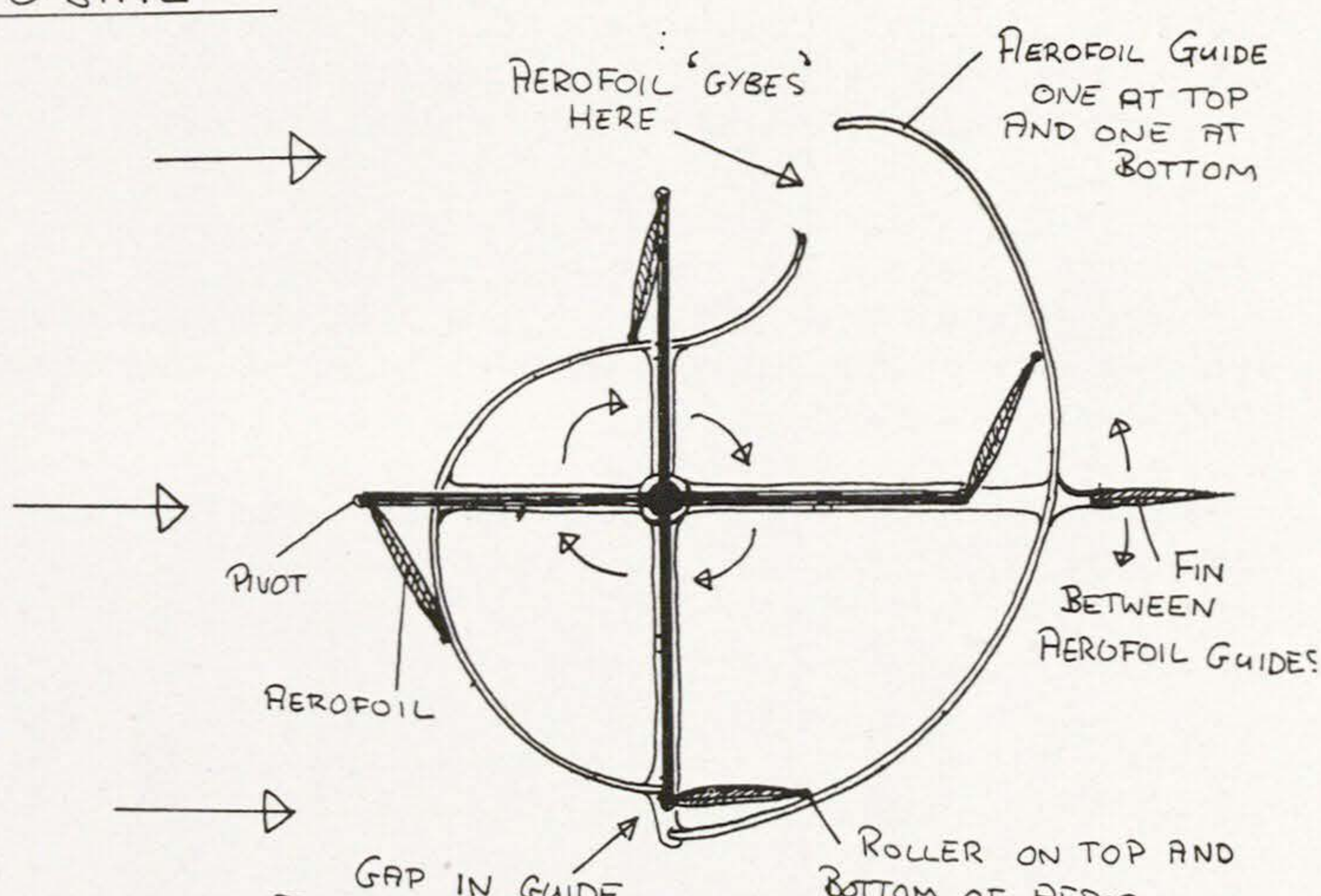
The 'sails' were made from thin Formica sheet, which bends to aerofoil shape under wind pressure, just like a soft boat sail does, with approximately a 15 to 1 section (Span/thickness). Aspect ratios tried, 4 to 1 and 10 to 1. Rotor diameter, 280 mm., aerofoil blades, 490 mm. long, Figure A5 illustrates a spring arrangement which might be used to allow the blades to set themselves at different angles of incidence, depending on wind strength.

Mk 1 ROTOSAIL
CROSS SECTION OF ROTOR



SH Sanderson

Mk 2 ROTOSAIL
CROSS SECTION OF ROTOR



GUIDE GIVES POWER FROM AEROFOILS FOR $\frac{3}{4}$ OF THE CYCLE

CH Sanderson

EXPERIMENTS USING WINDMILLS TO PROPEL A MODEL CATAMARAN

by

Simon H. Sanderson
Mistletoe Cottage, Brancaster Staithe, King's Lynn, Norfolk.

Figure B1 shows an inclined propeller type windmill coupled to a water screw, photographs B2 and B3, a Savaronius type windmill, and the vertical axis windmills explained in section A were also tried.

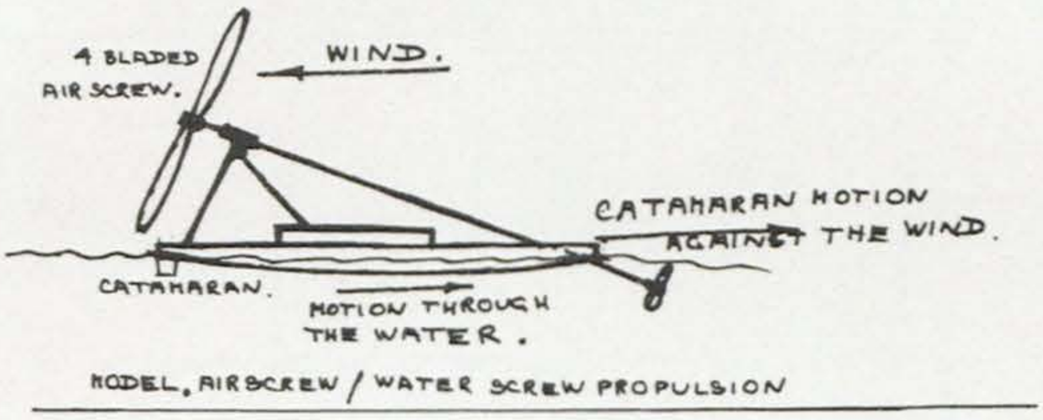


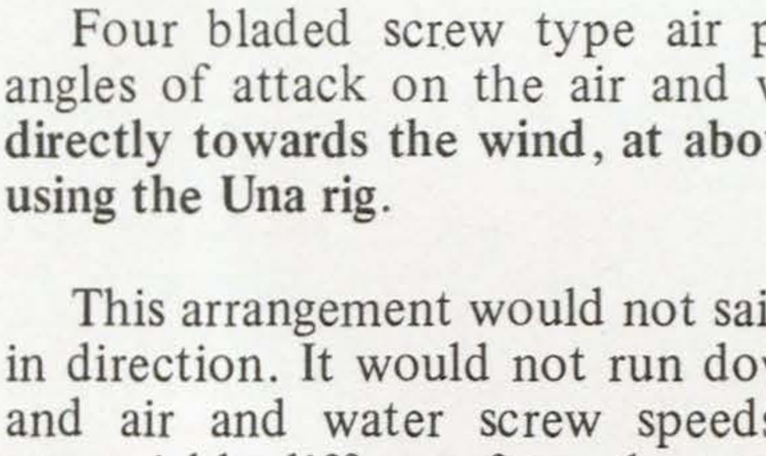
Fig. B1

Four bladed screw type air propellor. After experimenting with blade angles of attack on the air and water screws, **the catamaran made progress directly towards the wind, at about the same speed as the speed made good using the Una rig.**

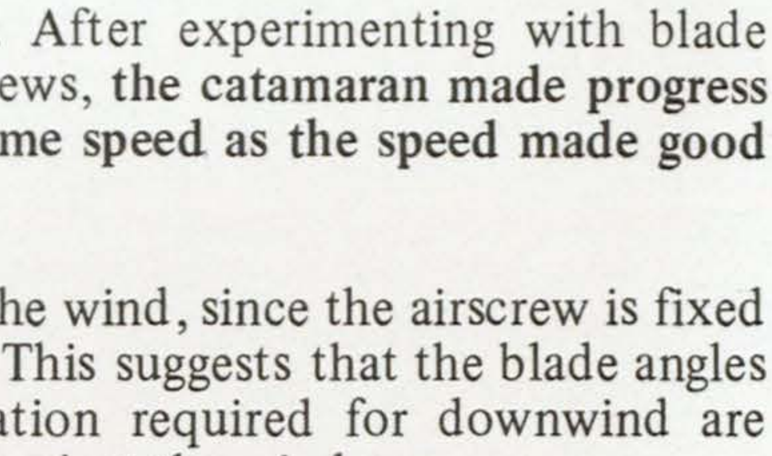
This arrangement would not sail across the wind, since the airscrew is fixed in direction. It would not run downwind. This suggests that the blade angles and air and water screw speeds of rotation required for downwind are appreciably different from the settings for against the wind.

I then tried the vertical axis rotosails, against the wind. At first the model went astern. I thought that aspect ratio might be too big, 10 : 1 and altered the blades to give aspect ratio of 4 : 1. The cat now made progress to windward, but slowly. This was with the Mark 1 rotosail. Mark 2 not yet tested on the model catamaran.

The arrangement using a vertical axis Savaronius type rotor has not yet been tested.



B2



B3

Test Models: Savaronius Rotor.

CONSTRUCTIONAL DETAILS OF A MODEL TRIMARAN, PROPELLED BY AIRSCREW AND WATER SCREW

by

Kenneth R. May
Brook House, Middle Street, Salisbury, Wilts.

Photograph C illustrates. This model has been exhibited on the A.Y.R.S. stand at a London Boat Show, along with a windmill propelled model wheeled vehicle. The latter propelled itself against the stream of air from a fan.

Ken writes – I was unable to develop the model trimaran, because there is nowhere convenient to my home where I could test it. I enjoyed the high precision lathe work, necessary to get friction in the drive to a low figure. I also made the wheeled Mecanno model which was demonstrated at the Boat Show, and used it to test various types and numbers of blades. This model would propel itself against the wind stream from a vacuum cleaner, and against the wind outside on the pavement. It was clear that the optimum number of blades was four, of aerofoil section, twisted to give nearly constant angle of attack along each blade. Fine pitches and high rotational speeds were the most effective.

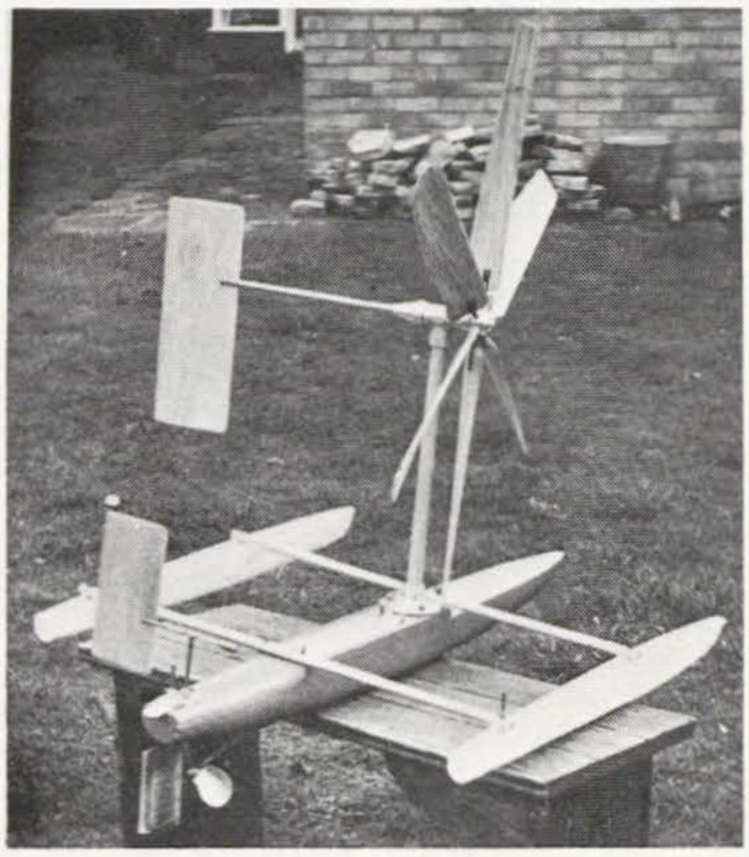


Photo of K. R. May's Windmill driven tri, exhibited at the A.Y.R.S. stand at the Boat Show, Earls Court, London. Precision ball races were used for all bearings, except the prop. shaft.

On a boat, catamaran or trimaran, rolling and pitching will be accompanied by gyroscopic effects. The wide beams of multihulls would appear to make them more suitable than a monohull for windmill propulsion.

Windmill driven water craft have the unique capability of being able to propel themselves straight into the eye of the wind, and any other course as well. Articles on windmill propelled craft in Amateur Yacht Society publications – Issues 33, 41, 58, 61 and 70.

For model makers, windmill boats offer immense scope for experiment, ingenuity, skill and competition.

THE DEVELOPMENT OF A WINDMILL PROPELLED CATAMARAN

by

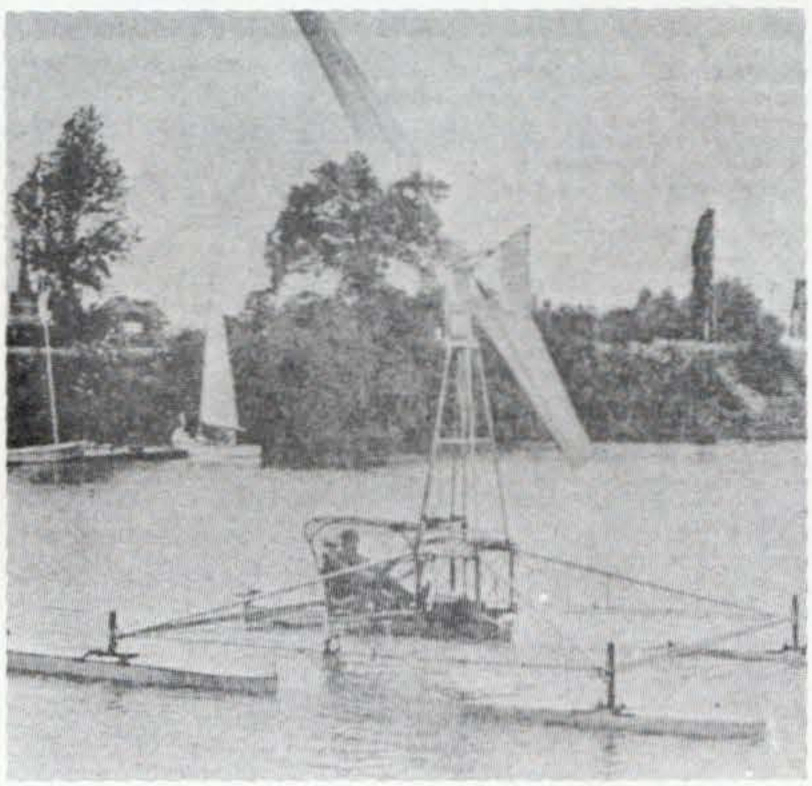
George Webb
Rosses Lane, Wichenford, Worcester.

The aim is to develop a craft capable of making sea voyages.

A windmill propelled marine craft offers the possibility of moving directly against a headwind without tacking, in addition to all other headings. Another advantage is the possibility of using the windmill to generate power, when the craft is anchored, and in strong winds. This power may be stored in batteries and used to provide propulsive power during lulls in the wind, as well as other auxiliary requirements such as lighting, cooking and operation of navigational instruments.

Since this sort of craft is new, there is little previous experience to go on, and the pioneer has to experiment and find ways of meeting the essential requirements for a sea going craft.

The experiments so far have been done on a craft floating on four pontoon like floats, placed at the corners of a rectangular frame. The windmill was a 20ft. diameter, two bladed airscrew, mounted on a four legged pylon, connected via chain and bevel gearing to a water propeller. Since the water propeller sometimes acts to extract power from the water, operating as a 'watermill' or, to use another term, a water turbine, it will be referred to as the water screw. Both the air and the water screws have variable pitch control. In the original arrangement, the gearing was fixed ratio.



George Webb's Windmill propelled Catamaran – Test model using four pontoons.

The airscrew also turned about a vertical axis, and could weathercock to face the wind, or be set at any desired angle to the wind using a sort of steering wheel. The craft had a rudder, but in the early stages, no centre plate, which meant that it did not sail too close to the wind.

The four floats were filled with foam, and were spaced far enough apart to provide more than adequate stability against capsizing.

Each of the two airscrew blades weighed only seven pounds. They were made using aluminium tubing, with plastic sheet overlay, like a sock pulled over.

The supporting structures were light, strong and rigid, utilizing aluminium tubing and other sections, braced with wire cable. Most of the weight was in the foam filled floats. Even so, total weight including crew of one, was only 11 cwt. The aim was to test and develop the airscrew and its control gear, and the transmission, the four floats providing a safe, stable test bed. Later, it was intended to replace the floats with two 32 ft. catamaran hulls, modified to suit the airscrew propulsion. The water screw was a conventional boat propellor, definitely too small and running too fast, but it was available and later an efficient propellor will be developed to suit the novel requirements of this craft.

Trials in 1977. Initially, an 18 acre shallow lake was used. The BBC had sent a camera crew to record the performance, and before they arrived, the craft was being tested. Acceleration from rest was found to be dramatic. Control involved steering, altering the pitches of the air and water screws, as well as ensuring the airscrew was setting correctly relative to the wind – at 90 degrees for downwind. Unfortunately, during these preliminary runs, the water screw hit a shallow bank, the gearing jammed up, most of the teeth of the bevel gear up against the airscrew hub sheared, and, such was the shock the heavy duty motor cycle drive chain stretched one link in twenty. This unfortunate occurrence had some value. It found some weak parts of the drive, but also demonstrated the strength of other parts and of the airscrew. If the airscrew had been heavier, damage would have been more serious. One conclusion is that on a commercial craft, there should be a slipping mechanism between airscrew and transmission, which releases at a preset torque.

Since the BBC were due to film, the water screw was uncoupled, the airscrew allowed to spin freely, and runs were made using the airscrew in auto gyro mode, propelling the craft by its axial force, able to run downwind, and to tack, but not go directly against the wind.

During the demonstration for the BBC, the wind, which had been gusting up around 8 to 9 mph when the mishap occurred, had weakened. However, the airscrew kept spinning freely in auto gyro mode at about two revs. per second and the craft progressed across the water fast enough to satisfy the camera crew and director.

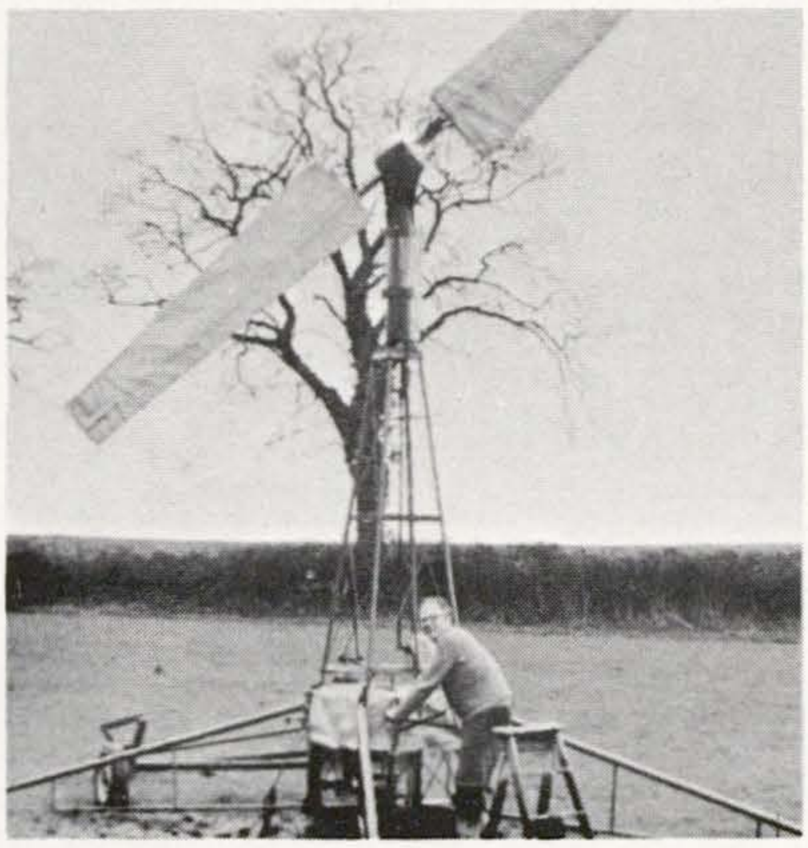


Photo of George Webb's Windmill propelled Catamaran.
Airscrew and its supporting structure.

Later tests were carried out on a 28 acre lake. One conclusion from the tests was the desirability of a larger diameter, slower rotating water screw.

Some measurement of the axial thrust of the airscrew may be of interest to readers. The craft was tethered to the bank, a spring balance inserted in the mooring line to indicate the force acting. It has to be remembered that the airscrew was spinning freely, and therefore the forces measured have to be related to auto gyro mode of propulsion. Also to be remembered is that when sailing, it is the relative wind which counts, and downwind, this is slower than the real wind.

[Interjection by Reg Frank. This is surprisingly high. The exact diameter is 20.2 feet, swept area, 320 sq. ft. A wind speed of 8 mph corresponds with 11.73 ft. per sec. Inserting in the lift formula, and regarding the swept area as equivalent to the area of a soft sail, we have–

$$\text{Lift coefficient } C1 = \frac{2 \text{ x Lift force } 1021\text{lbs. x g } 32.18\text{ft./sec}^2}{0.078 \text{ air density x } 320 \text{ sq. ft. x } (11.73 \text{ ft./sec})^2} = 1.91.$$

It seems likely that the wind was stronger than estimated, over the upper parts of the swept area. Nevertheless, this lift coefficient is very impressive, especially since the airscrew blades are nowhere near to being precise aerodynamic sections].

Another test was to push the craft against the airscrew axial force using a 4 horsepower rated outboard engine. This resulted in a speed of only 1 mph in a calm with no wind. When the blades were feathered and stopped rotating, the speed on engine was exactly the same as speed in auto gyro mode, downwind, propelled by the airscrew, in the 8 mph wind.

The static pull in a 5 mph breeze was 18 lbf. This is a falling off larger than would be the case with a sail, unless the wind speed had been higher than 8 mph. (Assuming thrust is dependent on the square of wind speed, this suggests the effective wind speed had been, not 8 but 11.9 mph. W.R.F.).

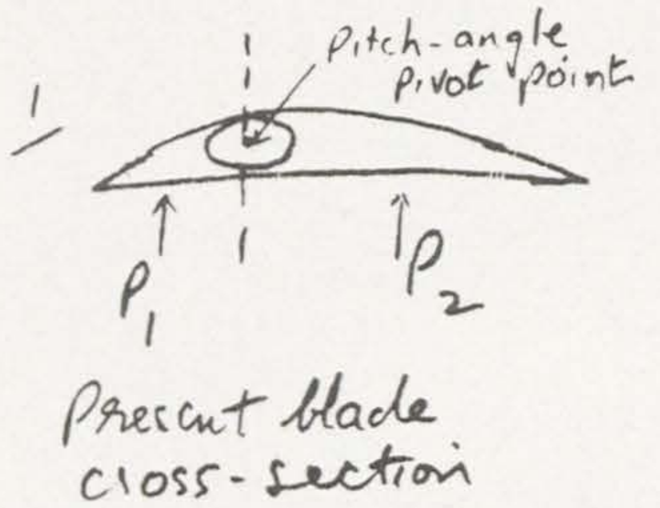
Developments during 1978

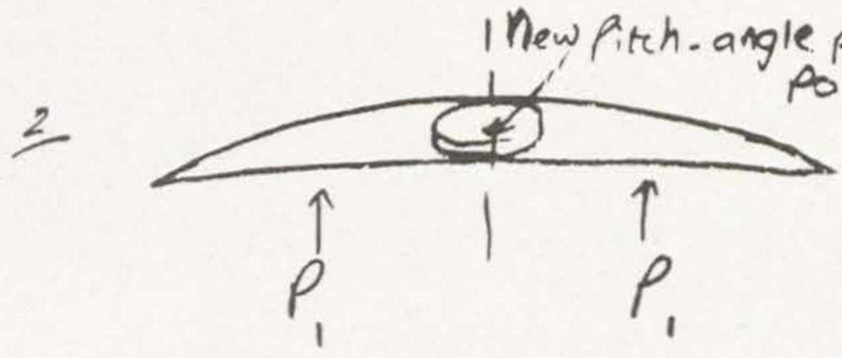
I am increasing the height of the "mast" and also the rotor diameter to 24 feet. The stability of the boat is sufficient to take this.

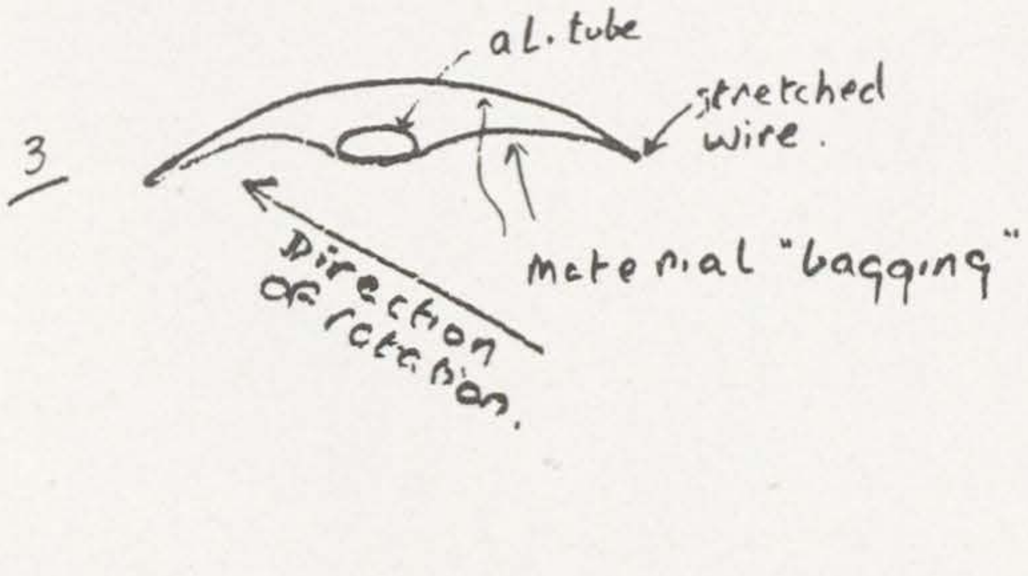
I am also covering the blades in 24 swg. aluminium sheet and moving the pivoting-axis of the blades to coincide with the centre of pressure. At the moment the pivoting-axis (which provides the variable pitch), is too far towards the leading edge. This was intentional in order that, should the pitch control mechanism fail, the differential pressures on each side of the pivoting axis would ensure that each blade would move automatically to a fully feathered position, thus stopping rotating. What happened in practice was that, in winds of over 25 mph (rotor speed of some 3 r.p. second), the differential pressure on the blade imposed a constant high pressure on the pitch control mechanism (trying to return the blade to a fully feathered position). So I am centralising the blade pivoting-axis to make the control of pitch neutral – that is, to stay where put until moved manually at any wind speed.

Covering with aluminium is for two reasons. At high wind speeds, I noticed that bagging of the blade covering occurred. This happened quite suddenly at a certain rotor speed (using the pitch control lever) and as soon as it happened there was vibration of the covering at the blade tips (about G above middle C), and no further increase in blade rpm. The aluminium should cure this. I shall also cover the aluminium with "lunar foil." This is self-adhesive al. foil faced with clear plastic. It has a very smooth finish, and is weatherproof. I want to reduce skin friction as much as possible. I shall try the blades without and with the foil and record the respective performances, and moving seat to improve visibility.

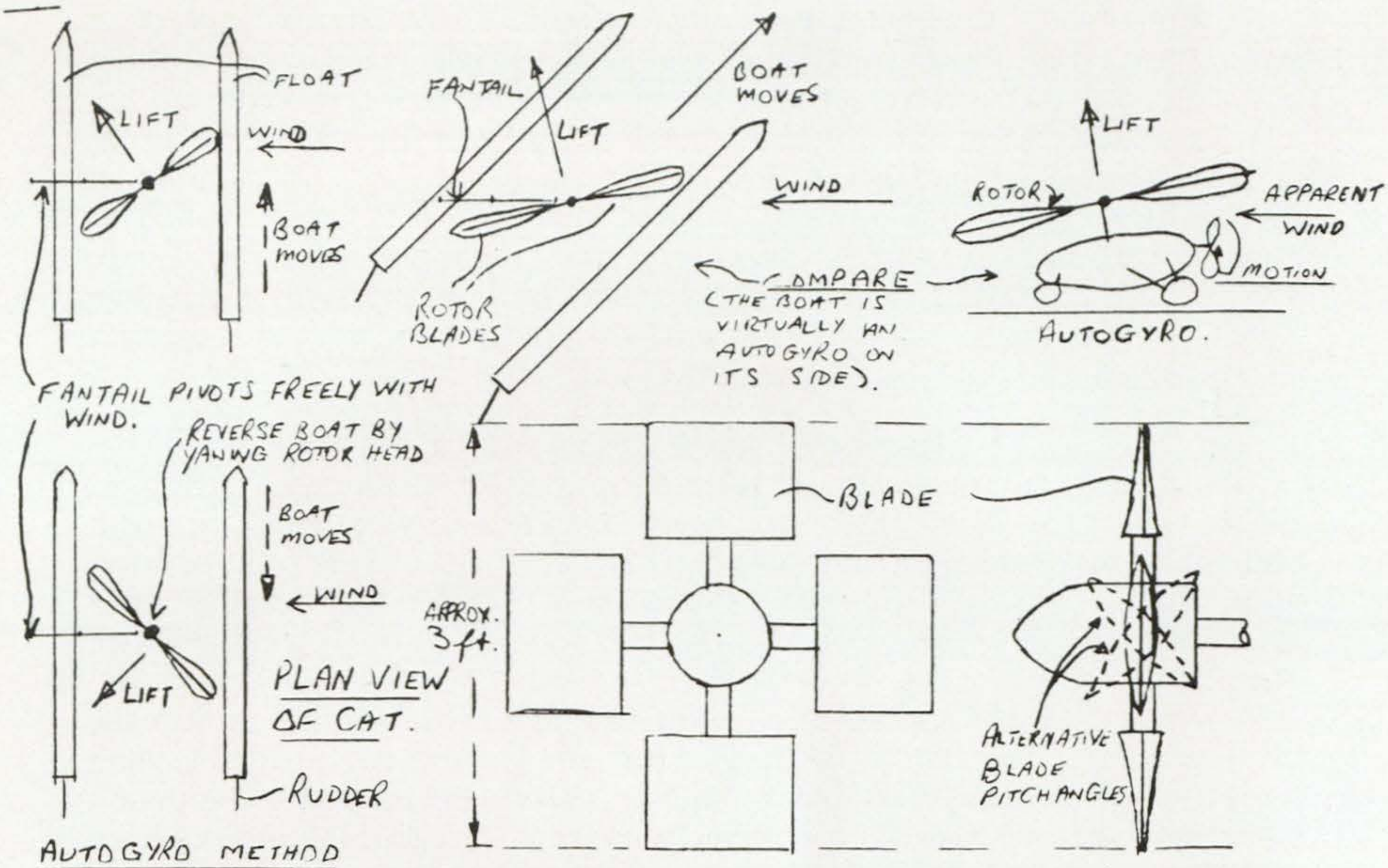
I am building a constant-rotor speed control, which will work automatically to retain the rotors at any selected rpm. It acts through a governor, which varies the blade pitch according to changing windspeed, or load. The tricky bit is designing an automatic self-start after blade stall, or wind drop. You see, as wind increases, the pitch is made coarser to slow rotor speed, and vice-verse. But if wind speed falls too much, the rotor stalls with finest pitch on, whereas it would still give power if rotating slowly at coarse pitch. Also, if load is applied which slows the rotor, the governor will make the pitch finer and try to increase rotor rpm (equivalent to falling wind speed), whereas really the pitch requires coarsening to derive maximum power at this lower speed. I am trying to solve it by switching a time-delay sequence which, if the rotor stops, automatically returns blades to fully feathered, and then progressively makes the pitch finer until rotation recommences and the normal sequence of control takes over. I am also adding a raisable and steerable centreboard forward of the airscrew pylon, to reduce leeway.







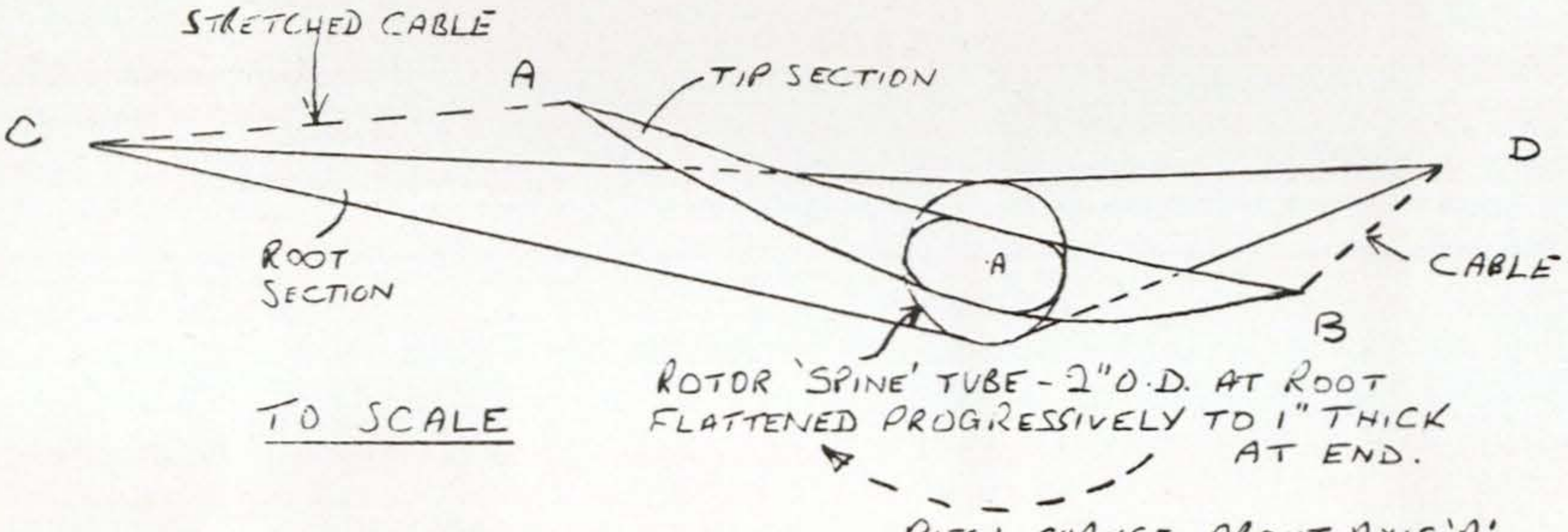
1 & 2 show the proposed moving of the blade axis.
3 shows the manner in which the soft material covering the blade 'bags' when high wind-speeds occur.



AUTOGYRO METHOD OF PROPULSION

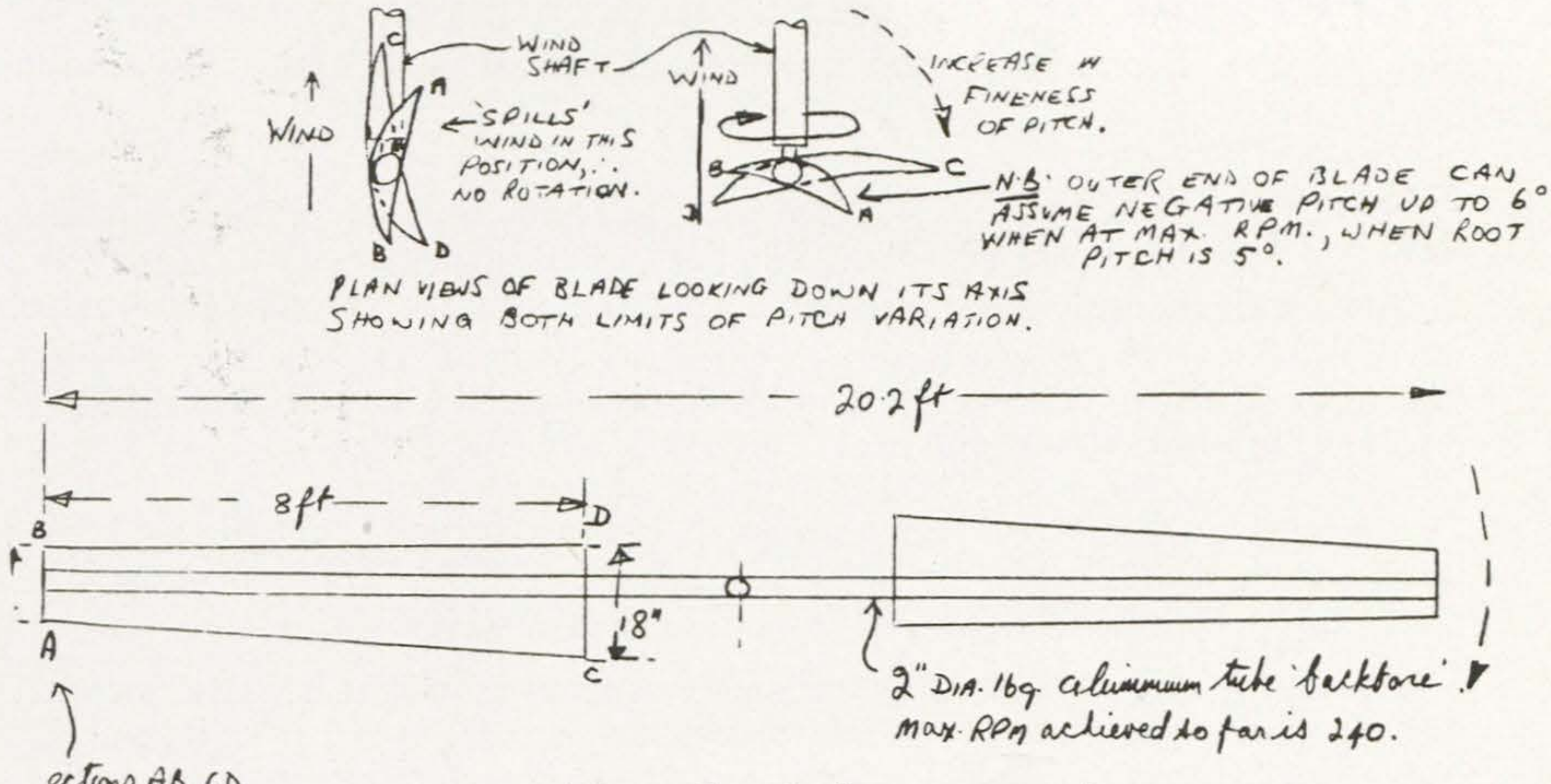
PROPOSED WATER PROP. (NOT TO SCALE)

G.H.WEBB

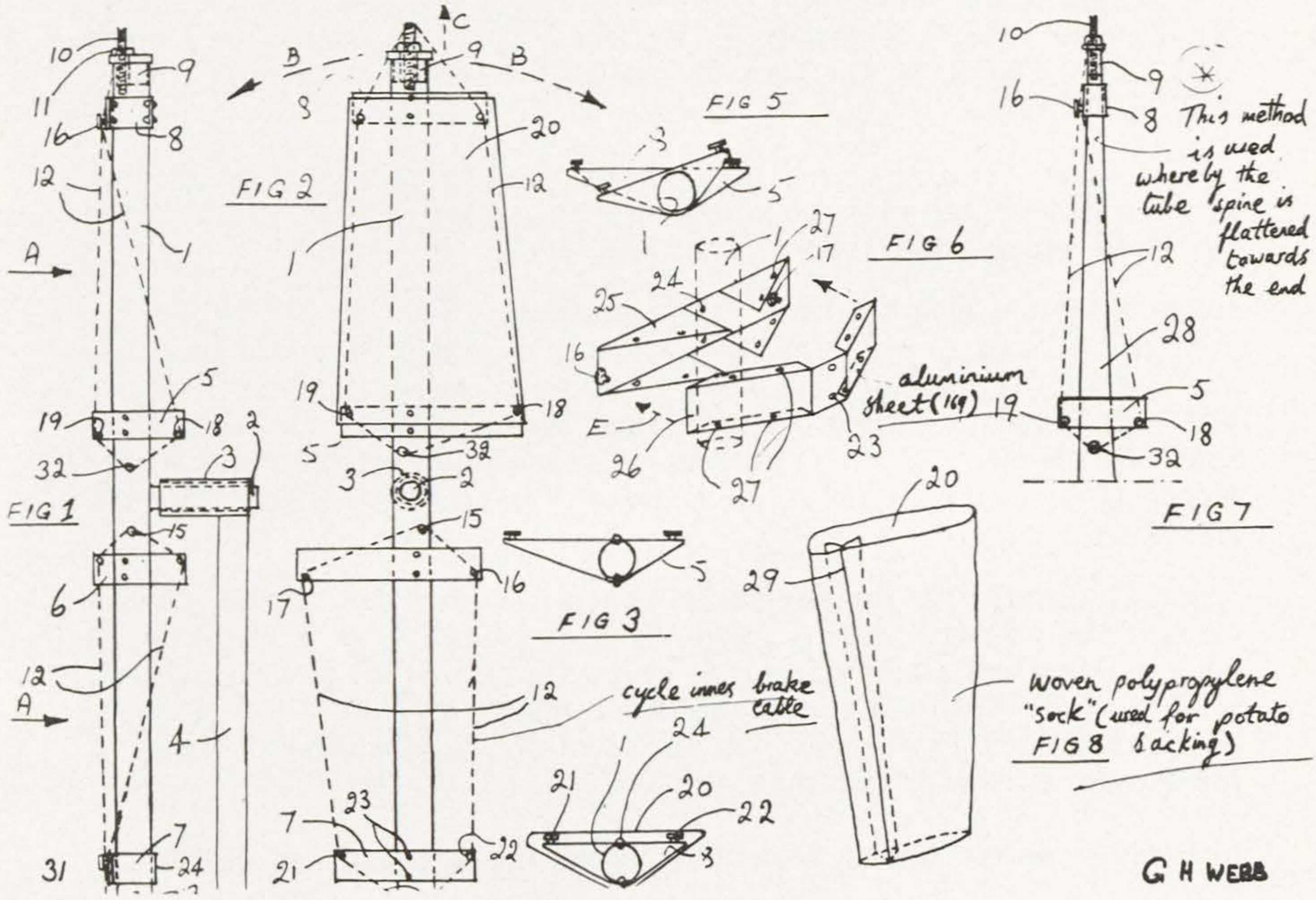


WIND ROTOR SECTIONS AB, CD SUPERIMPOSED TO SHOW ANGLE OF TWIST OF BLADE.

G.H.WEBB.



WIND ROTOR (NOT TO SCALE)



POWER FROM THE WIND – BACKGROUND INFORMATION

Reg. Frank, 87 Staincross Common, Mapplewell, Barnsley, Yorkshire. S75 6NA.

BASIC PRINCIPLES
MASS, ENERGY AND POWER.

Start with energy. If you lift a mass which weighs 4 lb., through a distance of 6 ft., the work you have done against gravity is 24 ft. lbf. Now release the mass. When it reaches the ground, it has converted gravitational energy of 24 ft. lbf., into kinetic energy of 24 ft. lbf.

Consider a fluid. If we pump a mass of 4 lb. up through a height of 62 ft., during each second, then the energy being put into the fluid per second is 24 ft. lbf. per second. Energy per second is called power.

Masses are measured in units obtained by dividing weight by acceleration due to gravity. If weight is in lb. force, then mass is lbf./g., in units called slugs. If weight is in poundals, mass is in poundals/g., which are lb. mass units.

One slug mass weighs 32.18 lb. force. One lb. mass weighs 32.18 poundals. One kilogram mass weighs 9.81 newtons.

The kinetic energy of a mass M is given by $½.M.V^2$.

A stream of area A, density ρ, moving at velocity V, has a mass ρ A.V., for a length equal numerically to V. This length V. passes a fixed point during one second. **So the mass M. passing per second, in a fluid stream, is ρ. A.V.** Fig. 1A.

The kinetic energy of the mass passing per second is $½.M.V^2$. Kinetic energy flow per second is the same as the power in the fluid stream. **Power in a Fluid Stream = $½.\rho.A.V^3$.**

Extracting Power from the Wind, using a Windmill – Fig. 1B.

If the mass of air through a windmill per second is M, and if this mass had a velocity V1 well upwind, equal to free wind speed, and later a velocity V2, well downwind, then corresponding kinetic energies per second are $½.M.V1^2$ upwind, $½.M.V2^2$. downwind. The reduction in kinetic energy per second is $½.M. (V1^2. -V2^2.)$, and this energy has been transferred into the windmill (or lost).

Unfortunately, we do not know either the mass per second flowing through the windmill, nor its speed V2 downwind. To get any further, in understanding how a windmill works, we have to utilize part of what is called, ideal windmill theory. Explanations are complicated, and found in books on aerodynamics. Fortunately, we can make do with only one little bit of this theory, and this part is simple. Fig. 2A.

It is a rule for finding velocities through the windmill and downwind.

IF THE FREE WIND SPEED IS V, THEN THE SPEED OF THE AIRSTREAM SOME DISTANCE UPWIND IS ALSO V. AS THE STREAM PASSES THROUGH THE WINDMILL, ITS SPEED IS (V –v) WELL DOWNSTREAM, THE SPEED HAS FALLEN FURTHER, TO (V –2v).

Mass M flowing per second through the Windmill = ρ.A.(V −v).

This mass had kinetic energy per second upwind of ½.M.V^2. It finishes downwind with kinetic energy per second of ½.M.$(V - 2v)^2$.

Ideal Power from the Wind

= Kinetic energy lost per second from the wind = ½.M. (V^2. − $(V - 2v)^2$.).
½.ρ.A. (V −v). (4). (V −v). (v).

Power Transferred from Wind to Windmill = 2.ρ.A.v. $(V - v)^2$.

Maximum Ideal Power Fig. 2B.

When we calculate numerical values for power, for a wind speed V, and different speed reductions v, plotting a graph, figure 3, we find that there is one value for v, equal to one third wind speed for a fixed windmill, which results in maximum power. When we substitute v = V/3 in the ideal power formula, the maximum power is expressed as:−

Maximum Ideal Power from a Fixed Windmill = 16/27. x ½.ρ.A.V^3.

The speed Vw through the windmill is then two thirds of free wind speed.

MOMENTUM EXPLANATIONS Fig. 1A and 1B.

When we move onto water craft and vehicles propelled by windmills, explanations can be shorter, using a different approach from the kinetic energy one. This other approach utilizes a law originally suggested by Newton that force equals rate of change of momentum.

Momentum is mass times velocity. So when a fluid stream of density ρ., area of section A. flows through a windmill at velocity (V −v), the mass per second is ρ.A.(V −v).

When velocity upstream is V, and downstream is (V −2v), change in velocity is 2v. So the momentum of the mass flowing per second has changed through ρ.A.(V −v). (2v). This is also equal to the axial force exerted by the windmill on the airstream AXIAL FORCE EXERTED BY WINDMILL ON AIR STREAM = F = 2.ρ.A.v.(V −v).

The work being done per second by the axial force on the wind, which is equal to the power being transferred from wind to windmill, is given by:− POWER TRANSFERRED FROM WIND TO WINDMILL = p = F. x wind speed through airscrew, (V −v), = 2.ρ.A.v. $(V - v)^2$.
This power is a maximum when v = V/3, and wind speed through windmill = 2V/3.

'EFFICIENCY' OF THE IDEAL WINDMILL

When we substitute v = V/3 in P = 2.ρ.A.v. $(V - v)^2$., Max. power = 2.ρ.A. (V/3). ($2V/3)^2$ = 2.ρ.A.(4/27).V^3. = (8/27).ρ.A.V^3.
= 16/27 x ½ρ.A.V^3.

This gives the impression that the efficiency is 16/27. Not so, because the area A is the swept area of the windmill. The area of the air stream upwind was originally A.x 2/3. Divide 16/27 by 2/3, and we get 8/9. THE WINDMILL IS EXTRACTING EIGHT-NINTHS OF THE POWER ORIGINALLY IN THE WIND. The ideal windmill is 100% 'efficient,' in the sense that nature imposes the limits. We ought to compare the power outputs of practical windmills against the corresponding ideal powers.

This ideal efficiency is very important when we go on to study windmill propulsion of vehicles and boats. Nature imposes limits on the maximum power which can be extracted from wind, and the most perfect windmill cannot exceed these ideal powers.

VERTICAL AXIS WINDMILLS WHICH UTILIZE AEROFOIL SECTIONED BLADES

One type was invented by Darrieus. It uses a circular hoop of metal strip which has an aerofoil section, and is being investigated in the U.S.A. and Canada.

In this country, a vertical axis windmill with vertical straight blades is being developed at Reading University, and is described elsewhere in this publication.

This windmill has fixed blades, and does not require control of blade angles. It has to be spun up to speed using an external source of power. From then on it generates power.

Since it is not obvious, even to many windmill enthusiasts, just how these windmills work, I have included an explanation.

Behaviour is certainly complicated, since as a blade rotates about the vertical axis, angles of incidence of wind to blade alter, lift forces alter, so do drag forces. The wind speed is not uniform across the windmill, since maximum power is being extracted only whilst blades are moving at nearly 90 degrees to the wind direction, whilst on one side, drag slows down the wind a little, on the other side, speeds up the wind. The formulae I have deduced may be modified to take account of these variations in wind speed across the windmill. In order to explain the principles involved, I have assumed uniform wind speed Vw.

VELOCITY DIAGRAMS FOR A STRAIGHT BLADE, VERTICAL AXIS WINDMILL, WITH FIXED BLADES
Figures 3, 4 and 5.

In figure 3, I have drawn separate velocity diagrams around the circle of rotation. This comes out complicated, so in figure 4, I have combined them in a single diagram. Rotational linear speed Vf is taken as datum, and the wind line Vw rotates, exactly as the helmsman of a boat observes the wind as he alters course. The relative wind, Vr, now oscillates from side to side, as it does for a boat tacking. Its maximum angle of incidence has to be smaller than stalling angle. Tangential speed Vf = revs. per sec. x circumference of path, and is assumed kept near enough constant by the flywheel effect.

Angles of incidence α, are always small; I assume not more than 12 degrees, and their cosines can be taken as equal to unity.

The wind line Vw is inclined at angle θ, to line Vf, and is zero when Vf is in the free wind direction.

We can relate sides and angles of the triangles by using the cosine and sine rules, finally expressing everything in terms of angle θ.

BLADE LIFT FORCE L.

This is altering all the time, being given by:– $L = Cl.\rho/2. \times S.Vr^2$. COEFFICIENT OF LIFT Cl. can be written equal to $k.\alpha$. where α is the angle of incidence in radians. It is more convenient to write, $Cl = k.\sin\alpha$., and I have done this; I have put the numerical value of k as 5, which is typical for a high aspect ratio blade.

S IS THE AREA OF ONE BLADE

Air density is taken as 0.078 lb. mass/cu. ft., = 0.078/32.18 slugs/cu. ft.

BLADE DRAG. This is altering all the time. It is a sum of three sorts of drag.

Surface Drag, with coefficient Cs, but use 2S instead of S, because it acts on both sides of a blade. In formulae, alternatively use 2.Cs along with S.

Profile Drag. Depends on blade dimensions and aspect ratio. Coefficient is a.

Induced Drag is essential for an aerofoil to develop lift, and depends on aspect ratio. Coefficient of induced drag = $Cl^2./b$. I have used b = 16.

Since $Cl = k.\text{sine}\,\alpha$., **coefficient of induced drag = $k^2.\ \text{sine}^2\alpha./b$.**

To simplify, let 'a' include both surface drag and profile drag together.

COEFFICIENT OF DRAG = $a. + Cl^2/b = a + (k^2.\ \text{sine}^2\alpha.)/b$.

We now have– LIFT FORCE = $L = (k.\ \text{sine}\,\alpha.)\,(\rho/2).\ S.Vr^2$

DRAG FORCE = $D = (a + k^2.\ \text{sine}^2\alpha./b).\ \times (\rho/2.)\ S.Vr^2$.

TRACTIVE FORCE Ff = $L\ \text{sine}\alpha. - D.\ \text{cosine}\,\alpha.$, but cosine α is nearly equal to unity, so we can leave it out. We therefore write:–

TRACTIVE FORCE Ff = $L.\ \text{sine}\ \alpha - D.$

$$= (Cl.\ \text{sine}\,\alpha. - Cd.).\,(\rho/2).\ S.Vr^2.$$

$$= \left(k.\ \text{sine}^2.\,\alpha. - a - \frac{k^2.\ \text{sine}^2\alpha.}{b}\right)\left(\frac{\rho}{2}\right).(S.Vr^2.)$$

POWER = TRACTIVE FORCE Ff x BLADE SPEED Vf

Speed Vf is limited by stalling.

I have taken the maximum angle of incidence as 10.8 degrees.

Maximum angle of incidence is reached when velocity line Vr is tangential to the circle, and at right angles to Vw. Therefore the sine of α max. = Vw/Vf.

We have specified α max. as 10.8 degrees, Vw as, say, two thirds free wind speed, so we can find the corresponding value for Vf.

It is possible to alter these formulae replacing angles of incidence α by angles θ.

We use the sine rule to give sine α = (Vw/Vr). sine θ.
and the cosineformula to give $Vr^2 = Vw^2 + Vf^2 - 2.Vw.Vf. \cos.\theta$.

$$\text{or } (Vr/Vw)^2 = 1 + (Vf/Vw)^2 - 2.(Vf/Vw) \cos. \theta.$$

$$= 1 + (1/\text{ sine}^2 \alpha \text{max.}). - 2. (1/\text{sine } \alpha\text{max.}). \cos.\theta.$$

When we re-arrange the expressions, we arrive at:– Fig. 5.

$$\text{POWER} = \text{Vf.Ff.} = \frac{\rho \text{ S. } Vw^3}{2 \text{ sine}\alpha\text{max.}} \text{ x } \left((\text{Sin}^2 \theta) (k - \frac{k^2}{b} \right) + \frac{2a \cos \theta}{\sin \alpha \text{max.}}$$

$$- a \left(1 + \frac{1}{\sin^2 \alpha \text{max.}} \right)$$

$$\text{Sine}^2 \theta = \frac{1}{2} - \frac{\text{Cos } 2 \theta.}{2}$$ and its average value over 360 degrees is ½.

The average value of (cos θ) over 360 degrees is zero.

Average Power over 360 degrees is:

$$= \frac{\rho. \text{ S.}Vw^3}{2 \text{ Sine } \alpha \text{max.}} \text{ x} \left(\frac{1}{2} \left(k - \frac{k^2}{b} \right) - a \left(1 + \frac{1}{\text{Sine}^2 \alpha \text{max.}} \right) \right)$$

Maximum power is obtained when:

$$\text{Sine } \alpha \text{max.} = \sqrt{\frac{6a}{k (1 - k/b) - 2a.}}$$

OPTIMUM BLADE AREA

The maximum ideal power from windmill theory occurs when wind speed through the windmill is two thirds of free wind speed. This maximum ideal power is given by:–

Maximum ideal power = $16/27 \times \frac{1}{2}.\rho.A.V^3$.

The corresponding maximum ideal power, from the vertical axis windmill power formula, obtained by putting drag zero is:– (When θ = 90 degrees, $\text{sine}^2\ \theta$. = 1)

$$\text{Maximum ideal power} = \frac{\rho b.S.Vw^3.}{2.\ \text{sine}\ \alpha\text{max.}} \times \frac{k}{2} \quad \text{and } Vw = \frac{2V.}{3}$$

Equating the two expressions gives:–

$$\text{Total blade area } bS = \frac{4.\ \text{sine}\ \alpha\text{max.}}{k} \times \text{swept area A.}$$

b = number of blades.

Example:–

Two vertical blades, each 5 ft. long, diameter, 10 ft. b = 2.
Area opposing the wind, A = 50 sq. ft.

Total blade length = 10 ft., blade width c ft., blade area bS = 10.c. sq. ft.

Operate so that the maximum value of angle of incidence, α max., is 12 degrees. k will be near to 5.

$$10c = \frac{4 \times \text{sine } 12 \times 50}{5} \quad \text{from which c = 0.832 ft., = 10+ inches chord.}$$

Speed of rotation. e.g. When free wind speed V = 20 ft. per sec..

Vw for maximum power = 2/3 x 20 = 13.33 ft. per sec.

Linear speed of rotation Vf = Vw/sine αmax. = 13.33 / sine 12 = 64.13 ft./ sec.
Circumference = 10 x 3.142 = 31.42 ft.
Revs. per sec. = 64.13/31.42 = 2.04 rps = 122 rpm.

Efficiency. If we regard the efficiency of the ideal windmill as 100%.
Efficiency relative to ideal windmill =

$$\frac{\tfrac{1}{2}(k - k^2/b) - a(1 + 1/\text{sine}^2 \alpha\,\text{max.})}{\tfrac{1}{2}k}$$

$$= \left(1 - \frac{k}{b}\right) - \frac{2a}{k}\left(1 + \frac{1}{\text{sine}^2 \alpha\,\text{max.}}\right)$$

Putting k = 5, b = 16, a = 0.02, αmax = 12 degrees.

Efficiency relative to the ideal windmill =
(1 –5/16) – (0.04/5). (1 + 1/sine^2 12.) = 0.688 –0.193 = 0.495

The value of 0.02 for 'a' is too big for a large windmill, but will be typical for the smaller sizes which amateurs might build. Larger size windmills might be expected to have efficiencies at design wind speed of about 70% relative to the ideal windmill,70% x8/9 = 62%.

When testing these windmills, remember that the area A for maximum power is 3/2 times the area of the original wind stream. The original wind power was therefore: ½. (2/3 x A.).ρ.V^3.

WINDMILLS - Horizontal Axis and Vertical Axis Types –
BLADE REYNOLDS NUMBERS, Re

Blade Reynold's number $Re = \frac{\rho Vr.c.}{\mu} = \frac{Vr.c.}{\nu}$

Where Vr is air speed relative to the blade, approximately equal to speed of rotation Vf.

Viscosity, μ kinetic viscosity ν , and density ρ .

For the windmill studied above, Vf was 64.13 ft. per sec. Chord width was 0.832 ft. The kinematic viscosity of air can be taken as approximately 0.000157 ft.^{2}/sec.

$$Re = \frac{64.13 \times 0.832}{0.000157} = 340{,}000$$

This value for Re is satisfactory. If it drops below about 180,000, the surface drag increases quickly, and stalling angle reduces.

WINDMILL BLADE ANGLES Fig. 6.

We could copy sail boat practice. Regard the windmill blade as a sail, and refer to the angle between the relative wind and the movement of the blade as Beta.

The blade is set at an angle α from β. For windmill operation, the blade angle will be $(\beta - \alpha)$. For propellor operation, it will be $(\beta + \alpha)$.

When we are designing the airscrew, we can decide on a suitable speed of rotation, then find ideal power from the ideal windmill formula. Put blade area as S, and work out the ideal power again, but using aerofoil formulae, with drag zero and with a suitable value for lift coefficient $Cl = k.\alpha$. Equate the expressions, which allows a value for blade area S to be found. Since we have decided on foil speed Vf, and obtained wind speed through the air-screw from the ideal windmill formula – e.g. 2/3 x wind speed for a static windmill, for maximum power, this gives us angle β. We take away α to arrive at blade angle.

This 'sailing' approach results in simple formulae, but it is not the way used in the books. Their formulae make β the actual blade angle.

When we move on to study **windmills mounted on wind vehicles and water craft**, the book approach lets us in for many complications. The windmill is then behaving partly like a windmill, and partly like a propellor.

So we use the concept of pitch angle γ, to deal with that part of the blade motion relative to ground or water, and we use β for the angle between foil path and the relative wind. Then we subtract angle of incidence α for windmill operation, but add it for propellor operation. It sounds complicated, but is in reality exactly the same case as a boat tacking relative to the wind. Pitch angle corresponds with course angle. β is the angle between boat course and the relative wind.

WINDMILL PROPELLED BOATS, OTHER WATER CRAFT, AND WHEELED VEHICLES.

Introduction

Propulsion using an airscrew, which derives the power which it needs from the wind, appears at first sight to be an exceedingly complicated process. A prospective builder of a windmill boat would soon realise this. He would have to guess how many airscrew blades to use, blade width, speed of rotation angles at which blades are set. Then he would have to decide how to operate a water screw. He would be in some doubt as to how the water screw efficiency could be improved, and have to decide blade shape, diameter, rotational speed.

If he were to use a fixed gear ratio between airscrew and water screw, he would find that performance is satisfactory over only a small range of wind and boat speeds.

Since the force of the wind on the airscrew hinders boat motion against the wind, but helps downwind, the power involved in this force has to be included in studies. The builder might, for example, be allowing the airscrew to rotate too fast, building up an excessive axial wind force. Alternatively, he might be rotating it too slowly, allowing wind to pass easily without giving up much of its power. To add to the complexity, allowing the airscrew to rotate too quickly results in excessive power loss in drag, whilst going too slowly might result in a large part of each blade stalling.

It is possible to get some guidance through this maze by using ideal windmill theory.

Velocity diagrams, which illustrate airscrew propulsion. Figs. 7, 8 and 9.

We can compare the behaviour of airscrew vehicles and boats with conventional sail boats. One vital piece of information is missing. We do not know what wind speed Vw to use. We have to use the ideal windmill theory to find the most suitable value for Vw, the speed of the wind relative to ground or water, as it passes through the airscrew.

IDEAL WINDMILL THEORY EXTENDED TO INCLUDE WINDMILL PROPELLED VEHICLES AND WATER CRAFT. Figs. 10 and 11.

A windmill mounted on a vehicle or water craft is influenced by the speed of the wind relative to itself, and we can utilize windmill theory, simply by replacing free wind speed V, by relative speed Vr = free wind speed – vehicle or water craft speed = V – Va.

The velocity rule becomes– Relative speed upwind is Vr = V – Va. Speed through the airscrew, measured relative to the airscrew = Vr –v, = V –Va –v. Speed downwind = Vr –2v = V –Va –2v.

When we write Va = nV, and v = pV, the velocity sequence becomes– Upwind, V.(1 –n). Through airscrew, relative to airscrew, V.(1 –n –p). Downwind, relative to airscrew, V (1 –n –2p).

Velocities, **relative to ground or water**, are V, V –v, V –2v, or using n and p, are – Upwind, V. Through airscrew relative to ground or water, V.(1 –p). Downwind, V.(1 –2p).

MASS PER SECOND THROUGH THE AIRSCREW = air velocity through the airscrew relative to the airscrew x swept area x density.
$= M = \rho.A.V.(1 - n - p)$.

AXIAL REACTION F = Mass per second x its change in velocity between upwind and downwind.

$F = M \times 2v = M \times 2.V.p. = 2.\rho A.V.(1 - n - p).(pV).$
$= 2.\rho A.V^2.(1 - n - p).(p).$

Work being done per second on the air by the axial reaction, which acts to slow down the air = Force x air velocity through the airscrew. This velocity can be measured relative to the airscrew, giving power relative to airscrew–

rotary power, corresponding with the ordinary windmill power. Alternatively, the velocity can be measured relative to ground or water, giving power relative to ground or water.

ROTARY POWER = F. x (Vr–v) =
= 2.ρ.A.V^2. (1 –n –p). (p). (1 –n –p).V.
= 2.ρ.A.V^3. (1 –n –p)^2. (p).

POWER MEASURED RELATIVE TO GROUND OR WATER = F. x (V –v) =F. x (V). (1 –p). = 2.ρ.A.V^3. (1 –n –p). (p). (1 –p).

POWER RELATIVE TO GROUND OR WATER = ROTARY POWER + AXIAL POWER

Each of these powers can be positive or negative when we substitute numbers. When the windmill is moving against the wind, the axial power opposes, and is negative. When the windmill is moving with the wind at less than wind speed, it can be operated in two different ways. The rotary power can be positive, and also the axial power positive. I have referred to this as windmill operation.

Blade angle can be altered to make the airscrew function as a propellor, when the axial power propels, and the rotary power opposes. The positive and negative signs then become a little confusing, and are explained later.

But, whatever the mode, the general algebraic equation, that power relative to ground or water equals rotary power plus axial power applies. When we substitute numbers, making velocities in the free wind direction positive, against, negative, the formulae provide the correct answers.

IDEAL POWER FORMULAE

ROTARY POWER = 2.ρ.A.V^3. (1 –n –p). (p). (1 –n –p).

AXIAL POWER = 2.ρ.A.V^3. (1 –n –p). (p). (n). i.e. (Axial reaction x speed).

POWER RELATIVE TO GROUND OR WATER = 2.ρ.A.V^3. (1 –n –p). (p). (1 –n).

Note that the first and second formulae add to give the third.

For each value of n = v/V, there will be a corresponding value for p, which I have referred to as optimum p, which when substituted gives the maximum ideal power. We can find these values for p by drawing graphs, or by using calculus. We differentiate power relative to p, then equate to zero and solve. There are always two solutions, but for movement upwind, only one solution provides power from the wind. For movement downwind slower than the wind, two solutions both provide power, and these are the windmill and propellor modes of operation mentioned above.

The general formula obtained by using calculus is:–

OPTIMUM IDEAL VALUES FOR p = v/V, which result in maximum values for power are given by: –

$$\textbf{Opt. p.} = \frac{(2 - n). \pm \sqrt{n^2. - n. + 1.}}{3} \qquad \text{Fig. 13.}$$

The static windmill case is included (put n = 0.).

These ideal powers do have one useful function when studying practical windmills, either static, or moving – used to propel vehicles or water craft–. We can use the ideal powers to obtain wind speeds to use in velocity diagrams.

When we do this for the static windmills, it comes down to assuming that the wind speed through the airscrew for maximum power, is two thirds free wind speed.

When the windmill is propelling vehicle or water craft, at speeds small relative to wind, we can use the ideal wind speeds. However, for higher speeds, airscrew drag, resistances in gearing to road wheels or water screw, and for water craft, power losses in the water screw, alter these optimum values for p significantly.

We also can use the ideal powers to find the most suitable blade areas and rotational speeds.

OPTIMUM VALUES FOR p, WHEN AIRSCREW EFFICIENCY, GEARING EFFICIENCY, AND WATER SCREW EFFICIENCY, ARE INCLUDED AND THE CORRESPONDING POWER VALUES. Fig. 12.

The basic assumption is that power passes from the wind to the airscrew, and **after that**, some of this power is lost in drag and resistances.

When the rotary power is positive, in particular when moving against the wind, it is transmitted to road wheels or water screw, and is used by them. What comes out is the original ideal rotary power, times an efficiency which we can find by testing. Some of this power is then needed to push the airscrew against its own reaction.

When the rotary power, and also the axial power, are positive, the flow of rotary power is to road wheels or water screw, and what is available for use, is ideal rotary power times efficiency, plus axial power. (Downwind).

Further notes on the power formulae.

Mass per second is given by ρA.V. (1 –n –p). When p equals (1 –n), this bracket has zero numerical value. For p larger than (1 –n), flow through the airscrew is reversed, relative to the airscrew, but is still in wind direction relative to ground or water. The numerical value of the bracket becomes negative. p has to lie between 0 and 1 for power to be extracted from the wind

Terms (p) and (1 –p) are still numerically positive. The power now comes out negative, but since it is still propelling vehicle or water craft forwards, in usage it is positive. We therefore interpret the negative sign for power as indicating propellor operation, when the power flow is from axial pull via water screw or road wheels, via gearing, back to airscrew to provide torque for turning it.

Note that when p lies outside the range 0 to 1, that the airscrew is absorbing power.

MOST SUITABLE BLADE AREA AND ROTATIONAL SPEED FOR AN AIRSCREW. Figs. 6 and 14.

We can compare the ideal windmill formula against aerofoil formula with drag zero.

For a static windmill. Put drag zero.

$$\text{Lift } L = Cl. \frac{\rho}{2}. S. Vr^2. = Cl. \frac{\rho}{2}. S. \frac{Vw^2}{\sin^2\alpha}$$

$$\text{Power} = L.\text{sine}\,\beta\,.\ Vt. = Cl. \frac{\rho}{2} S. \frac{Vw^2.}{\sin^2\alpha}\ \text{Sine}\,\beta\,.\ Vt.$$

For maximum power, static windmill, Vw = 2V/3.

We can specify a suitable value for Cl., e.g. 0.6.

We then have options for altering area S, rotational speed Vt, and angle Beta.

We can equate against the ideal windmill power, 16/27 x ½.ρA.V^3.

WIND VEHICLES AND WATER CRAFT.
Explanations of how the Airscrews, and Water Screws function, in Windmill Mode of operation, and in propellor mode of operation.

The airscrew can operate in two different ways. The first, which I have called windmill mode, is the only way when moving against the wind. The rotary power is primary, the axial force of the wind on the airscrew opposes motion, and some of the power generated by rotation has to be used to push the vehicle or water craft against this force. The balance of the power can be used to overcome other resistances to motion.

When the vehicle or water craft is moving downwind slower than the wind, the airscrew can operate in windmill mode. The axial force of wind on airscrew is now helping motion.

The airscrew can alternatively, when moving downwind, operate in what I have called propellor mode. The air is now moving from ahead to astern through the airscrew, but note, in order to extract power from the wind, this air is still moving in wind direction through the airscrew, relative to ground or water.

Power Flow explanations Figs. 15, 16 and 17.

Windmill operation, against the wind, rotary power Ft.Vt is positive. Axial power, Fa.Va. is negative. **Nett power = Ft.Vt. –Fa.Va.**

Windmill operation. Downwind. Fa.Va. is now positive. **Nett power = Ft.Vt + Fa.Va.**

Propellor operation. Downwind.

Fa.Va. is positive. Ft.Vt is negative. **Nett power = Fa.Va. –Ft.Vt.**

In all cases we have to deduct losses of power in the gearing.

Values for Fa and Ft include the effects of aerofoil drag. i.e. are not ideal powers.

In windmill operation, power Ft.Vt., less gearing losses, flows to water screw or road wheels. Some of it is used to push against airscrew axial force. Remember that water screws have to carry the rotary power Ft.Vt. less gearing losses, and have to utilize some of this to balance wind forces on the airscrew.

In propellor operation, the airscrew lift force, or rather, the component of lift in the axial direction, is hauling the vehicle or water craft along. The airscrew is exerting a torque opposing motion. A Water screw has therefore to operate as a turbine, being towed along by the airscrew axial force, in order to provide a balancing torque for the airscrew. We may regard this as a flow of power in the opposite direction to windmill power flow.

AIRSCREW PROPELLED VEHICLES AND WATER CRAFT
Velocity Diagrams. Figs. 15 and 16.

These are similar to velocity diagrams for boats. There is a relative velocity Vr between blade and wind. But remember that this is not the free wind, since the airscrew slows down that wind which passes through it. The wind speed we use in diagrams is $Vw = V(1 - p)$, and the value of p for optimum power alters for different vehicle and boat speeds. Optimum values for p were tabulated earlier in this review.

Lift force L is at right angles to the relative wind direction, and so there is a choice. When the vehicle or boat is moving downwind slower than the wind, we can draw L either pulling in the direction of vehicle or boat movement or alternatively against this movement. In this case it is clear that L has to be in the direction of the wind. L will lean to one side in windmill mode, making power Ft Vt positive, but the other way in propellor mode, when Ft Vt is negative.

In windmill mode upwind, L IS DRAWN IN THE OPPOSITE DIRECTION TO THE BOAT OR VEHICLE MOVEMENT, making Ft Vt positive, but Fa Va negative. Note that in all cases, lift L is in the same direction as the wind, but inclined to it. Drag D is simpler. It always opposes and is in line with vector Vr.

If we want to draw in the aerofoil chord, we have to decide which side relative velocity Vr. We incline it to the side which results in the correct direction for lift. It is one side of Vr for windmill mode, the other side for propellor mode. Angle between Vr and chord is angle of incidence.

Drag may make one of the modes of operation impossible. The test is that the resultant of drag and lift, F, has to lean in direction of foil movement Vf. We can short cut the $\pm$ Ft Vt $\pm$ Fa Va operation by finding nett power direct. It is Ff Vf, where Ff is the resultant of lift and drag in direction of foil movement, i.e. in direction Vf.

Drawing procedure. Find tangential velocity Vt at the effective radius, e.g. ¾ tip radius. This is done by comparing ideal windmill and ideal aerofoil formulae, explained earlier. Vehicle or boat speed is Va. Draw Vt and Va. Join ends to get foil path relative to ground or water, pitch angle gamma.

Now refer to Fig. 13 to find the optimum value for p, which gives wind speed through the airscrew, **relative to ground or water**, Vw. Draw Vw. Join ends to get relative velocity, Vr. This also provides angle beta. Draw lift L in the desired direction. Do some calculating to find numerical values for velocities, lift and drag.

AIRSCREW VEHICLES AND BOATS WHICH DERIVE THEIR POWER FROM THE WIND. Tacking Upwind and Downwind.

Fig. 18.

Sketch 1 is for tacking in windmill mode against the wind.
V1 is the wind velocity, represented in the sketch by line AO.
Va is boat or vehicle velocity, represented by BO.
Vh is the relative velocity between wind and boat or vehicle.
As Vh passes through the airscrew in windmill mode it is reduced to Vh −v, and after leaving the airscrew to Vh −2v.

V1 is the initial speed of the wind, V2 is the final speed, and the power lost by the wind is given by: –

Power from the wind = ½ x Mass per second through airscrew x $(V1^2 - V2^2)$.

Mass/Second = Speed through airscrew x ρ A, where A is airscrew swept area,
= (Vh – v) x ρ A.

Power from the wind = ½ ρ A. (Vh – v) $(V1^2 - V2^2)$.

Sketch 2 is for tacking downwind in windmill mode.

Figures 7, 8 and 9, compare airscrews tacking against sails.

In windmill mode, the water screw is operating as a propellor, pushing the boat. Hull drag pulls against boat motion.

But in propellor mode, the water screw acts like a turbine, i.e. like a water mill. The hull is pulling the water screw, which extracts power from the water flow, and transmits this power to the airscrew to provide the reaction torque.

One comment here. We usually discuss getting power from the wind. We ought to discuss getting power from the relative velocity between wind and water, and it is just as logical to regard the wind as stationery and the water as moving, as it is to regard wind as moving and water as stationery. Likewise, we can regard wind as stationery, and the ground as moving. So we can say that the power comes from the movement of the water relative to the wind, or movement of the ground relative to the wind. The airscrew can function as a windmill and the water screw as a water propellor. The water screw can function as a water mill and the airscrew as an air propellor.

AUTO GYRO MODE OF OPERATION

Airscrew Vehicles and Boats. Fig. 19.

Imagine two windmills, A and B.

Both windmills are feeding power into a common gear box which transmits the total power to an external absorber.

Now refer to the sketch top right. Windmill A is feeding power into airscrew B. B can not do anything with this power except feed it back into the wind, so after pitch has been set to a suitable angle, the airscrew will function as a propellor, and will first reduce the speed of the wind passing through it, and then it might reverse the direction of flow of this wind relative to the ground.

That is, if it is set to oppose the wind. It could be set to accelerate this wind in the original free wind direction.

Another use might be to put vanes around the airscrew like paddle wheels, and use these to set up an air circulation, which sailors could use to get a Magnus effect to propel boats.

The usage we are interested in here is using airscrew B as a propellor to reduce the wind velocity and possibly reverse it. I think that it will be clear to readers that this reversal could happen.

Now refer to the bottom left sketch of a single blade, and to the lower right sketch. The central parts of the blades are functioning as a windmill, powered by the wind. Power taken from the wind flows radially outwards along the blades. Pitch is set so that the outer parts of blades act as propellors feeding power back into the wind, just as airscrew B did.

The axial thrusts of both the windmill parts and of the propellor parts are in the same direction.

The bottom right hand sketch shows overall air flows. Through the central parts of the airscrew, the wind flows in the normal way. Power transfers into the airscrew blades, flows to the outer parts of blades, where air flow is reversed through the airscrew, or reduced in speed considerably.

The wind must now deflect around the airscrew, and there is drag, exactly as there is with a sail going directly downwind. There will also be stagnation pressure. In all, a complicated flow pattern.

The nett result will be that the airscrew will produce lift because of drag, like a sail does, but on top of that, it will produce windmill lift, and propellor lift. In toto, lift is likely to be considerably more than a sail gives, of the same area as the swept area.

To study the behaviour, we need flow patterns for flow around the airscrew. Note that auto gyro mode is one sort of windmill mode, so speed downwind cannot exceed wind speed. Also, airscrew drag is larger than for efficient sails, so the boat or vehicle will not tack as close to the wind as when using an efficient sail.

But also note that the airscrew could be coupled to an engine, to propel a boat or vehicle against the wind, and when there is insufficient wind. It avoids the need for a water screw.

USING VERTICAL AXIS WINDMILLS TO PROPEL A WIND VEHICLE OR WATER CRAFT.

The ideal windmill theory explained earlier applies equally well to vertical axis windmills.

In order to find a suitable blade area combined with rotational speed, the formulae worked out earlier for the vertical axis windmill power may be used, putting drag zero. Then equate against the ideal windmill power.

When the vertical axis windmill is propelling a wind vehicle or water craft, it will operate only in windmill mode. It might be possible to devize suitable blade angle control, so that the rotor operates like a propellor. However, for boats, this might be a waste of time, because hull drag is so big. When the boat is moving downwind, it might be simplest to allow the rotor to spin freely, when axial reaction will provide the hauling force.

With both airscrews and vertical axis rotors, it has to be remembered that there can be very large wind forces on airscrew or rotor, and when moving against the wind, without tacking, the stern will tend to be forced down. When moving downwind, the bows will be forced down. Hull shapes will no doubt have to be developed to suit this method of propulsion.

The vertical axis windmill will not operate as an auto gyro, unless a suitable blade angle control is incorporated, except directly downwind.

In principal, if a vertical axis windmill were fitted with vortex generating vanes, a small amount of windmill power might induce a powerful circulation, and the device operate like a Flettner rotor. The inter-action of wind and this circulation would generate a lift force at right angles to the relative wind, and the device would behave like a sail. However, a simpler way is to use a little engine help to spin a vertical cylinder, as Flettner did.

The main advantage of the vertical axis windmill for propelling ships would be its ability to work with wind from any direction, including directly ahead and directly astern. Its objectionable features include inability to tack using the windmill as an 'auto gyro,' and also, a rapid fall off in power developed when moving downwind. With sails, we can increase sail area downwind, but with the windmill, are stuck with its designed area. Another comment is, that windmills, both vertical axis and horizontal axis, can be used along with sails and with small engines to get the best from all these means of propulsion. Again, Flettner rotors, with a small engine, and sails as 'auxiliary power,' seem to be more suitable for practical requirements.

ANGLES OF ATTACK AND ANGLES OF INCIDENCE

Readers who intend to study the published data for aerofoil sections, will find that usually, lift is not zero at zero angle of attack. If we use another term, angle of incidence, we can always regard this as zero at that inclination of the wing which gives zero lift. Then since the lift to angle graphs are nearly straight lines up to near to stall, in this range we can replace the coefficient of lift by lift factor k times either the sine of the angle of incidence or its value in radians.

LIFT AT 90 DEGREES TO DIRECTION OF MOTION

This is a convenient convention, but is not true. An ideal foil, which generates zero drag, still meets resistance to motion. There have to be vortices which require energy. So the ideal lift force includes some resistance to motion, and is inclined to the direction of motion.

But aerofoils and hydrofoils always generate drag, and in practice, it is convenient to draw a lift force at 90 degrees to the relative velocity air to foil and a drag force in the direction of this relative velocity.

Readers who try to delve deeper into the fundamentals of energy extraction from air and water will come up against this contradiction.

The lift is not 90 degrees to direction of motion, and there are two sorts of drag – drag inherent in the operation of foils and drag from sources like turbulence and surface friction.

AIR STREAM FROM WINDMILLS, WATER STREAM FROM PROPELLORS.

In these theories, the streams extend from infinity ahead to infinity astern, with no mixing with surrounding fluid. In practice there is mixing, and the wake disappears after a time. We know that it does disappear, and the theories explained in this report therefore tend to clash with our instinctive understanding.

FLETTNER ROTORS

Flettner rotors were tried during the twenties for propelling ships. Flettner was a well known aircraft designer in Germany.

These rotors are so simple that a diagram is not required to illustrate. They are vertical rotating cylinders, driven by a small auxiliary engine. They behave like a spinning ball. The effect of the rotation is to increase the speed of the air as it passes one side, leading to lower pressure on that side, whilst air speed is reduced on the other side, with increase in air pressure.

This difference in pressure produces a force, at right angles to the cylinder axis, and at nearly right angles to the wind. Since some power is needed to maintain a circulation and a trailing vortex, and since there are power losses owing to air viscosity, the cylinder experiences a linear drag force in the direction of the incident wind, and an angular drag torque, which is overcome by the engine.

Since the force generated is always at nearly 90 degrees to the wind, the Flettner Rotor will not drive a boat or ship directly downwind, except by the drag force acting on the projected area of the cylinder. This area cannot be increased as it can with soft sails, so engine power will then be needed to drive the water propellor.

The rotor will also not drive the boat or ship directly against the wind. They have to tack.

Practical sailors will appreciate another restriction. The projected area cannot be 'reefed' in gales and storms. The cylinders could be made telescopic to allow some reduction in area.

One unanswered question is the drag to lift ratio. If this were to be much smaller than for a soft sail, then the boat could tack close to the wind. However, what information there is suggests that the drag angle is large. But do not take my word for this. The Flettner Rotor is so simple that model boat enthusiasts could investigate its behaviour, or one could be set up on a full size boat for experiments.

Other circulation devices.

Sails produce lift because an air circulation is generated around them, which, superimposed on the wind stream, gives the flow patterns published in books on wings. There are also trailing circulations to balance out the angular momentum and satisfy Newton's Laws.

Various arrangements act to assist the circulation. These are usually high lift devices with larger drag angles than simple sails.

USING AIRSCREWS AND WATER SCREWS TO GENERATE AUXILIARY POWER IN A BOAT. e.g. For Battery Charging.

Data Used

Gravitational acceleration g = 32.18 ft./sec.^{2} = 9.81 metres/sec.^{2}.

Weight = Mass x g. Mass M in slugs, weight is 32.18 x M in lbf. (pounds force).
Mass M in lbm. (pounds mass). Weight 32.18 x M in poundals.
Mass M. in kilograms mass. Weight 9.81 x M in newtons.

Units of energy

Energy is related to work. Both are measured by the product of force times displacement. When the mass is in slugs, energy in pounds force times feet. (usually written ft.lbf).

When mass is in pounds mass, energy is in foot poundals.
When mass is in kilogrammes, energy is in newton metres.
One Joule = One newton metre. 1 kilowatt hour = 3.6 x 10^6 joules.

Power, is energy flow per second.

One watt of power = One joule per second. 1 kilowatt = 1000 watts = 1000 J/sec.
One kilowatt hour is 1000 watts flowing for 1 hour = 1000 J/sec for 3,600 secs.
One horsepower = 550 ft. lbf. per sec. = 0.746 kw. = 746 watts.

Densities

Densities are measured as mass per unit volume.
Density of air varies with temperature and pressure. In these calculations, it is taken as 0.078 pounds mass per cubic foot $\frac{0.078}{32.18}$ slugs per cubic foot.
Density of water varies with temperature, and salt content. In calculations, taken as 62.4 pounds mass per cubic foot = $\frac{62.4}{32.18}$ slugs per cubic foot.

USEFUL AERODYNAMIC AND HYDRODYNAMIC FORMULAE USED IN CALCULATIONS

Lift = L. Drag = D. Resultant of lift and drag = F., at drag angle ϵ to L. Foil area S. Chord c. span b.

Lift $L = Cl. \frac{\rho}{2} S. V^2$ Drag $D = Cd. \frac{\rho}{2} S. V^2$.

Where Cl. is the coefficient of lift, Cd the coefficient of drag.

Lift factor k. When lift is proportional to alpha (see below), we can write $Cl. = k. \alpha$. (Lift is proportional to sine alpha, but angles are small, and alpha in radians does not differ much from sine alpha).

Lift and Drag.

The lift factor k (Lift Coeff. $Cl. = k.\alpha$), has a theoretical value of 2π for a wing of infinite aspect ratio, but is smaller than this for practical wings.

The drag coefficient Cd may be expressed as:

$$a + \frac{Cl^2}{b} = a + \frac{(k.\alpha)^2}{b}$$

Minimum drag angle in radians: (of the aerofoil section).

$$\frac{Drag}{Lift} = 2.\sqrt{\frac{a.}{b}}$$

SIZES OF AIR TURBINE (WINDMILL) AND WATER TURBINE (WATER SCREW), likely to suit Battery Charging on a boat.

Wind speed relative to windmill (air turbine), 20 ft. per second. Power will drop off rapidly in lighter winds, but stronger winds cannot be fully utilized because of inflexibility in turbine design.

Water turbine – Boat speed relative to the water of 8 ft. per second. Sailing boats typically go up to a characteristic speed in a strong breeze, but not much faster in stronger winds.

We will allow 50% efficiency in extracting power from wind or water, relative to the ideal efficiency and 40% efficiency to cover the electrical generator, mechanical drives, and battery losses during charging.

Power stored therefore equals ideal power from wind or water x 0.5 x 0.4 Overall efficiency is 0.2, or 20%. This is on the low side, and it should be possible to improve on it.

Suppose we want to charge at 2 amps against 12 volts, i.e., at 24 watts. This, at 20% overall efficiency means that we must have 120 watts, or 0.1609 hp = 88.5 ft. lbf./sec., as ideal output from the turbine.

Air turbine

Ideal maximum power = 16/27 x ½ x air density x swept area x free wind speed cubed.

From which swept area $A = \dfrac{88.5 \times 27 \times 2}{16 \times 0.078 \times 8000} \times 32.18 = 15.39$ sq. ft.

Dia. = 4.43 ft.

Water turbine similarly.

Swept area $= \dfrac{88.5 \times 27 \times 2 \times 32.18}{16 \times 62.4 \times 8^3} = 0.301$ sq. ft. Dia. = 0.619 ft. = 7.42 inches.

This diameter is small for a water screw, and I would opt for a larger one to get quicker battery charging. However, we are comparing wind against water power generation, so we will keep to the same base and study the small water screw. Air speed through the airscrew for maximum ideal power extraction from wind = 2/3 of free wind speed = 2/3 x 20 ft./sec. = 13.33 ft./sec.

Water speed through water screw for maximum ideal power extraction from water = 2/3 x boat speed relative to water = 2/3 x 8 ft./sec. = 5.33 ft./sec.

Fig. 19. Blade angles. Air turbine (windmill) Fig. 6.

Other studies have suggested that aerofoil efficiency will be biggest for a beta angle of 9 degrees. There is one possible objection. This fine 'pitch' may result in the airscrew not self starting. However, angles increase towards the hub, and when the dynamo is declutched, or possibly switched off, the torque on the central parts of blades may accelerate the airscrew, Outer parts will initially be stalled, but unstall as the airscrew speeds up.

When we make beta equal to 9 degrees, the tangential velocity corresponding to speed 13.33 ft./sec. will be 13.33/tan 9 = 84.2 ft./sec. This is at the effective diameter, which if we follow aeroplane practice is taken as being at ¾ tip diameter, and 4.428 x ¾ = 3.321 ft. Revs. per sec. comes out as 8.07 = 484 rpm. A little too slow for a dynamo, which would be geared to run faster.

The relative velocity between blade and air flow at the effective diameter will be 13.33/sine 9 = 85.2 ft. per sec. = Vr.

Airscrew, Optimum blade area and chord

Compare the ideal power obtained by using the ideal windmill theory, against the ideal power for an aerofoil which has zero drag.

Lift = 0.6 x ½ x (0.078/32.18) x blade area of all blades, S x 85.2^2 = 5.28.S. lbf.

Ideal aerofoil power = Lift x sine 9 x tangential velocity Vt. = 5.28.S. x sine 9. x 84.2 = 69.5.S. and we equate with the ideal windmill power of 88.5. This gives a value for the total blade area for all blades of 1.27 sq. ft.

The diameter of the airscrew was 4.43 ft., and blade area of 1.27 sq. ft. and for two blades, gives mean blade width of 1.27/4.43 = 0.287 ft. = 3.44 inches.

To be on the safe side, a slightly wider blade which is 4 inches wide at the effective radius might be used, narrower at tips and wider towards hub for strength.

AIR TURBINE (WINDMILL).
Blade angles and twist

We have a value for beta at the effective radius of 9 degrees. Beta values at other radii are related by tangent values. Effective radius = ¾ x tip radius. So the tan of the tip beta angle will be ¾ x tan 9 = 0.1188, and tip beta = 6.77 degrees. Tan beta at ¼ tip radius is at 1/3 of effective radius and its tan is 3 x tan 9. = 0.475 corresponding with 25.4 degrees.

Say we decide to use a constant angle of attack of 6 degrees, all along each blade, then we take 6 degrees away from each beta angle to obtain blade angle. Tip blade angle becomes 0.77 degrees. Effective radius(¾ tip rad.) angle 3 degrees. ¼ tip radius blade angle is 19.4 degrees.

It will not be possible to keep exactly to this twist. The blade can be set with tip and quarter radius angles correct, when the effective radius angle will come somewhere near to what is desired.

Blade sections. Refers to books on aero dynamics. e.g. 'Theory of Flight.'

Actual power generated. The windmill is too small for reliable estimates. However, we started off by assuming a low value for the efficiency, and the power will probably be larger rather than smaller.

Water turbine

Calculations gave very narrow blades, which would be too weak and so we will operate with beta angle, not 9 degrees, but 20 degrees. Efficiency will be reduced.

Using the same procedure as for the air turbine:–

Water speed relative to and through screw = 5.33 ft./sec.

Tip diameter was 0.619 ft., effective dia. is ¾ tip dia. = 0.464 ft. Revs./sec. = 10.1. Vt = 14.7 ft./sec.

Relative velocity water to blade at effective radius is 5.33/sine 20 = 15.6 ft./sec. Lift = 0.6 x ½ x (62.4/32.18) x total blade area S x 15.6^2 = 142 S. Tractive force Ft = L.sine 20 = 48.4.S. lbf.
Tractive power = Ft.Vt. = P = 48.4S x 14.7 = 711S. Equate against the ideal 'windmill' power we obtained of 88.5 from which S = 0.125 sq. ft. For two blades and tip dia. 0.619 ft., (since S = 0.619 x chord width). Chord width = 0.202 ft. = 2.4 inches at the effective diameter. This comes out wide, so we might rotate faster to get narrower blades.

Blade angles – Water turbine

Beta angle at effective radius of ¾ tip radius = 20 deg. and tan 20 = 0.364. Tan of tip beta angle = 0.364 x ¾ = 0.273. Tip beta angle = 15.3 degrees. Tan of beta angle at ¼ tip radius = 3 x tan at eff. radius = 1.09. and the corresponding beta angle = 47.5 degrees.

Take away 6 degrees angle of attack along the blade and blade angles become – Blade angle at tips = 9.3 degrees. At effective radius of ¾ tip radius = 14 degrees, and at one quarter tip radius = 41.5 degrees.

Comments:–

Blade angles for the airscrew came out small, and drag losses might be reduced by rotating at a lower speed, having larger blade areas, and also larger beta angles.

The water turbine should be larger in diameter, which means narrower blades, the beta angle could be reduced to 15 degrees.

MASS, MOMENTUM, POWER, IN A STREAM.

DENSITY. ρ = MASS/UNIT VOLUME.

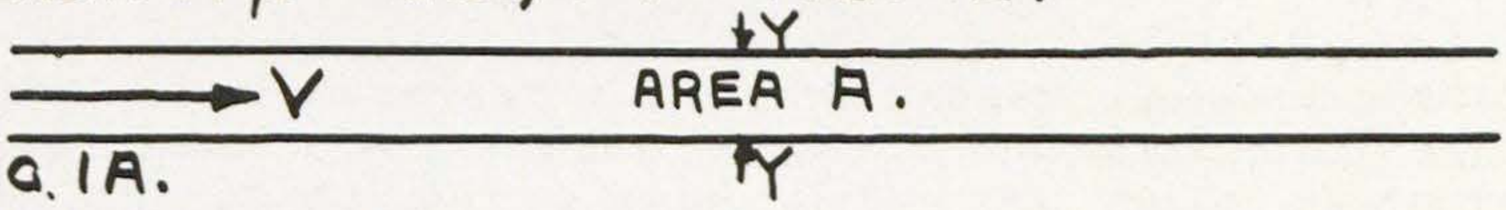


FIG. 1A.

MASS FLOWING/SEC PAST YY = M/SEC = $\rho A V.$
MOMENTUM " " " " = M.V = $\rho A V^2$
KINETIC ENERGY/SEC = POWER = $\frac{1}{2}.M.V^2 = \rho.A.V^3/2.$

<u>WHEN YY IS MOVING WITH VELOCITY V_A →</u>
MASS FLOWING/SEC PAST YY = M/SEC = $\rho.A.(V-V_A)$
MOMENTUM " " " " = M.V = $\rho.A.(V-V_A).(V).$

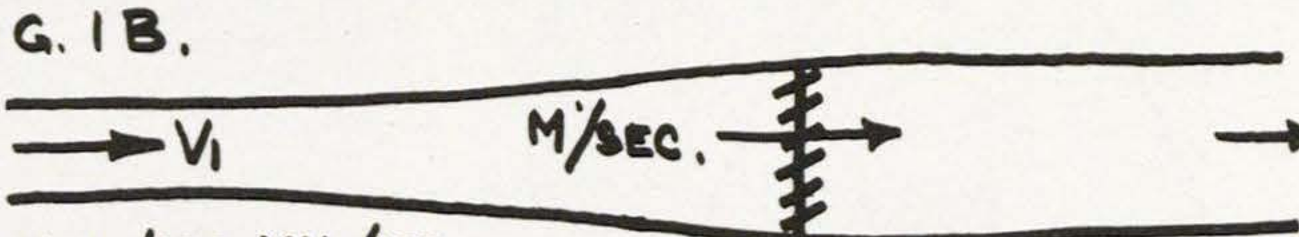
KINETIC ENERGY FLOWING/SEC PAST YY
= <u>POWER FLOWING PAST YY = $\frac{1}{2}.M.V^2 = \frac{1}{2}.(\rho A)(V-V_A)(V^2).$</u>

<u>EXAMPLE</u>. AIR STREAM. ·078/32·18 SLUGS/CU FT. 8 SQ FT. 20. FT/SEC.
YY MOVING AT 4 FT/SEC DOWNWIND. REL.VEL $V-V_A$ = 16 FT/SEC.
MASS/SEC PAST YY = ·078/32·18 × 8 × 16 = 0·310 SLUGS/SEC
<u>POWER RELATIVE TO YY</u> = $\frac{1}{2}$ × ·310 × 16^2 = 39·7 FT. LBF/SEC.
<u>POWER RELATIVE TO GROUND</u> = $\frac{·310}{2} \times 20^2$ = 62·0 FT. LBF/SEC.

POWER AVAILABLE FROM A STREAM.

ASSUME AN IDEAL POWER EXTRACTING DEVICE 100% EFFICIENT.

FIG. 1B.



MOMENTUM/SEC MV_1/SEC.
POWER $\frac{1}{2}.M.V_1^2$

REACTION
= MOMENTUM CHANGE /SEC
= $M(V_1-V_2)$/SEC.
IN UNITS OF FORCE.

MV_2 = MOMENTUM/SEC
POWER = $\frac{1}{2}.M.V_2^2$

<u>POWER TRANSFERRED FROM STREAM TO DEVICE</u>
= $\frac{1}{2}MV_1^2$/SEC − $\frac{1}{2}MV_2^2$/SEC = $\frac{1}{2}.M.(V_1^2-V_2^2)$

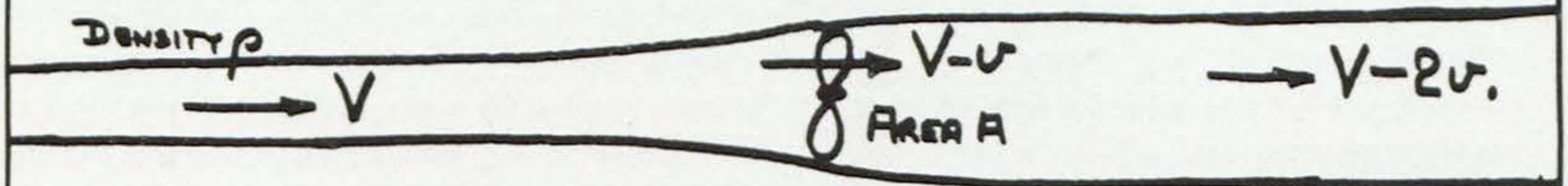
WE ARE NOT YET ABLE TO PUT A VALUE TO M.

<u>EXAMPLE.</u>
FREE WIND SPEED V_1 = 20 FT/SEC. V_2 = 8 FT/SEC.
IF MASS/SEC THROUGH A WINDMILL = 4 SLUGS/SEC.
<u>AXIAL REACTION AGAINST THE WIND</u> = 4 × (20−8) = 48 LBF.
<u>POWER LOST BY THE WIND</u> = $\frac{1}{2}M(V_1^2-V_2^2)$ = 672 LBF. FT/SEC.
= 672/550 HP = 1·22 HP (× ·746 = 0·91 kW)

IDEAL WINDMILL OR TURBINE.— POWER FROM A FLUID STREAM.

FIG. 2A.

IDEAL WINDMILL THEORY SAYS, AND TESTS CONFIRM, THAT THE FLUID SPEED AS IT PASSES THROUGH THE WINDMILL OR TURBINE IS THE ARITHMETIC MEAN OF THE VELOCITIES FAR UPSTREAM (FREE WIND VELOCITY) AND FAR DOWNWIND. THIS WOULD BE FOR AN IDEAL FLUID. WE CAN COMPARE WINDMILL AND TURBINE PERFORMANCE AGAINST THE IDEAL.



MASS/SEC = M = $\rho.A(V-v)$. (STATIC WINDMILL, MAX POWER WHEN $v = V/3$)

CHANGE IN MOMENTUM/SEC. = $M.2v = \rho A.(V-v).2v$ = REACTION R.

POWER FROM THE FLUID = $\frac{1}{2}\cdot M.(V^2-(V-2v)^2) = 2.\rho.A.(V-v)^2.v$.

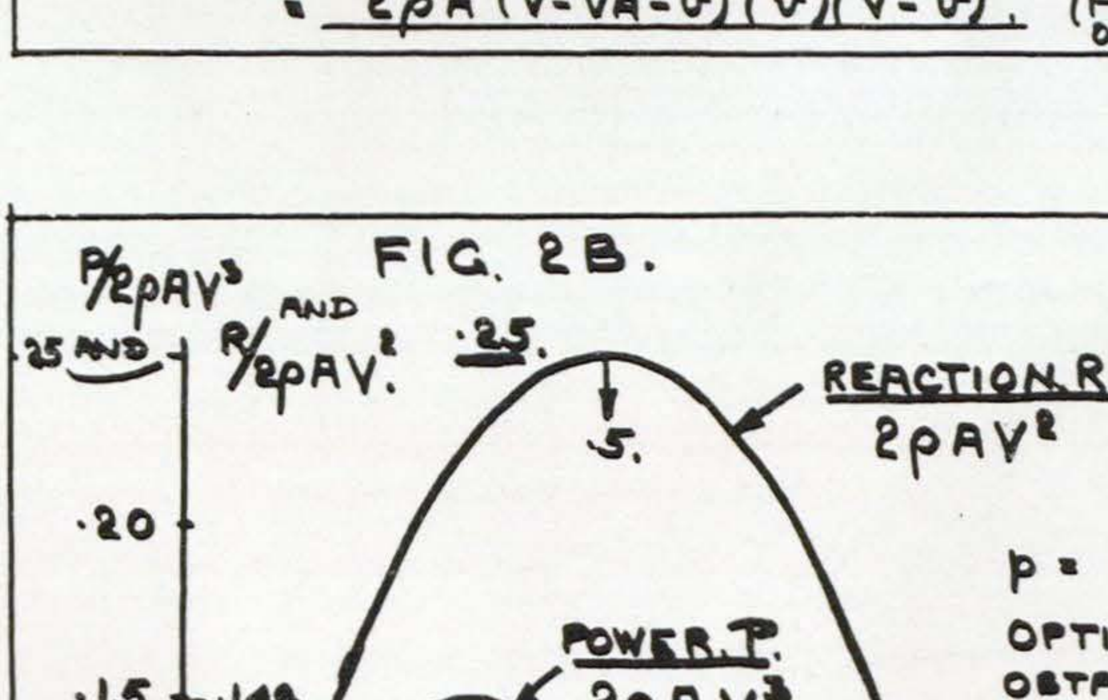
WHEN THE WINDMILL IS MOVING AT VELOCITY Va →

MASS/SEC = $\rho.A.(V-Va-v)$. REACTION = $\rho A.(V-Va-v).2v$.

POWER = $\frac{1}{2}\cdot(\rho A.(V-Va-v)).(V^2-(V-2v)^2)$ (FOR VALUES OF v SEE FIG 3)

= $2\rho A(V-Va-v)(v)(V-v)$. (FOR MAX POWER $v = V/3$ ONLY WHEN $n = 0$)

FIG. 2B.



STATIC WINDMILL

IDEAL REACTIONS AND POWERS.

MAX. REACTION WHEN $p = 0.5$

MAX $R = .25 \times 2\rho AV^2$

$= \frac{1}{2}\cdot\rho AV^2$.

$p = v/V$.

OPTIMUM POWER IS OBTAINED WHEN $p = 1/3$. WHEN THE OPT. POWER IS GIVEN BY:-

$P_{OPT} = .148 \times 2\rho AV^3$

$= 16/27 \times \frac{1}{2}\cdot\rho.A.V^3$.

REACTION WHEN $p = 1/3$

$= 2/9 \times 2\rho AV^2$

$= 4/9\,\rho AV^2$.

VELOCITY THROUGH WINDMILL = $(1-p)V$

FOR OPT. POWER = $2/3\,V$

POWER = $R \times V(1-p)$

$= 4/9\,\rho AV^2 \times 2/3\,V$

$= 8/27\,\rho AV^3 = 16/27 \times \frac{1}{2}\rho AV^3$.

FIG 3. VELOCITY DIAGRAM FOR EACH BLADE OF A VERTICAL AXIS HIGH SPEED WINDMILL

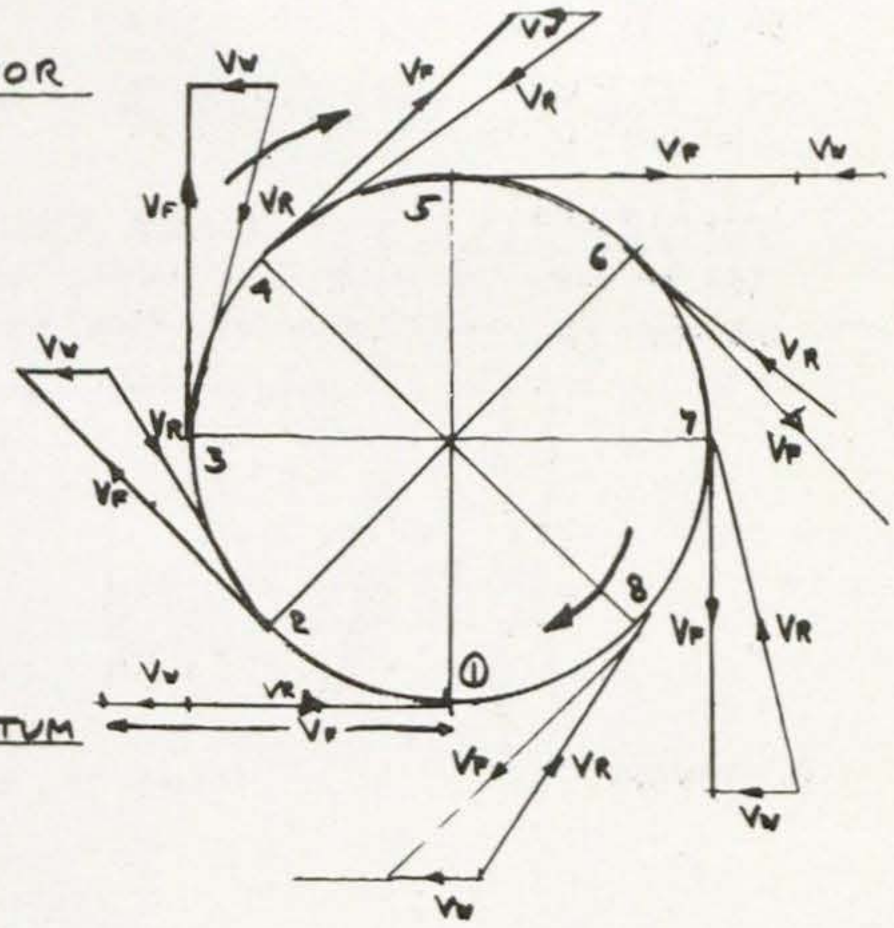
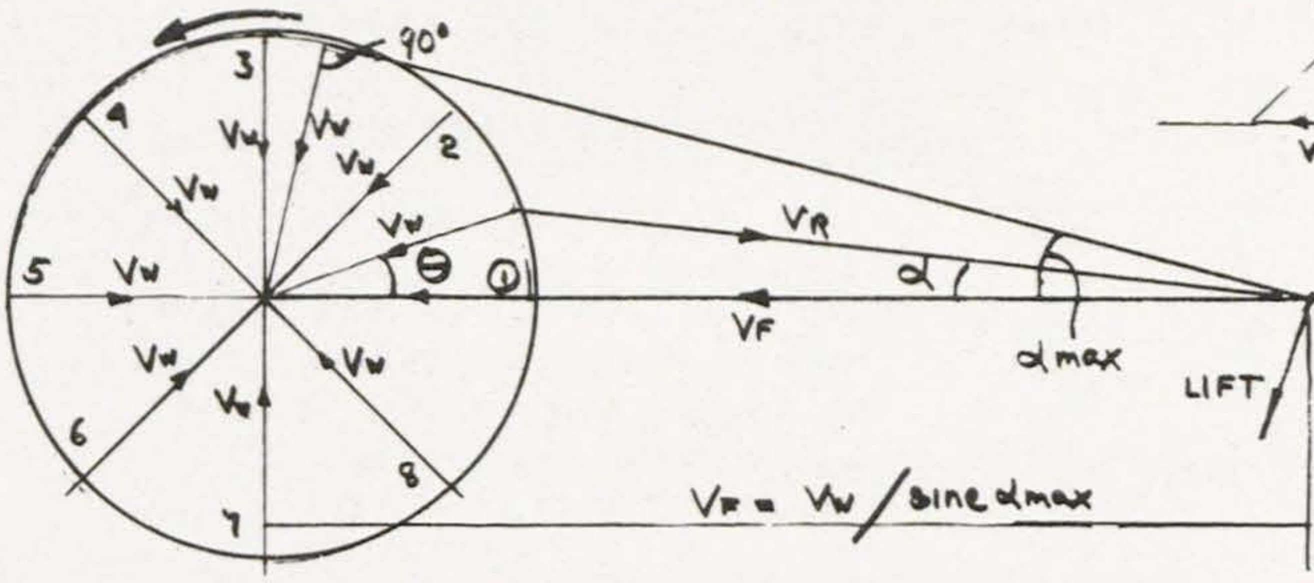


FIG 4 THE SAME BUT WITH VF AS DATUM

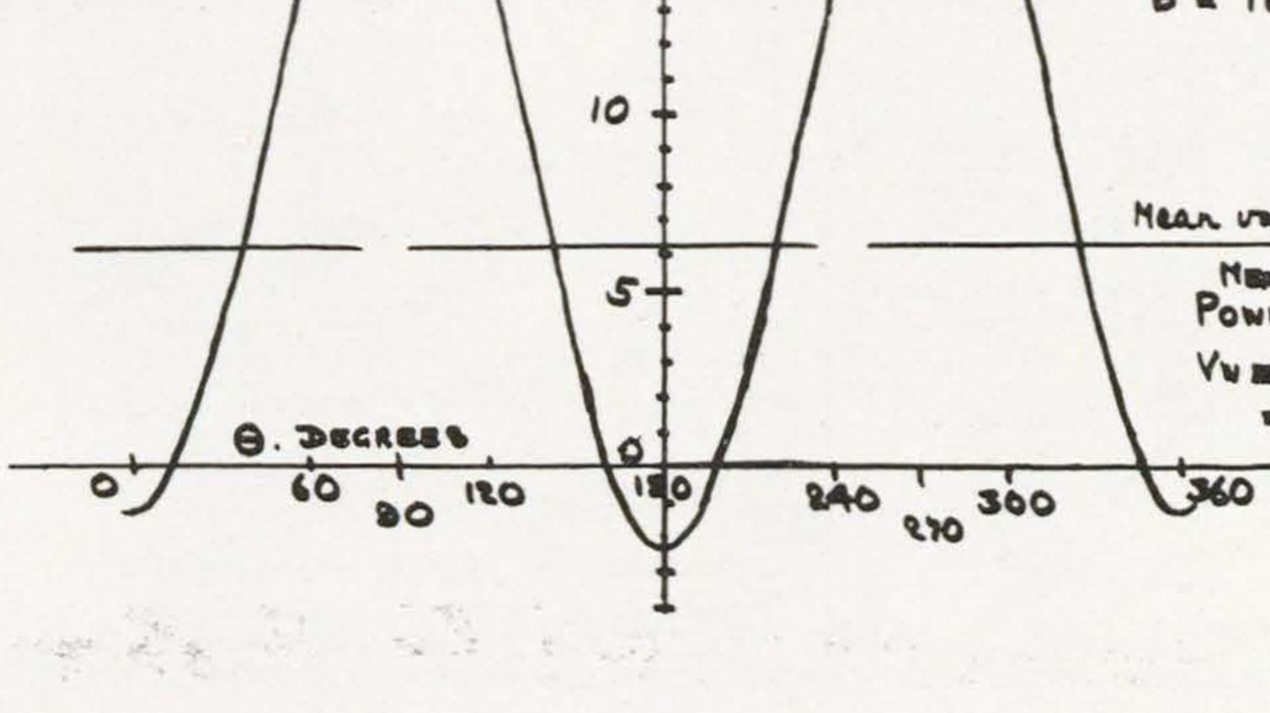


FOILS SET AT ZERO ANGLE OF INCIDENCE WHEN WINDMILL IS AT REST, IE AT ZERO LIFT ANGLE OF ATTACK.

∴ α ALSO EQUALS COURSE ANGLE β.

FIG. 5.

POWER GENERATED AROUND ONE REVOLUTION BY ONE BLADE OF A VERTICAL AXIS WINDMILL.



$\alpha_{MAX} = 9°$.

$k = C_L/\alpha = 5$

$C_D = a + \frac{k^2 \sin^2\alpha}{b}$

$a = .007$

$b = 16$

Mean value 6.03

MEAN POWER $= 6.03 \times \frac{1}{2} \cdot \rho . S . V_W^3$

$V_W = V(1 - p_{opt})$

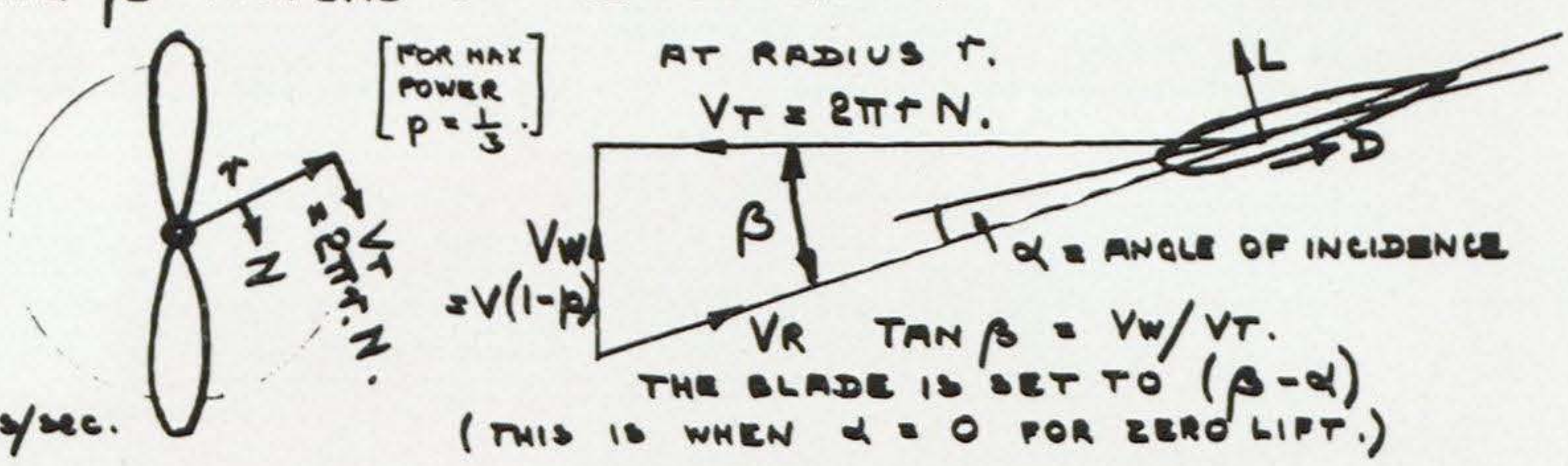
$= V(1 - \frac{1}{3}) = \frac{2V}{3}$

POWER $= 2.01 \rho S V^3$

FIG. 6.

BLADE ANGLES. STATIC WINDMILLS & PROPELLORS.

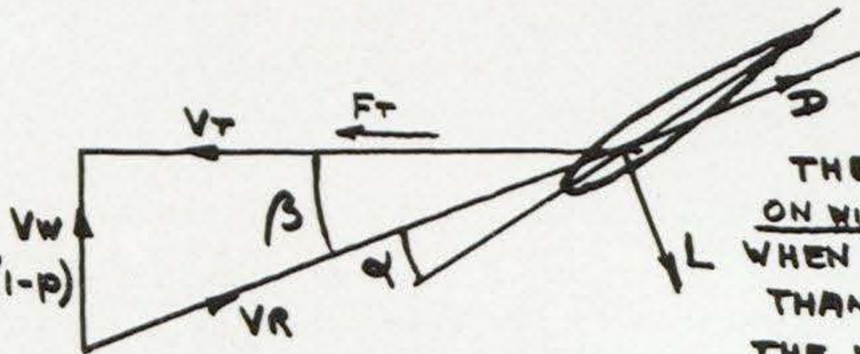
WINDMILLS – SINCE THE WINDMILL IS NOT MOVING RELATIVE TO THE GROUND, CONFUSION IS AVOIDED BY USING β INSTEAD OF THE CUSTOMARY 'PITCH ANGLE γ'.



$\tan\beta = V_W/V_T$.

THE BLADE IS SET TO $(\beta - \alpha)$

(THIS IS WHEN $\alpha = 0$ FOR ZERO LIFT.)



POWER $= F_T V_T$
$= (L[\sin\beta] - D\cos\beta)V_T$.

PROPELLORS.

THE BLADE IS SET TO $(\beta + \alpha)$ ON WINDMILL BOAT OR VEHICLE – WHEN p IS LESS THAN 1 AND GREATER THAN 0, POWER IS EXTRACTED FROM THE WIND. WHEN $p > 1$, POWER IS PUT INTO THE WIND. SEE EXPLANATIONS LATER.

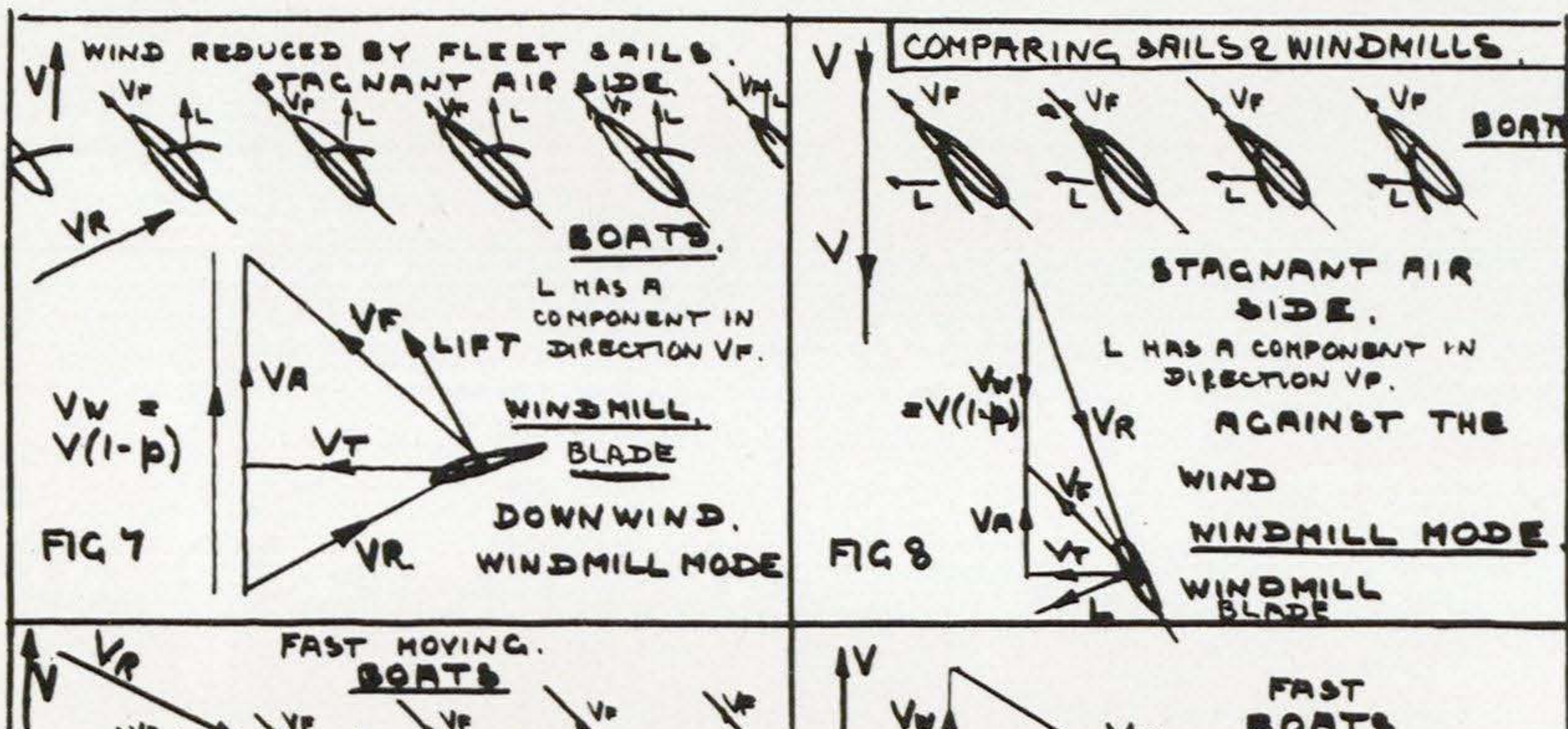
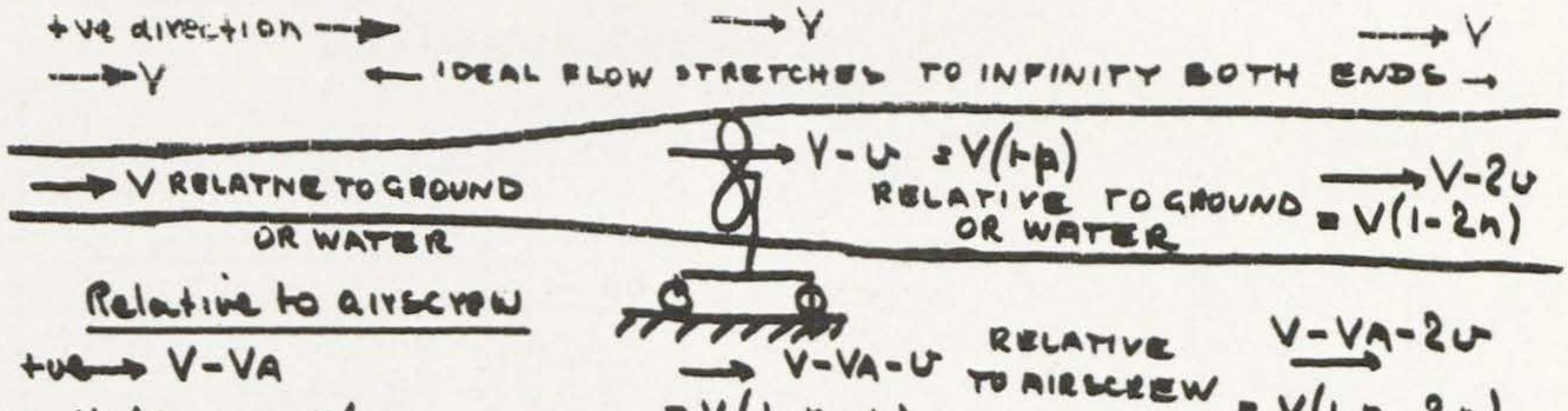


Fig. 10. WINDMILL VEHICLES & BOATS. POWER GENERATION.

+ve direction →



Relative to airscrew

+ve → $V - VA$ → $V - VA - u = V(1-n-p)$ RELATIVE TO AIRSCREW $\underrightarrow{V - VA - 2u} = V(1-n-2p)$

$n = VA/V \quad p = u/V$

MASS/SECOND THROUGH THE AIRSCREW $= \rho A V(1-n-p)$.

UPWIND.
Kinetic Energy/second
$= \frac{1}{2} \cdot \text{Mass/sec} \times \frac{V^2}{2}$ relative to ground or water

DOWNWIND
Kinetic energy/sec
$= \frac{1}{2} . M . V^2(1-n-2p)^2$

The wind loses KE/sec = power to the windmill of
$\frac{1}{2} \times \text{mass/sec} \times [V^2 - (V-2u)^2] = 2\rho A V^3(1-n-p)(p)(1-p)$ relative to ground or water.

Fig 11. More information may be deduced using: momentum changes. Use the figure from fig 10.

Momentum flowing/sec = Mass/sec × velocity.

Change in momentum/sec = force. (Newton)

Change in momentum/sec between upwind and downwind
= Mass/sec × change in velocity = Mass/sec × 2u

∴ Axial force exerted by the wind on the airscrew
= Mass/sec × 2u = R = $2\rho A V^2(1-n-p)(p)$

Power from the wind relative to ground or water = Reaction R, acting on the wind × wind speed through airscrew $V(1-p)$
$= 2\rho A V^2(1-n-p)(p) \times V(1-p)$

Rotary power = power relative to the airscrew itself
= Reaction R × wind speed through airscrew relative to airscrew
= Rotary power $= 2\rho A V^2(1-n-p)(p) \times V(1-n-p)$

Axial power = Wind force R × Vehicle or boat speed VA

Axial power $= 2\rho A V^2(1-n-p)(p) \times Vn$

Note that Axial power + Rotary power = power relative to ground or water.

Practical airscrews. In those studies, efficiency η has been applied to the rotary power.

In windmill mode multiply ideal rotary power by η and add to axial power

" propeller " divide " " " " η. and subtract from axial power.

W.R.F.

FIG 12.

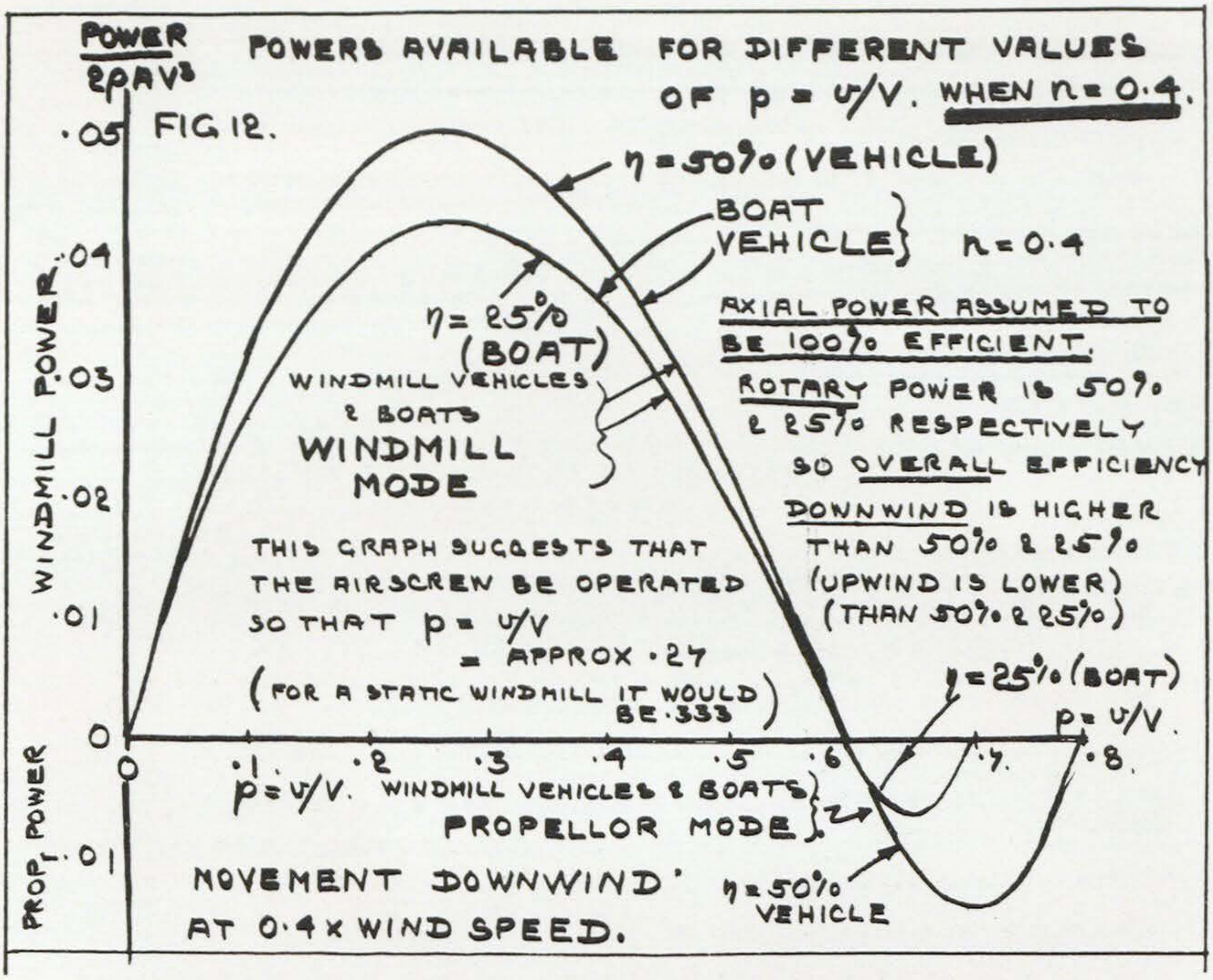
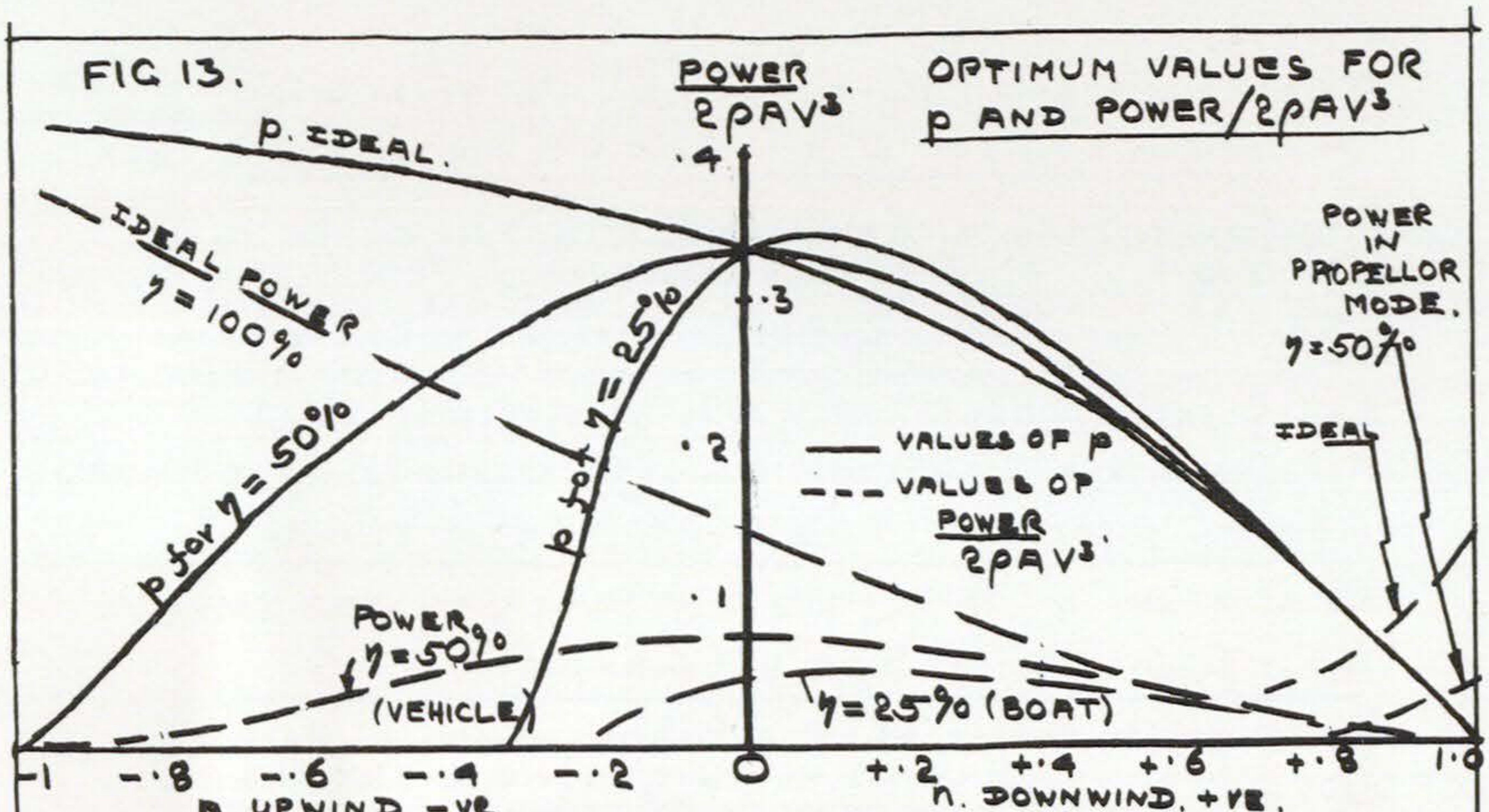


FIG 13.



POWERS WHICH CAN BE EXPECTED FROM WINDMILL PROPELLED BOATS AND VEHICLES.

IN WINDMILL MODE, POWER ASSUMED $= 2\rho A V^3 (1-n-p)(p) \times [(1-n-p)\eta + n]$

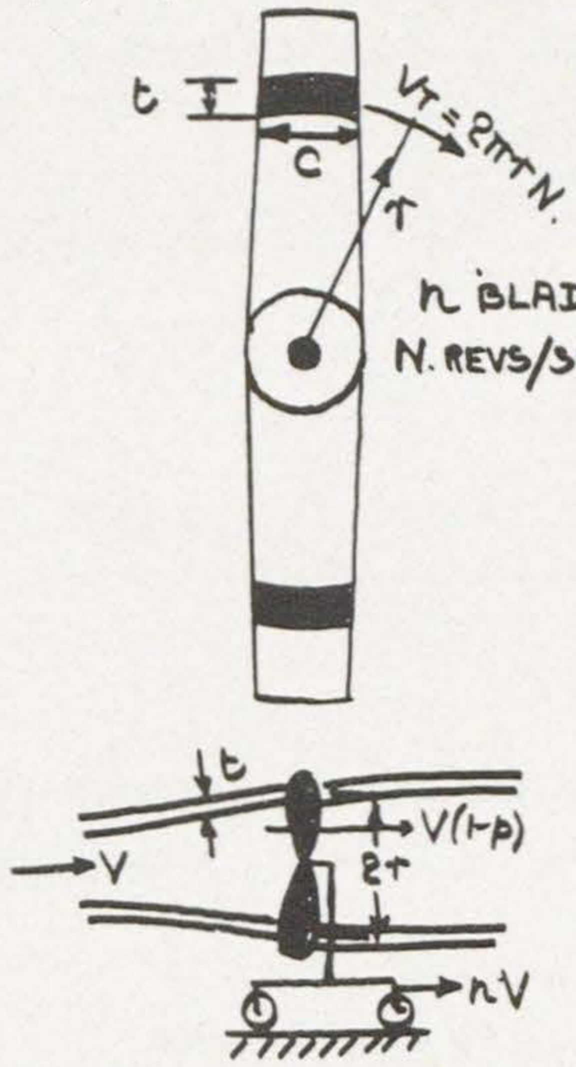
IN PROPELLOR MODE $- 2\rho A V^3 (1-n-p)(p)\left[\left(\frac{1-n-p}{\eta}\right) + n\right]$

FOR OPTIMUM POWERS, OPERATE AIRSCREWS AT THESE VALUES OF p = u/V.

W.R. Frank. Dec. 48.

FIG 14.

ESTIMATING VALUES FOR BLADE WIDTHS LIKELY TO PROVIDE OPTIMUM POWERS.



WINDMILL BOATS & VEHICLES & STATIC WINDMILLS.

BLADE AREA STUDIED = (ctn)

n BLADES. SWEPT AREA $A = 2\pi r t$.

N. REVS/SEC. AXIAL REACTION $R = 2\rho A V^2 (1-p)(p)$

USE THE OPTIMUM VALUE FOR p.

$$R = 2.\rho.(2\pi r b).V^2(1-p)(p) \quad -- (1)$$

FOR SMALL VALUES OF β [SEE FIGURES LATER WHICH EXPLAIN]

THE RELATIVE VELOCITY $V_R \simeq V_T$

$$\text{LIFT} = L \simeq C_L/2.\rho.(ctn).V_T^2 \quad -- (2)$$

FOR SMALL $(\gamma + \beta)$ ANGLES, LIFT L IS APPROX EQUAL TO AXIAL FORCE R

EQUATING $R \simeq L$ GIVES:-

$$\left(\frac{8\pi}{C_L}\right)\left(\frac{r}{nc}\right)(1-p)(p)\left(\frac{V}{V_T}\right)^2 = 1$$

WHEN C_L, p, V, V_T ARE SPECIFIED VALUE OF BLADE WIDTH c CAN BE FOUND

FIG 15 AGAINST THE WIND. WINDMILL MODE.

FREE WIND SPEED 20 FT/SEC. BOAT OR VEHICLE 4 FT/SEC

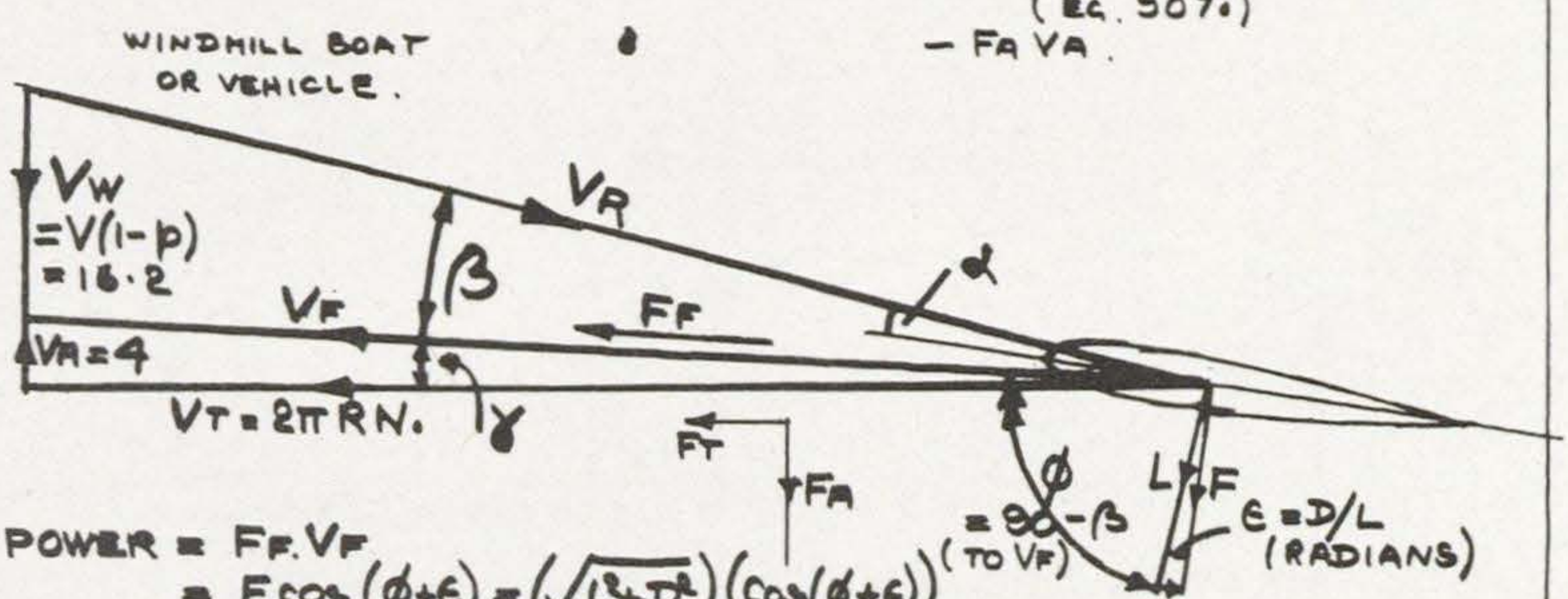
$n = -0.2$. FIG 13. $p_{OPT} = 0.19$.

FOR EFFICIENCY 50%.

WIND SPEED $V_W = V(1-p) = .81V$
$= 16.2$ FT/SEC.

POWER $= F_F V_F$
$= F_T.V_T - F_A.V_A$.

POWER TO WHEELS
$= F_T V_T \times$ GEARING EFFICIENCY (EG. 90%)
$- F_A V_A$.



POWER $= F_F.V_F$
$= F\cos(\phi+\epsilon) = \left(\sqrt{L^2+D^2}\right)\left(\cos(\phi+\epsilon)\right)$

ALSO $= F_T V_T$ (ROTARY POWER) $- F_A V_A$ (AXIAL POWER)

$$= \left(L\sin(\beta+\gamma) - D\cos(\beta+\gamma)\right)V_T - \left(L\cos(\beta+\gamma) + D\sin(\beta+\gamma)\right)V_A.$$

FIG 16. DOWNWIND. WINDMILL MODE. FREE WIND SPEED 20 FT/SEC
VEHICLE OR BOAT SPEED 4 FT/SEC. $n = +0.2$

FIG. 13. $p_{OPT} = \cdot 0.33$ FOR 50% η
$V_W = V(1-p) = 20(1-.33) = 13.3$ FT/SEC

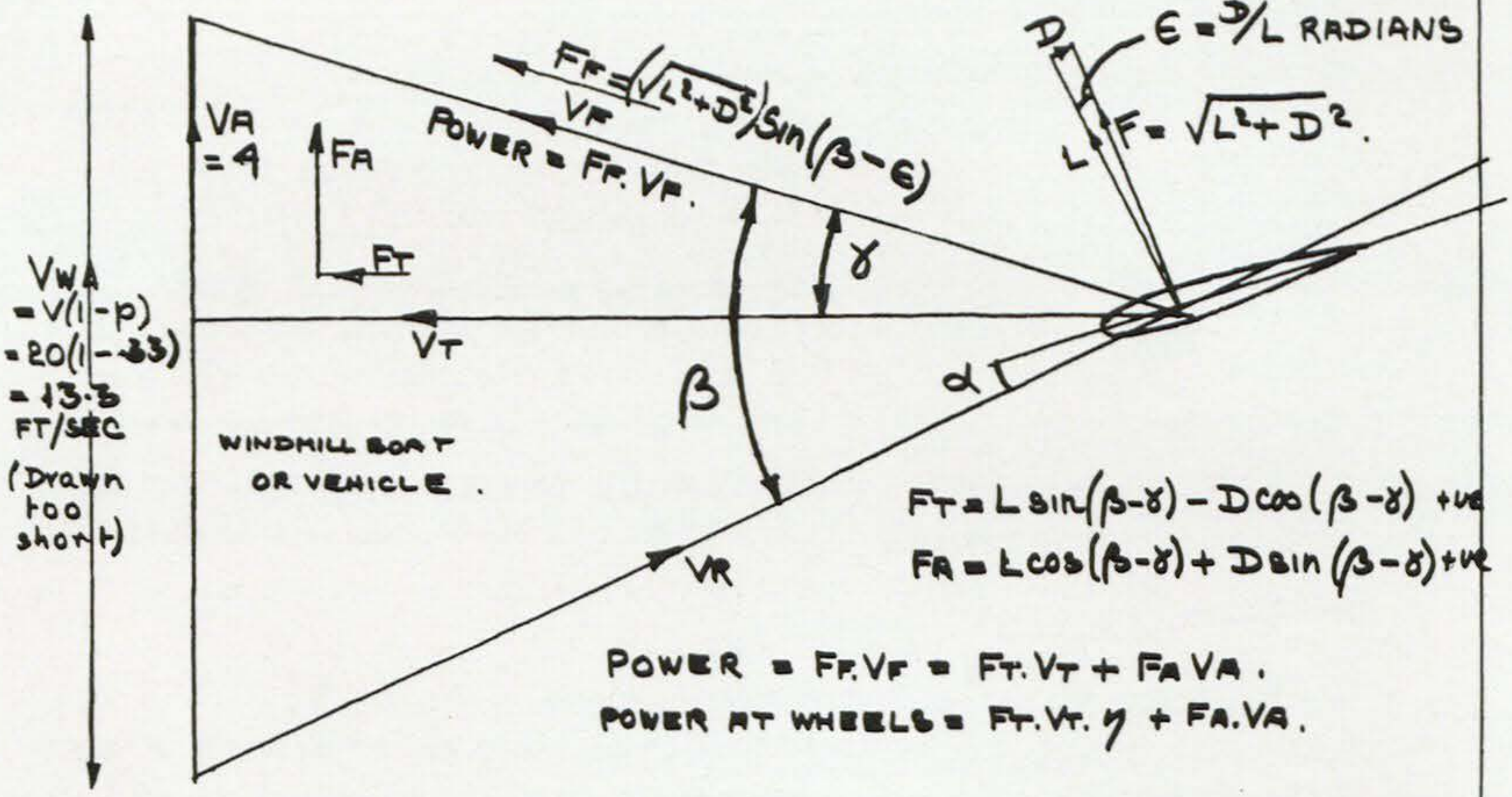


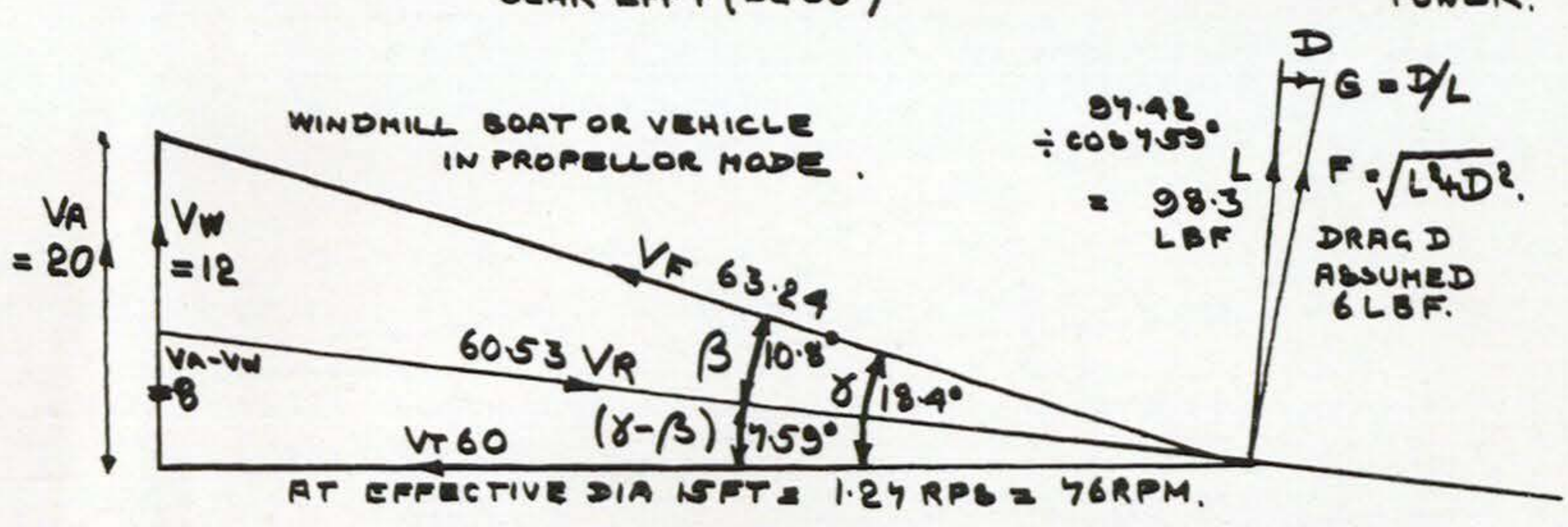
FIG 17. DOWNWIND AT WIND SPEED. PROP. MODE.

EFFICIENCY ASSUMED 60%. POWER $= 2\rho A V^3(1-n-p)(p)\left(\left(\frac{1-n-p}{\eta}\right)+n\right)$

$n = +1$. $p_{opt} = 0.4$ (ESTIMATED) POWER $/2\rho A V^3 = \cdot 0533$ PROP. MODE.

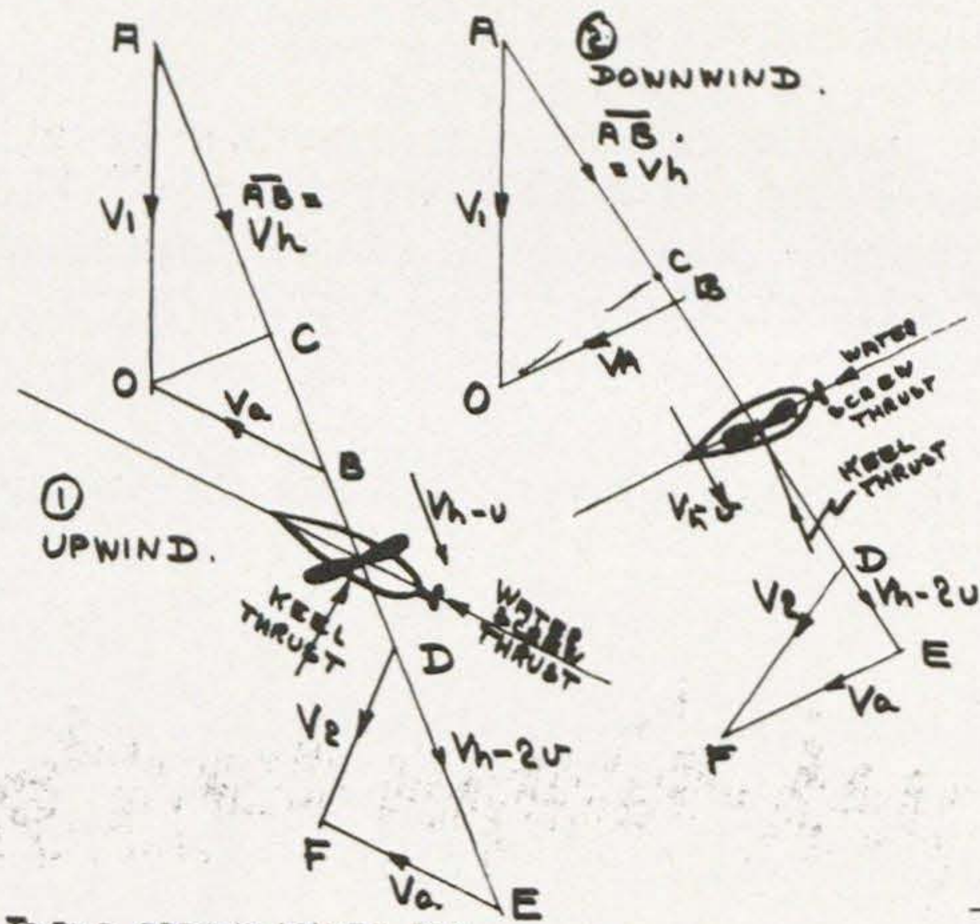
$V(1-p) = V_W = 20(1-0.4) = 12$ FT/SEC. $V_A = V = 20$ FT/SEC.

FOR NETT POWER, FIRST CHECK - ANGLE BETWEEN FORCE F AND LINE V_F HAS TO BE LESS THAN 90°. FR.
THEN CHECK - $F_A V_A - \frac{F_T V_T}{\text{GEAR EFFY (EG. 90\%)}}$ LEAVES ADEQUATE USEFUL POWER.



AIRSCREW 20 FT DIA. SWEPT AREA A. 314 SQ FT.
IDEAL REACTION $R = 2\rho A V^2(1-n-p)(p)$. $n = +1$. $p = 0.4$
$= 2\rho A V^2(-0.4)(0.4) = 2 \times \frac{.078}{32.18} \times 314 \times 20^2 \times (-.16)$
$= -97.42$ LBF.

THE NEGATIVE SIGN INDICATES THAT THE AIRSCREW IS OPERATING IN PROPELLOR MODE.



THE AIRSCREW IS SET AT 90° TO THE RELATIVE WIND V_h.
A KEEL IS ESSENTIAL.

V_h IS THE RELATIVE VELOCITY BETWEEN FREE WIND V_1 WELL UPWIND AND BOAT VELOCITY V_a.

V_h IS REDUCED TO $V_h - u = V_h(1-p)$ AS THE WIND PASSES THROUGH THE AIRSCREW

MASS/SEC = DENSITY ρ × SWEPT AREA A × $V_h(1-p)$

WIND RELATIVE VELOCITY DOWNWIND
$= V_h - 2u = V_h(1-2p)$

CHANGE IN RELATIVE WIND VELOCITY
$= 2u$

WIND FORCE ON AIRSCREW
= CHANGE IN RELATIVE MOMENTUM PER SEC $= M \times 2u = 2\rho . A . V_h^2 (1-p)(p)$

POWER FROM THE WIND
$= \frac{1}{2} M . V_1^2 - \frac{1}{2} M . V_2^2$
$= \frac{1}{2} . \rho A (V_h - u)(V_1^2 - V_2^2)$
where $u = p . V_h$

THIS SHOULD ALSO EQUAL AIRSCREW REACTION × SPEED THROUGH AIRSCREW RELATIVE TO WATER REQUIRING ANOTHER TRIANGLE OF VELOCITIES.

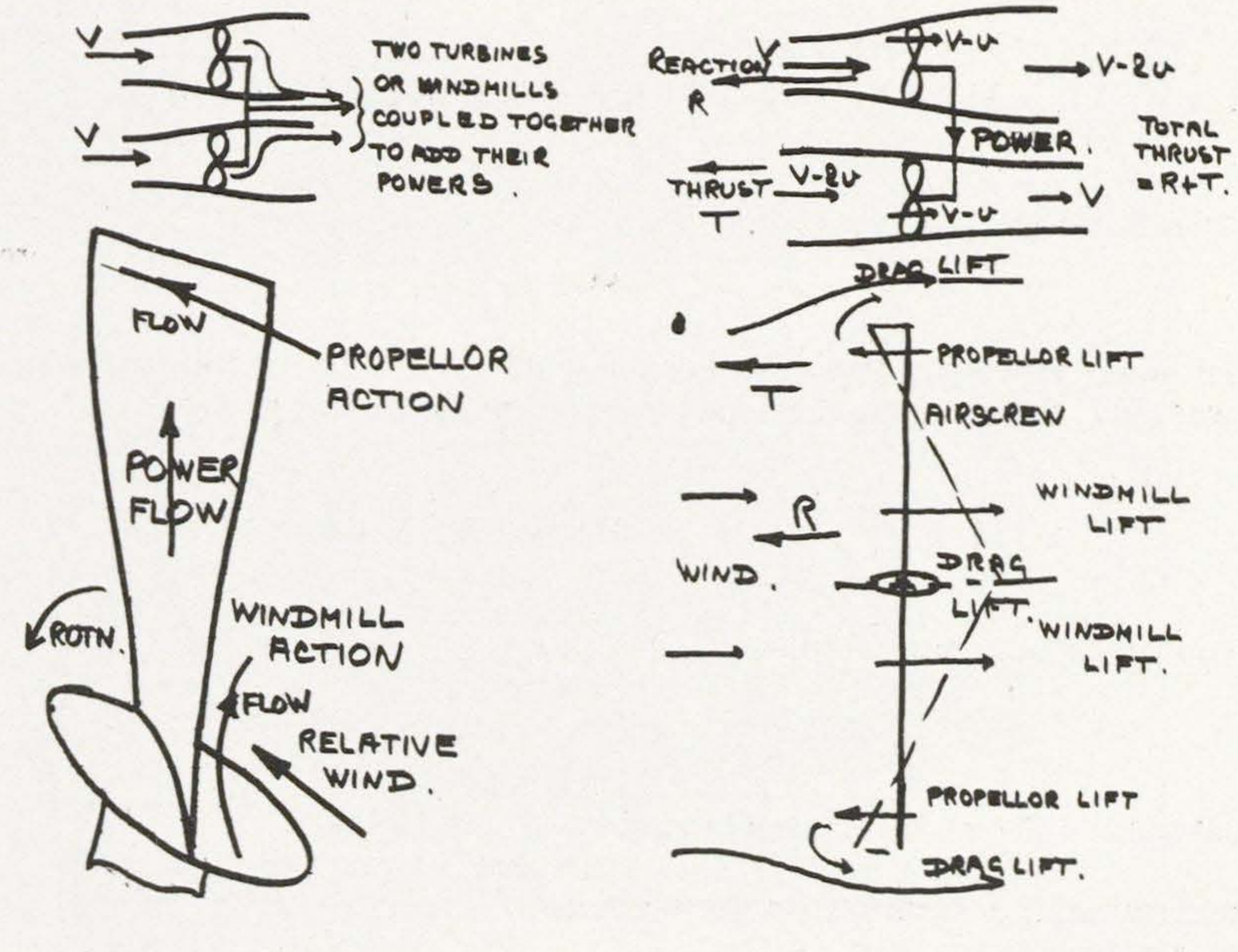
TO FIND OPTIMUM VALUES FOR $p = u/V_h$, the boat speed used is given by BC. BC/AB = n
• UPWIND IS -ve, DOWNWIND, CB/AB, +ve.

FIG 18 - WINDMILL BOATS (OR VEHICLES) TACKING AT ANGLES TO THE WIND.

NOTE - ALL THIS IS HYPOTHETICAL (IE GUESSING), AND AWAITING TESTS ON WINDMILL BOATS AND VEHICLES.

FIG. 19. 'AUTO GYRO MODE'.

THE OUTER PARTS OF BLADES PROBABLY WORK AS PROPELLORS.



WINDMILL CATAMARAN – Estimates of Performance

Example: A Catamaran has a 20 ft. diameter airscrew. Is it likely that it could move directly against the wind at 4ft./sec., in a 20 ft. per sec. wind? The efficiency of the airscrew plus gearing is assumed 60%, and the efficiency of the water screw 50%. Overall efficiency is 0.6 x 0.5 = 0.3 = 30%.

Rotary power = $2.\rho A.V^3.(1 + 0.2 - p)(p)(1 + 0.2 - p)$ and 30% of this is available.

Axial power = $2.\rho A.V^3.(1 + 0.2 - p).(p).(-0.2)$.

Nett power = $2.\rho A.V^3.(1.2 - p).(p).(0.3(1.2 - p) - 0.2)$.

$= 2.\rho A.V^3.p.(0.3p^2 - 0.52p + 0.192)$ and differentiating with respect to p, and equating to zero, then solving for values of p which provide the windmill and propellor solutions. p = 0.2307 is the windmill solution, p = 0.9249 the propellor solution. Using the windmill value for p of 0.2307, and substituting in the ideal power formula $P = 2.\rho A.V^3.(1 - n - p).(p).(1 - p)$, we get:–

Ideal Power, (Taken as 100% efficiency in these calculations).

$$= 2. \times \frac{0.078}{32.18} \times 314 \times 20^3 (1.2 - 0.2307) \times (0.2307) \times (1 - 0.2307).$$

= 2096 ft. lbf./sec.

Ideal power efficiency thru to water screw of 30%, = for the rotary airscrew power only, not including the axial power (formula for nett power).

$$= 2. \frac{0.078}{32.18} \times 314. \times 20^3 \times (1.2 - .2307)^2 \times .2307 \times 30\%$$

= 792 ft. lbf./sec.

Boat speed 4 ft./sec. Water screw thrust = $\frac{\text{Power}}{\text{Speed}}$ = 198 lbf.
Airscrew reaction against the wind = 136 lbf.
Force propelling the boat = 62 lbf.

Airscrew blade angles, speed of rotation, twist, blade area. Fig. 20.

Wind speed through the airscrew, but measured relative to the water, = V.(1 –p) = 15.3 ft./sec. Trial calculations showed that a rotational speed of 900 rpm, = 1.5 rps. might suit. Velocity tangentially, Vt at effective diameter 15 ft., is then 70.69 ft./sec. Blade area S sq. ft. = 20 ft. x blade width c. (Mean width, assumed as being width at the effective diameter.). Angle of attack constant along each blade at 6 degrees. and a coefficient of lift Cl = 0.6 has been assumed.

Boat speed Va of 4 ft./sec., and wind speed through airscrew of 15.3 ft./sec., correspond with air speed relative to airscrew of 19.3 ft./sec. Putting Vt as 70.69 decides the other speeds, shown in the diagram. Vf is foil speed at effective diameter relative to the water, at pitch angle 3.24 degrees, whilst 'course angle' Beta is 12.1 degrees. Vf = 70.8, and tangential speed at effective diameter is 70.69 ft. per sec.

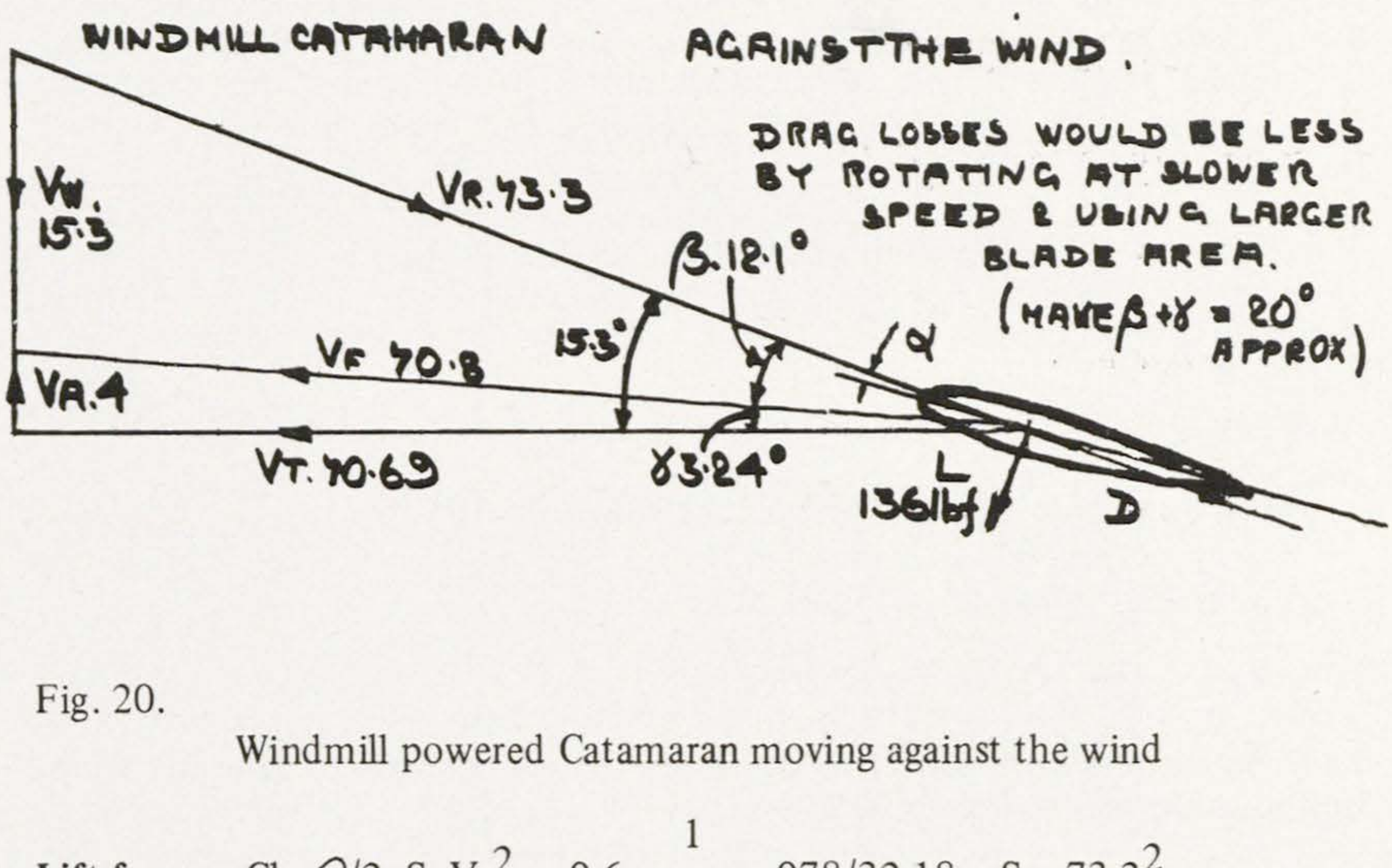


Fig. 20.

Windmill powered Catamaran moving against the wind

Lift force = $Cl.\rho/2.\ S.\ Vr^2. = 0.6 \times \frac{1}{2} \times .078/32.18 \times S \times 73.3^2$

= 3.907 S lbf.

Ff = component of lift along direction of Vf = 3.907. S. sine 12.1 = 0.815. S. lbf. Aerofoil power, assuming 100% efficiency = Ff.Vf. = 57.7 S. ft. lbf./sec. The corresponding ideal windmill power was 2096 ft. lbf./sec., so S = 36 sq. ft. and C = 1.8 ft. = 22 ins.

Blade widths. 22 inches is the width at the effective diameter of 15 ft. The blades will be made wider towards the hub for strength and narrower towards tips.

At effective radius 7.5 ft. phi. angle = 15.3 degrees., tan 0.2736. At tips, tan = 0.2736 x 3/4 and tip phi angle = 11.6 degrees.

At quarter radius, tan = 0.2736 x 4 and phi angle = 47.6 degrees.

For windmill operation with angle of attack constant along each blade at 6 degrees, blade angles become at effective diameter 9.3 degrees. At tips, 5.6 deg. At ¼ rad. 41.6 .

DOWNWIND PERFORMANCE. Fig. 21.

Now study the downwind performance of the catamaran. The airscrew is two bladed and 20ft. diameter. It can be set to any required pitch angle, but since twist is to suit performance against the wind, this will be a compromise for downwind. This means that some parts of the blades are operating at too small angles of attack, whilst other parts are set at too large angles with the possibility of stalling. However, in order to explain principles, we assume effective angle of attack 6 degrees and coefficient of lift 0.6 Blade area was 18.1 sq. ft. Efficiencies relative to the ideal windmill efficiency are 60% for the airscrew and its gearing, 50% for the water screw, giving overall efficiency 30% for rotary power. The axial power of the airscrew is assumed 100% efficient. The catamaran is propelled by the combined force compromising airscrew reaction against the wind, plus water screw thrust.

Value for n is 4/20 = 0.2 and is positive.

Airscrew rotary power = $2.\rho A.V^3.(1 - 0.2 - p).(p).(1 - 0.2 - p)$.

Power put into water by water screw will be 30% of this rotary power.

Airscrew axial power = $2.\rho A.V^3.(1 - 0.2 - p).(p).(0.2)$.

Adding nett rotary power to axial power

$= 2\rho A.V^3.(p).(0.352 - 0.68p + 0.3p^2)$.

Differentiate with respect to p, equate to zero and solve. Take the windmill solution which is p = 0.332.

Axial airscrew reaction against the wind = $2.\rho A.V^2.(1 - n - p)(p)$.

= 95 lbf. Rotary power appearing from the water screw

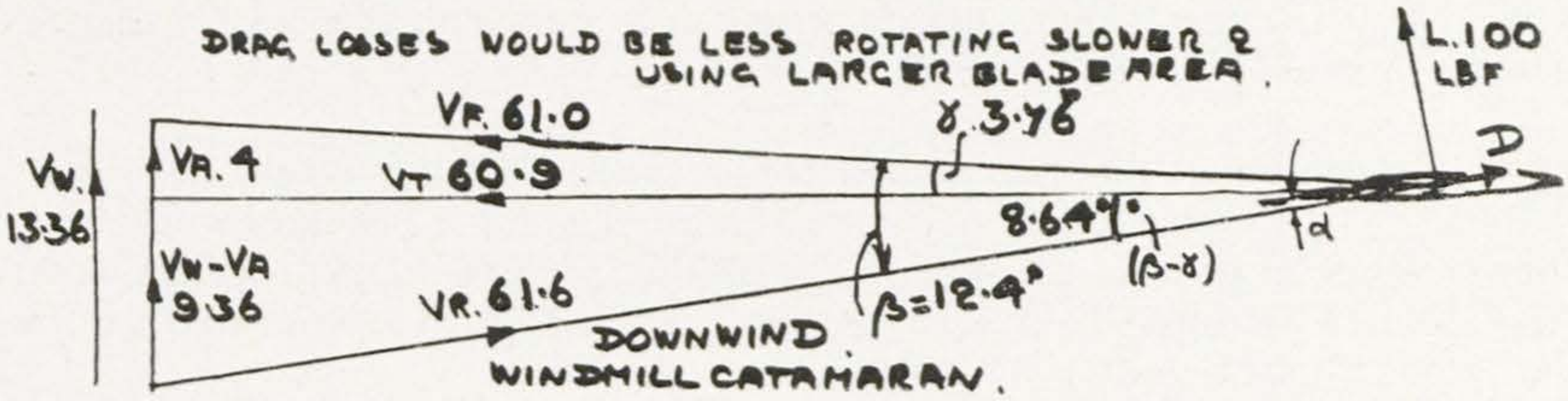
$= 2.\rho A.V^3.(0.8 - p)(p)(0.8 - p)$ times 30%.

and this comes out as 266 ft. lbf./sec. = thrust x boat speed.

With boat speed 4 ft./sec., thrust comes out as 67 lbf.

Add airscrew reaction of 95 lbf., and total propulsion force = 162 lbf.

With this force, the catamaran will probably accelerate to a faster speed.



Vector diagram for the windmill catamaran moving downwind at 4 ft./sec. wind 20ft./sec. Fig. 21.

We will utilize the axial reaction of the airscrew against the wind, obtained from windmill theory, but including for inefficiencies when estimating optimum value for p. We have to use the area of blades specified for movement against the wind, and so rotational speed will have to be altered. The airscrew reaction was estimated as 95 lbf., but since the blades are moving at a small angle, we need a slightly bigger lift, and will use 100 lbf., p = 0.332 V = 20 ft./sec. Wind speed through blades but measured relative to the water = V. (1 –p) = 13.36 ft./sec.

Lift $L = Cl. \rho /2. S. Vr^2$. or $100 = 0.6 \times 1/2 \times 0.078/32.18. \times 36.3. \times Vr^2$ from which Vr = 61.6 ft./sec.

The vector diagram can now be calculated and the beta angle at effective diameter of 15 ft. is found to be 9.4 degrees. This is not much different from the beta for upwind. Blade phi. angle at effective radius is 2.78 deg. only.

The tangential speed of 82.1 ft./sec. corresponds with rotational speed 1.75 rps or 105 rpm.

Note: There may well be arithmetical errors in this treatment, and also conceptual errors, but the final figures correspond near enough with the experimental work has been done by George Webb to provide some confidence that the analytical approach is at least along the right lines. At any rate, much of the mystery has been removed. It is unfortunate that calculations are complicated, and the supporting theories involve understanding of mass, energy, momentum and Newton's Laws.

A FIRST STUDY OF A WATER SCREW (PROPELLOR),

For use on the Windmill powered Catamaran with 20 ft. diameter airscrew.

This propeller differs from boat propellers in that the power from the airscrew is smaller than we normally get from an engine for the same size of boat. Secondly, we need a propellor thrust onto the water much larger than for a boat, in the same wind speeds, when moving against the wind, because the water propellor has to provide thrust to balance hull drag, plus other drag between wind and superstructure, plus the large axial reaction force of the wind on the windmill.

The sort of performance looked for is thrust 250 lbf. when the boat is moving at 4 ft. per second relative to the surrounding water, and with horse-power input to provide the 4 x 250 = 1000 ft. lbf./sec., plus propellor losses e.g. about 4 hp. input from airscrew. For this performance we would require an engine rated at about 8 hp minimum.

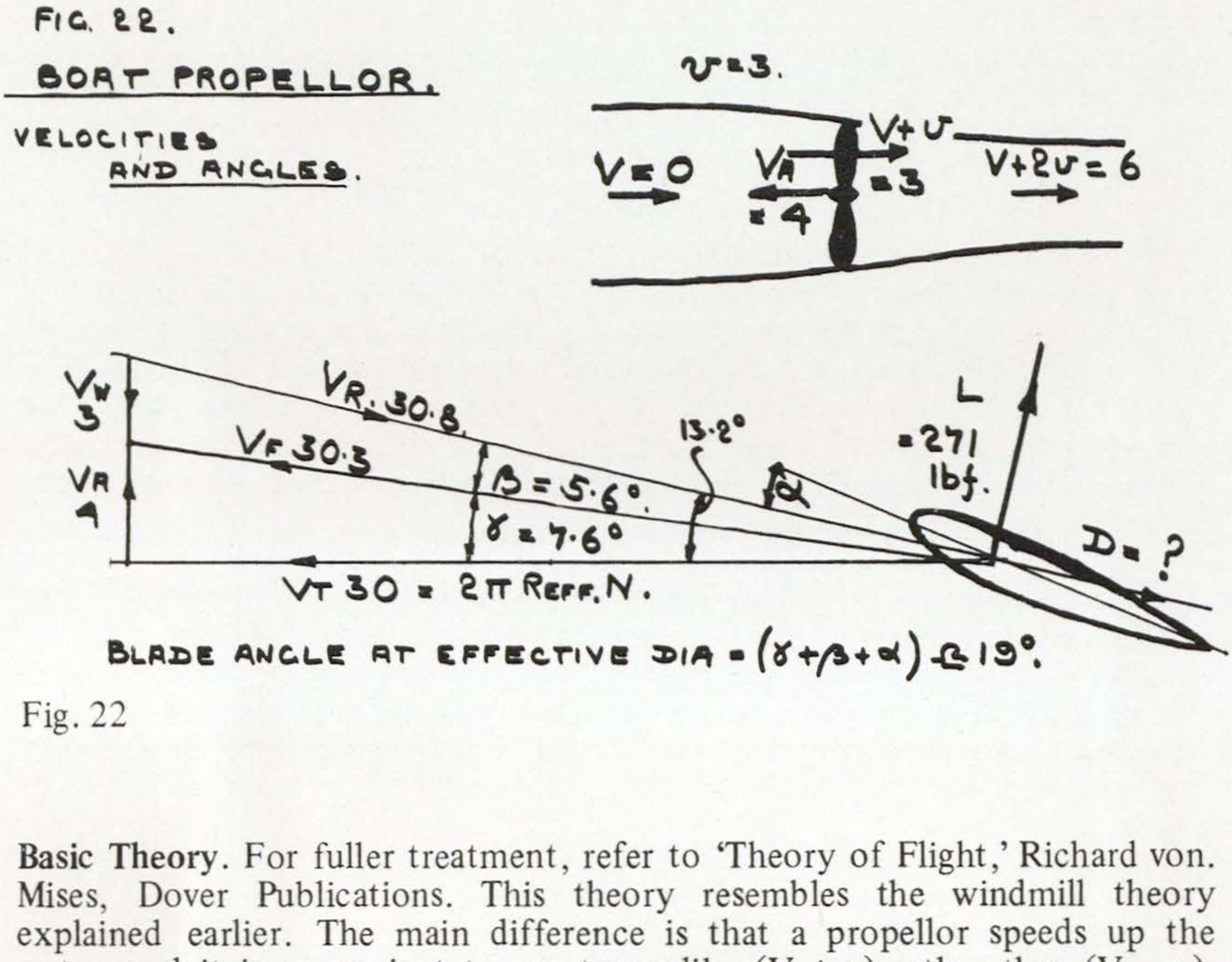


Fig. 22

Basic Theory. For fuller treatment, refer to 'Theory of Flight,' Richard von. Mises, Dover Publications. This theory resembles the windmill theory explained earlier. The main difference is that a propellor speeds up the water, and it is convenient to use terms like (V + v) rather than (V – v), with v numerically negative.)

Figure 22. Ideal Water Flow through a Boat Propellor

Water speed through the propellor relative to the surrounding water = v
Water speed through the propellor relative to the propellor = (4 + v).
Swept area A. Mass flow per second through the propellor M = A. (4+v).
This mass increases its speed from zero upstream to 2v downstream.

So increase in momentum per second = thrust T = Mass per sec. x increase in speed 2v.

Thrust = 2. ρ A. (4 + v). (v).

Ideal power into water = ideal power input from airscrew, since ideal efficiency is 100% = Thrust on the water times water speed through propellor measured relative to the surrounding water (v).

Ideal power = 2. ρ A. (4 + v). (v^2).

After trial calculations, I decided on a 2ft. diameter propellor, with value for speed increase v of 3ft. per second, boat speed, 4ft. per second. Speed through propellor relative to propellor of 7ft. per second. 286 r.p.m.

Mass per second through propellor = 3.14 sq. ft. x 7ft./sec. x approx 2 slugs/cu. ft. = 44 slugs per second.

This mass was originally not moving, but at 2v = 6ft. per second downstream, so increase in velocity is 6ft./sec., and increase in momentum per second is 44 slugs/sec. 6ft./sec. = 264 units of momentum per second numerically equal to the thrust. **Thrust = 264 lbf.** (Units M.L./t^2).

Ideal power = Thrust x water speed acted on by the thrust relative to water, = 264 lbf. x 3ft./sec. = 792 ft.lbf./sec. = 1.44 hp. With 50% efficiency, input power from windmill gearing would be 2.88 hp.

Lift = 271 = Cl. 0.6 x 1/2 x density, 62.4/32.18 x Vr^2 x S. From which, blade area comes out at 0.491 sq. ft. and blade width about 3 ins. at the effective diameter of 1½ ft.

Tractive force Ft = 271 sine 13.13 + 27 cos. 13.13 = 87.91 lbf.

Power input = Ft.Vt. = 87.9 lbf x 30 ft./sec. = 2636 ft.lbf./sec. = 4.79 h.p.

$$\text{Efficiency} = \frac{264 \text{ lbf. x } 4 \text{ ft./sec.}}{2636 \text{ ft. lbf./sec.}} = 40\%.$$

THE READING UNIVERSITY VARIABLE GEOMETRY VERTICAL AXIS WINDMILL

by

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Conventional windmills, such as the traditional Dutch windmill used for water drainage or milling, have blades which rotate about a horizontal axis. Recent windmill research has also concentrated on horizontal axis designs, such as the two bladed 100 kW NASA windmill completed in September, 1975 at Sandusky, Ohio and the two 1.5 Megawatt windmills now being built by General Electric, and due for completion in 1978. However researchers in Canada, the U.S.A. and Britain have recently shown that vertical axis windmills have some very attractive features, which may allow their construction at a cost significantly lower than that of conventional windmills.

As their name implies, in vertical axis windmills the blades rotate about an axis which is vertical. An important characteristic of these windmills is that they do **not** require orientation into the wind (unlike conventional windmills, where the blades are attached to a structure which must be continually turned so that the blades face into the wind). A second important characteristic of vertical axis windmills is that they can be supported by slender, guyed, towers, which are impracticable for conventional windmills. (The blades of a conventional windmill would cut the guy wires; conventional windmills therefore require relatively heavy and expensive self-standing towers, which usually resemble electricity pylons). Because of these two characteristics, vertical axis windmills are expected to be less heavy and less costly than conventional windmills of similar size.

Although the basic vertical axis windmill design was patented by Darrieus nearly 50 years ago, it was thought that the design was inherently inefficient. It was not until the early 1970's that Rangi and South, at the laboratories of the National Research Council, Ottawa, Canada, built a 14 foot diameter vertical axis windmill (similar in outline to the Darrieus windmill shown on the attached sketch) and showed that its efficiency was comparable with the best modern conventional windmills. The last five years have seen a rapid and worldwide upsurge of interest in vertical axis windmills, and the Canadian results have been duplicated in the U.S.A. and elsewhere.

Research at Reading University into vertical axis windmills commenced in mid - 1975, with the aid of a £16,000 grant from the Science Research Council. Though inspired by the earlier Canadian research, the Reading windmill differs in some important features from the Darrieus windmill, as the attached illustration clearly shows. Aero-dynamically, the ideal configuration for a vertical axis windmill is H-shaped. However if one attaches the blades rigidly to the cross-arm, blade stresses become excessive at wind speeds above 20 mph., i.e. the blades would break. In the Darrieus design, this problem is overcome by using curved blades, the shape being carefully designed so as to eliminate the dominant bending stresses. (The required curve is called a troposkien, and is the same as the shape obtained by rotating a rope about a vertical axis). However, curved blades are difficult and expensive to make and the guyed tower height of the Darrieus windmill is appreciably greater than that of a similarly rated conventional windmill. Also in very strong winds the tensile stresses in the curved blades become excessive, necessitating shut down or the addition of air brakes.

In the Variable Geometry windmill (patented by the N.R.D.C.) the ideal H. configuration is retained for near average wind speeds, when maximum efficiency is required. However the blades are hinged to the cross-arm, not attached rigidly. As the windspeed increases the windmill's rotational speed increases and the increased centrifugal forces make the blades incline outwards from the vertical. The tie wires, which run from the upper half of each blade to an extension spring within the central rotation shaft, ensure that the blade inclination increases steadily as the wind speed increases. This outwards inclination of the blades is clearly visible in the photograph, which shows the 10 foot diameter prototype in operation at Reading. Allowing the blades to pivot in this way, limits the blade stresses, and in very strong winds the stresses actually decrease. There is therefore no need for add-on air brakes, regardless of wind strength. The straight blades make for simple, low cost construction (from wood, glass fibre or aluminium) and the guyed tower height is appreciably less than that of the Darrieus design. The ground area required by the Variable Geometry windmill is also much reduced. As a consequence of all these factors the cost of the Variable Geometry windmill is expected to be significantly lower than that of the Darrieus windmills.

The variable geometry vertical axis windmill has a performance similar to that of a conventional horizontal-axis windmill of similar size. However, it is not self-starting. For battery charging applications, this is unimportant, as the windmill may be conveniently and automatically started with a car-starter motor. For irrigation applications, etc., aerodynamic self-start is essential, and a modified design which will provide this is to be tested later this year.

It is expected that a 4½ metre diameter variable geometry vertical axis windmill, with an electrical generator giving a 12V d.c. or 24V d.c. output, will be available commercially in late 1977.

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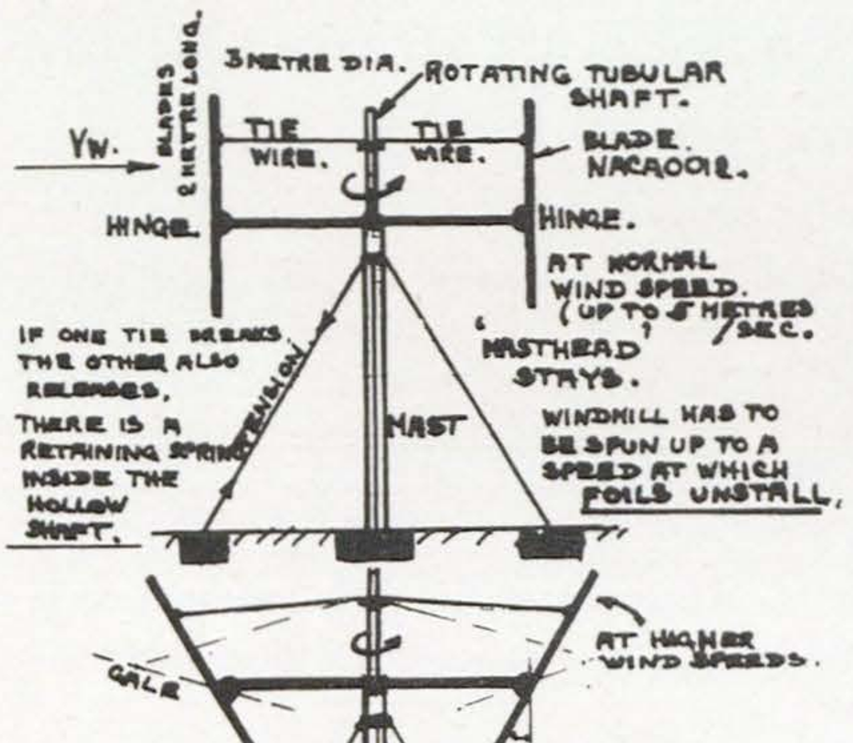
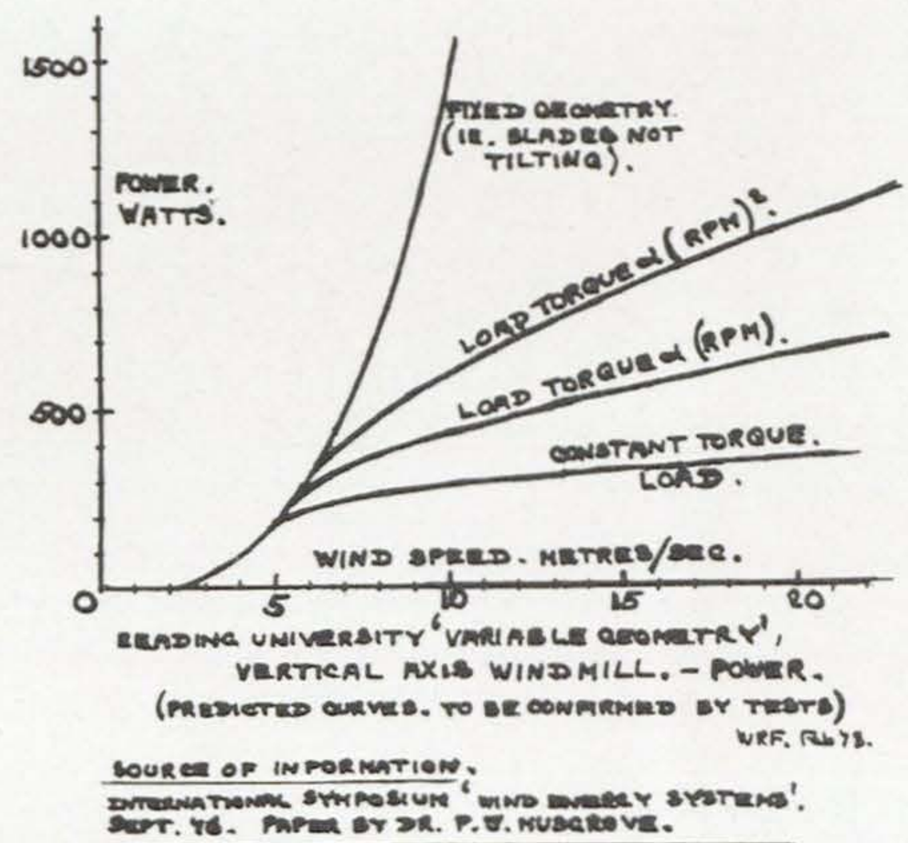




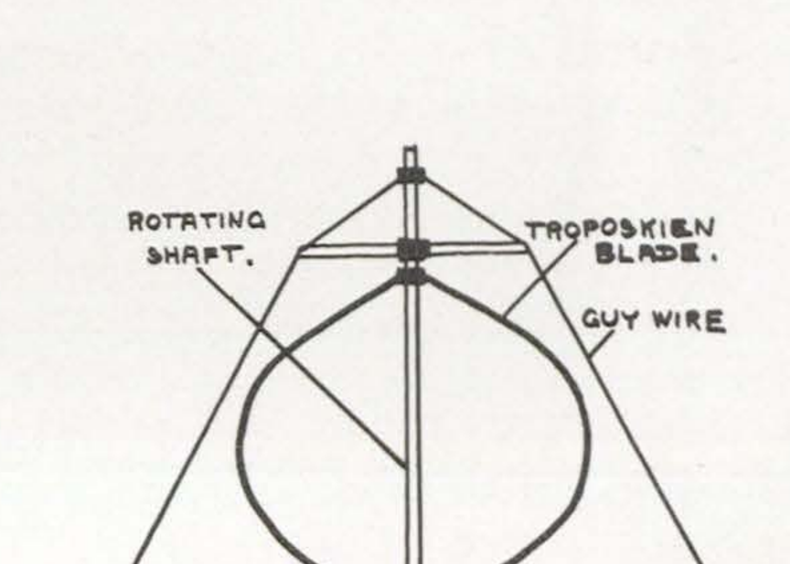


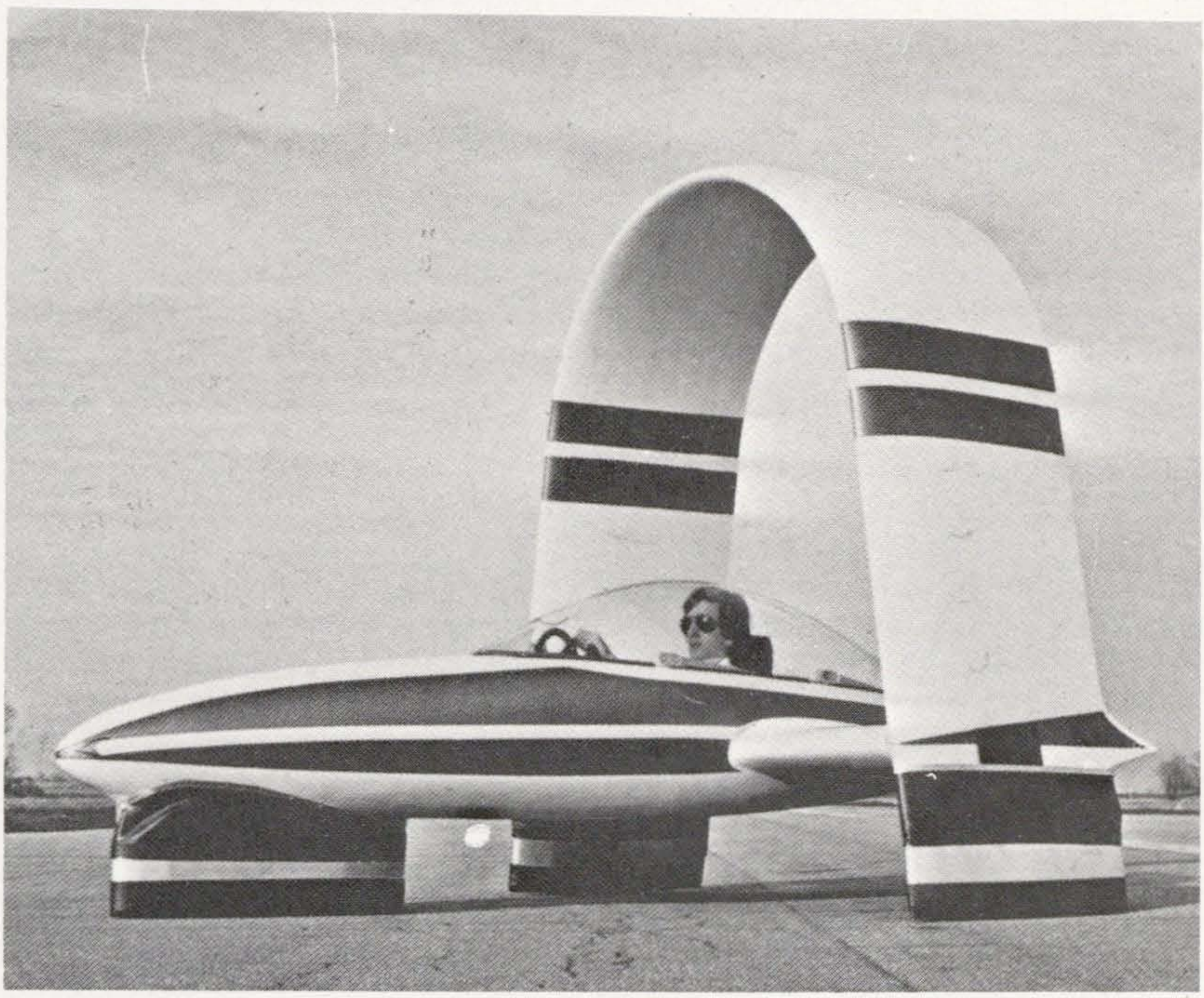
FIG. 1. DARRIEUS WINDMILL.

THE WINDMOBILE

by

James L. Amick of Ann Arboc,
Michigan, U.S.A.

The windmobile is a new breed of car that offers an alternative way to go – away to travel long distances without depending on fossil fuels. This well-streamlined aircraft-like vehicle cruises at highway speeds powered by the wind. For acceleration, and when the wind diminishes, it draws on electrical energy stored in batteries. These batteries, in turn, can be recharged by moving vehicle when wind conditions are favourable, or while decelerating.



The prototype windmobile sketched in Figure 1 can travel at a speed of 55 mph, powered only by a 12 mph wind blowing perpendicular to its course. Under these same wind conditions, the vehicle can maintain a speed of 45 mph while recharging its storage batteries at the rate of 400 watts. If, instead of travelling perpendicular to this wind, the windmobile follows a circular course (or any course with equal distances in all directions), it can cover 90 miles at 45 mph on one battery charge. Reducing the vehicle speed to 35 mph increases the range under the same conditions to 220 miles.

How it Works

The windmobile is actually a sailing vehicle, but its "sail" consists of a rigid arch-shaped airfoil having symmetrical cross sections, fixedly attached to a main body. It is the only known sailing vehicle in which the angle between the sail and the longitudinal axis is not adjustable. This fixed sail arrangement is made possible by the auxiliary electric power system, which is used to accelerate the vehicle to its sailing speed of three or more times the wind speed. At such high speeds relative to the wind, an adjustable sail would give only an insignificant increase in performance over the fixed sail, and it would be very much less practical in terms of structural and control problems.

The windmobile's fixed sail arrangement means the the driver's job is a simple one. No sailing skill is required. The driver merely steers and controls speed, just as in any automobile. The main effect of the wind is to change the amount of power required to maintain a steady speed, and the driver responds with appropriate adjustments of the speed control, as if he were driving up or downhill.

When the wind supplies more power than is needed, the driver applies the brakes enough to prevent a build-up of speed. The first stage of braking involves regeneration in which the excess wind energy is used to recharge the electrical storage batteries, with the windmobile's two drive motors acting as generators. If greater braking force is required, conventional mechanical brakes are activated.

Steering the windmobile is not very difficult, even in gusty winds. The side force produced by the wind is relatively large, but it acts near the centre of gravity, so that it has little tendency to turn the vehicle.

The arch-shaped airfoil which is the "sail" of the windmobile consists essentially of two more or less vertical airfoils, connected at their tops by a circular airfoil which serves to increase efficiency. (Without the top airfoil, the upper end of each vertical airfoil would experience additional wind resistances due to the generation of a tip vortex as the high pressure air on one side of the airfoil flowed toward the low pressure region on the other side). The cross sections of each aerofoil are symmetrical about longitudinal axes parallel to the centreline of the vehicle.

The two vertical airfoils are the key to the wind action that propels the vehicle. When a wind is blowing across the course of the vehicle, it causes the relative wind to approach the airfoils at an angle to their longitudinal axes. In flowing past the airfoils, the airstream is deflected so that it leaves in a direction more nearly parallel to the airfoil axes. This deflection produces a side force which is resisted by the wheels. More importantly, the airstream leaving the airfoils has somewhat more momentum in the rearward direction than before, so that a force is developed in the opposite direction, propelling the vehicle forward. (This is like a jet engine, which adds rearward momentum to a stream of air, thereby producing a forward thrust).

The forward-propelling force of the wind increases when there is an increase in the angle at which the airstream approaches the airfoils, because this increases the amount of deflection of the airstream. The approach angle of the airstream, in turn, increases with wind speed, and, for a given wind speed, is greatest when the wind direction is approximately perpendicular to the vehicle's course.

The windmobile is closely related in principle to the Darrieus windmill (the vertical-axis machine often likened to an eggbeater). The vertical airfoils of the Darrieus windmill work exactly like those of the windmobile. Both devices require auxiliary means to reach a speed at which they can begin to develop power, a speed which is in each case several times the wind speed.

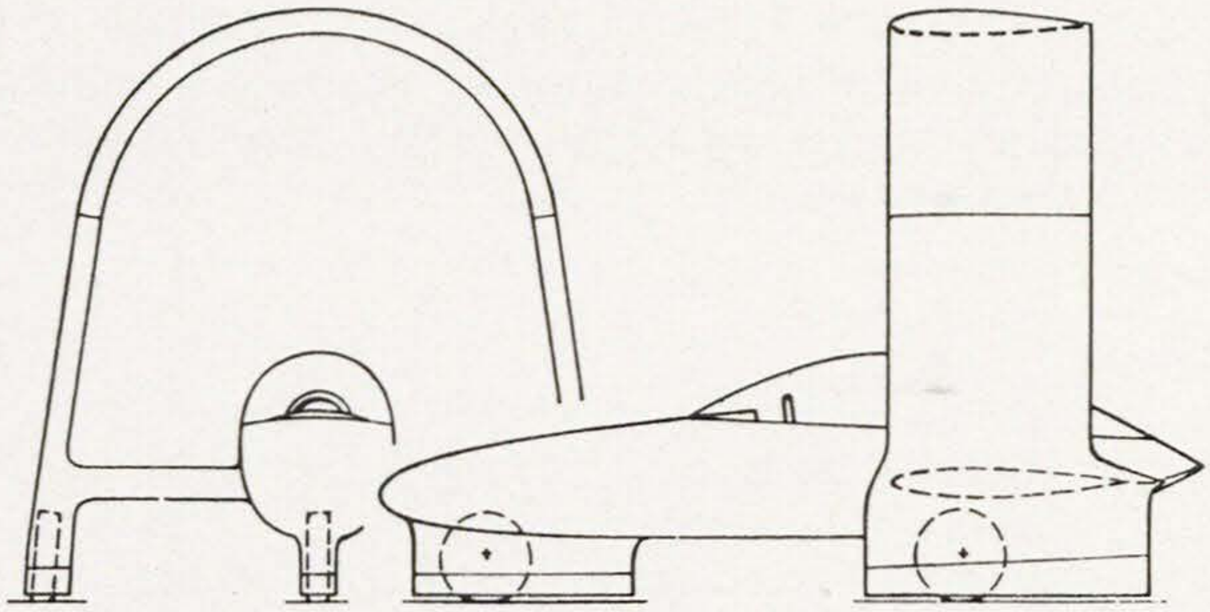


Figure 1. Prototype Windmobile

Performance

Performance data for the prototype windmobile have been calculated from the theoretical equations, using empirical coefficients adjusted to fit the limited number of actual measurements that have been made to date. Results of these calculations are shown in Figures 2 – 5.

Windmobile speeds when cruising on wind-power alone are shown in Figure 2 for a variety of wind speeds, plotted against the wind angle (the angle between the direction in which the vehicle is going and the direction from which the wind is coming). The dashed line represents the stall condition, in which the airstream approach angle is too great, and the air flow breaks away from the lee side of each airfoil, with the result that practically no forward force is generated. Below this line, some battery power is always needed.

The significance of Figure 2 can be shown with an example. Consider a windmobile heading north, with a steady 14 mph wind blowing from the northeast (wind angle of 45 degrees). According to Figure 2, battery power will be needed to reach a speed of 15 mph (the dashed line), after which the airfoils will unstall and wind power alone will accelerate the vehicle to an equilibrium speed of 31 mph. Higher speeds can be reached by using battery power or by changing course.

If the vehicle turns and heads northwest (wind angle of 90 degrees), wind power will accelerate it to 65 mph., unless regenerative braking or mechanical brakes are activated to maintain a lower speed. If, instead, the driver heads south or west (wind angle of 135 degrees), his equilibrium speed under wind power alone will be 51 mph.

Range capabilities of the prototype windmobile are depicted in detail in Figures 3 and 4, based on the assumption that the vehicle's batteries supply 2100 watts for one hour, or 1200 watts for two hours. For any given wind condition, the distance the vehicle can travel before its batteries are exhausted decreases with increasing vehicle speed. For wind speeds of 12 mph or greater, there is a wide range of values of the wind angle that can extend the vehicle range to 120 miles or greater. On the other hand, head winds can cause considerable reduction in range.

Under certain favourable wind conditions, significant amounts of excess energy can be supplied to the battery thru regeneration, as shown in Figure 5. More excess energy is available at lower vehicle speeds than at higher speeds.

Structural Details

The prototype windmobile is 11½ ft. long, 8 feet high, and 8 feet wide, with an empty weight (total weight without driver) of 750 pounds. It accomodates one person. Three lead-acid storage batteries supply electric power to two 1½ horsepower permanent-magnet motors through a transistorised speed controller. Each motor drives one of the rear wheels by means of a motorcycle chain and sprockets. The batteries are equipped with vent caps of the catalytic converter type, to reduce the danger from escaping hydrogen gas.

All three wheels have 10 inch diameter rims on which are mounted Goodyear 18 x 4.4 aircraft tyres. All wheels are spring and shock mounted in forks and enclosed by flexible airfoil-shaped fairings. Only the front wheel is steerable.

The upper curved part of the arch is detachable, for convenience in storage and for safety in high winds. With this part removed, the windmobile cannot be overturned by wind forces. unless the relative wind exceeds 100 mph. (The corresponding figure for the complete arch is 80 mph).

The structure of the windmobile is primarily a sandwich consisting of fibreglass cloth reinforced epoxy skins with a core of Styrofoam. The core thickness is one inch in the fuselarge, while in the airfoils the foam core comprises the entire interior. All external surfaces were smoothed with a plastic auto body filler and painted with acrylic lacquer.

Construction of the prototype windmobile began in 1971 and was principally the work of Douglas Amick, son of the designer, James L. Amick, Douglas, then 16, was assisted by his brothers Richard Amick, James R. Amick, and Ronald Amick, and by his father. Technical advice and financial support for the electrical system were furnished by SunWind Ltd., an alternative energy development company of Sebastopol, California.

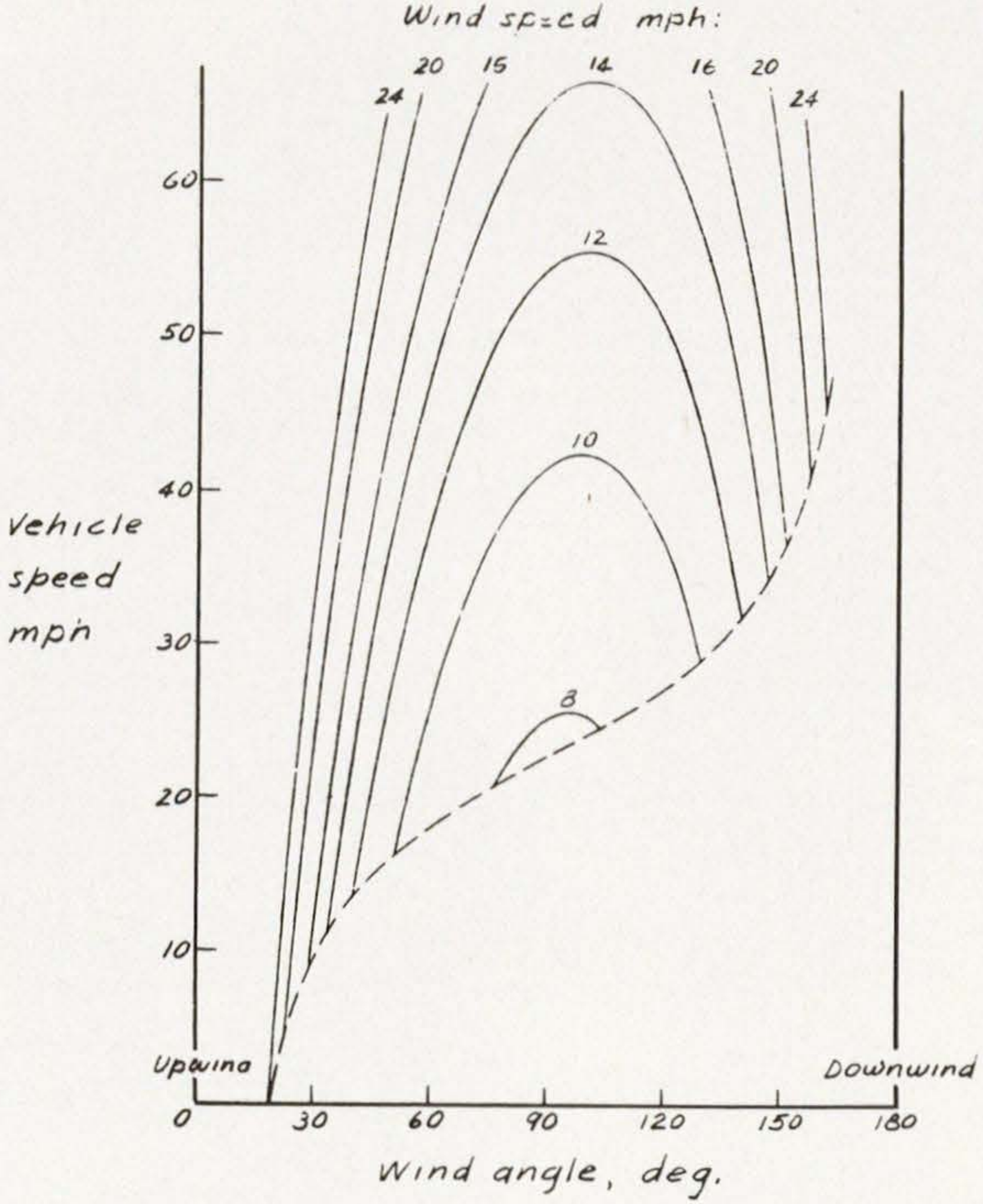


Figure 2. Equilibrium vehicle speeds, battery power off. Prototype windmobile.

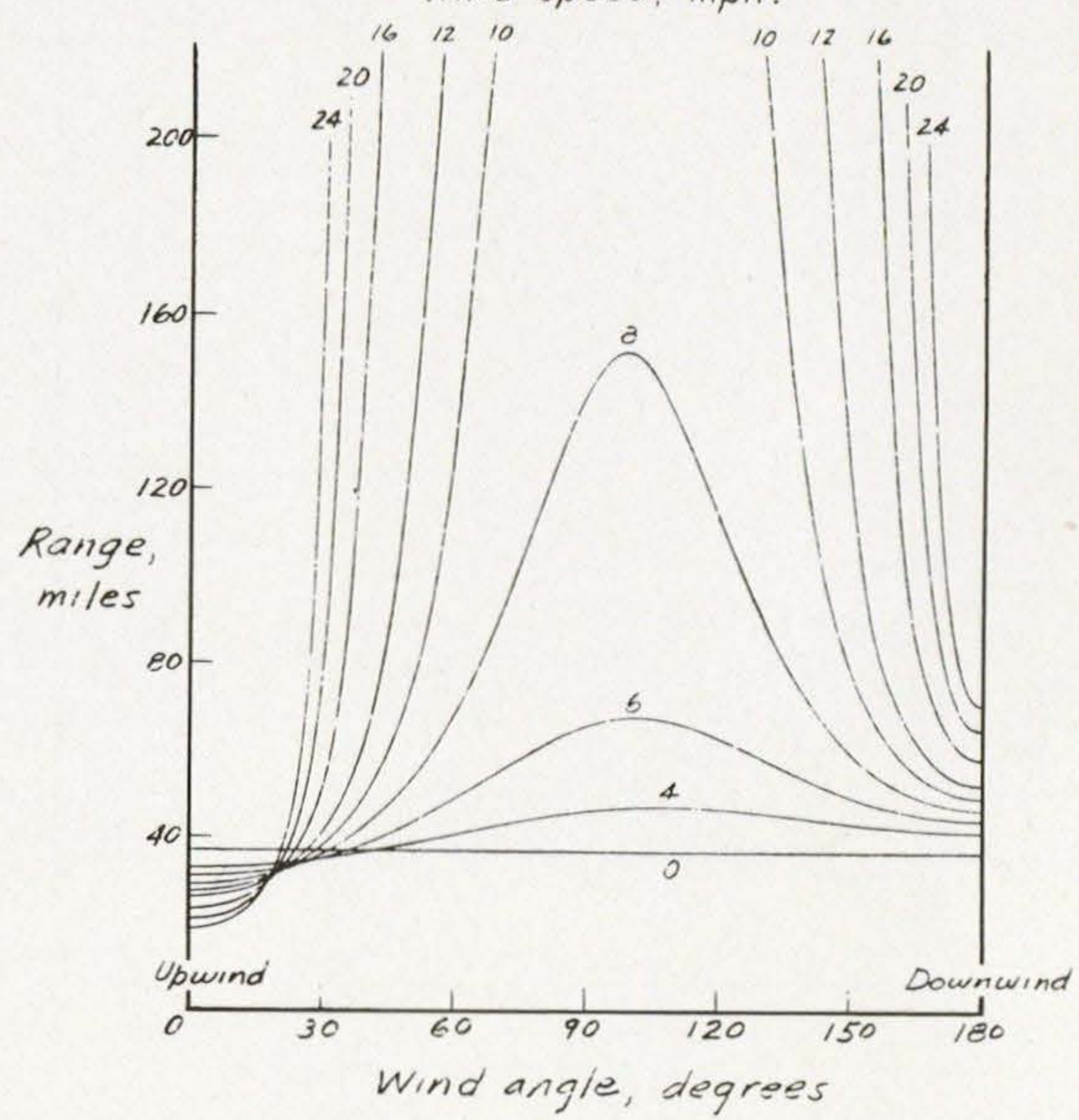


Figure 3. Maximum range of prototype windmobile at a steady speed of 40 mph, for various wind conditions.

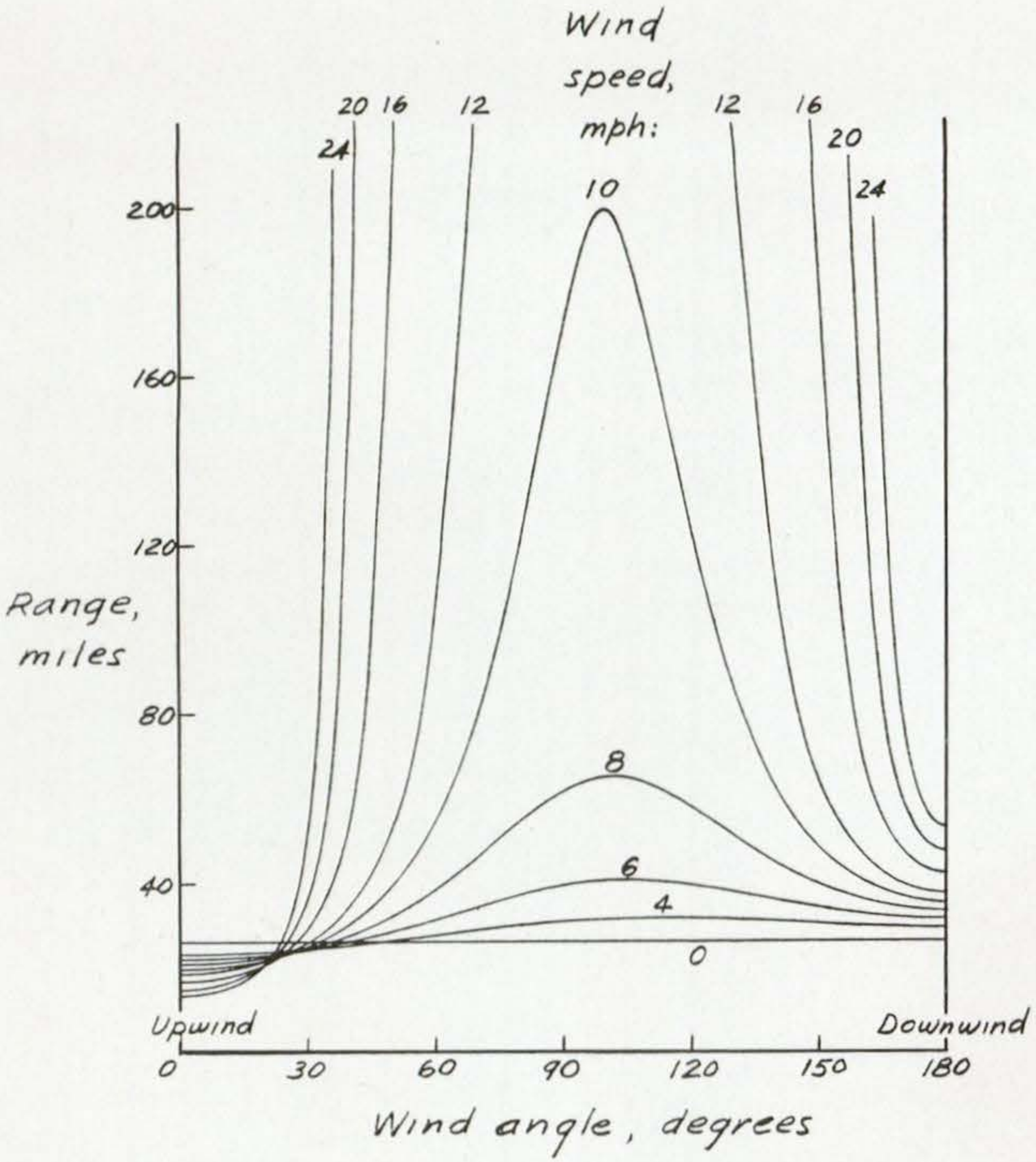


Figure 4. Maximum range of prototype windmobile at a steady speed of 50 mph, for various wind conditions.

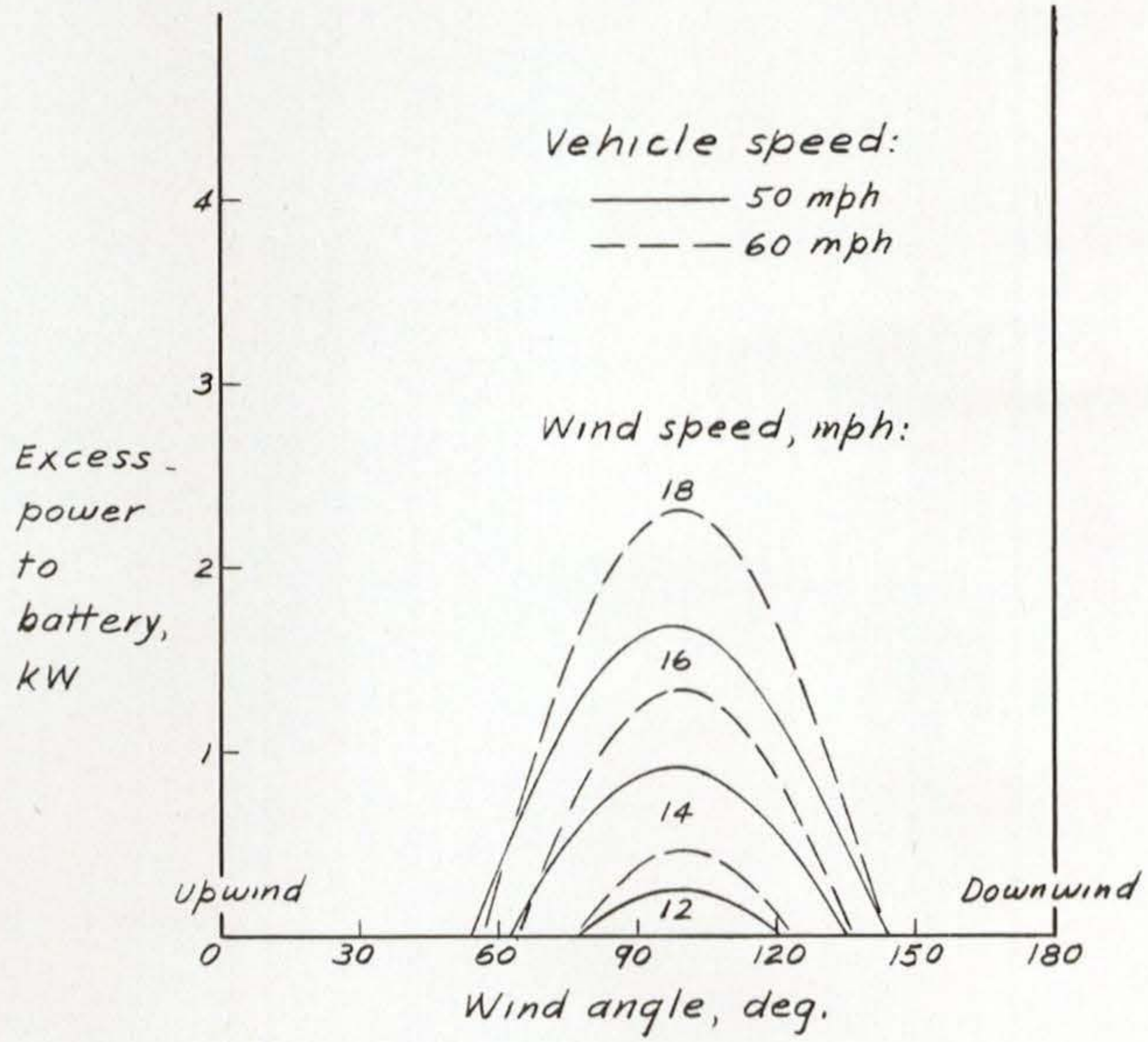
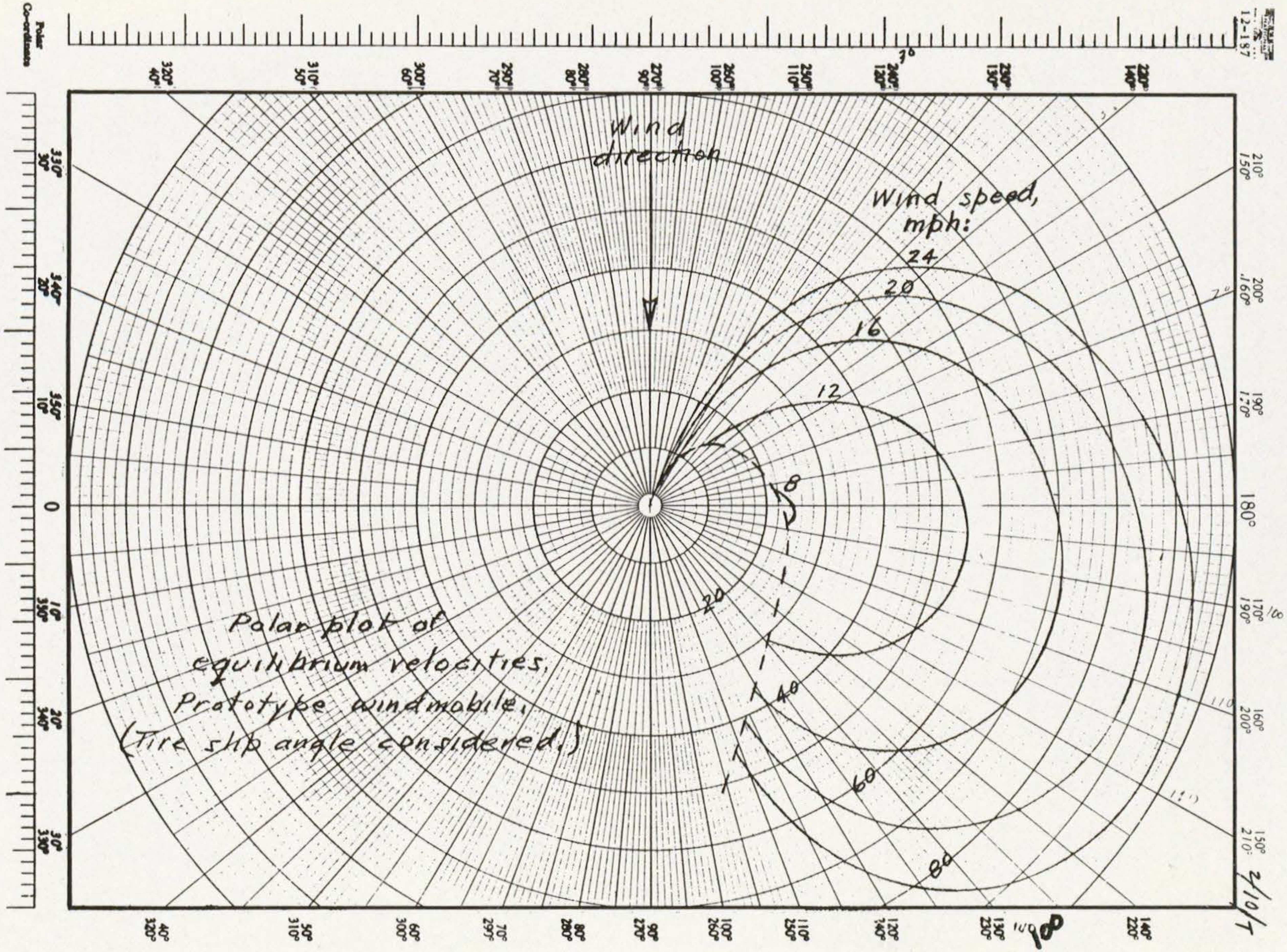


Figure 5. Excess windpower available for battery recharging, at two vehicle speeds. Prototype windmobile.


Wind direction
Wind speed, mph:
24
20
16
12
8
20
40
60
80
Polar plot of equilibrium velocities, Prototype windmobile. (Tire slip angle considered.)
2/10/7

Future Developments

The present windmobile is by no means the ultimate configuration of a wind-powered highway vehicle. Rather, it represents only one engineer's intuitive concept of an energy-efficient shape, developed without the benefit of any wind-tunnel testing. It seems quite likely that future work will reveal configurations having much better performance and utility.

It appears that a vehicle in the 2000 pound class, with accommodations for a driver and several passengers, could double the range of the present vehicle. It would use 10 or 12 batteries, larger motors, and a telescoping airfoil extending from a retracted height of 7 feet to a maximum height of 10 or 12 feet.

The fuel economy of a conventional lightweight car could be improved by a system of one or more small vertical airfoils.

SunWind Ltd. plans to produce a single-place sport model with width and height of 80 inches each, enough batteries to double the range of the existing prototype, and larger motors for better acceleration.

NOTES ON WINDMILLS, WATERMILLS AND PROPELLORS

by

John Morwood
Woodacres, Hythe, Kent.

Both windmills and watermills were devised to grind corn between two stone discs, the top one of which was made to revolve upon the lower one. The grain was put into a hole in the centre of the upper disc and came out at the outside of the discs.

Because of the purpose for which they were invented or were developed, it would be expected that both windmills and watermills first appeared with a vertical axle and axis of rotation. This in fact happened.

I have seen it stated that the first mention of a windmill was from Ancient Persia where some criminal had been executed. His occupation was given as a "Maker of windmills." Now, it is noteworthy that the Ancient Persians were great navigators. Indeed, when they were converted to Islam, they became the seamen of the Arab world. I like to think that they had come across the 'Oceanic Lateen' sail in the Pacific and converted it into the Arab lateen sail.

It would seem natural that a race of seamen, who are all natural inventors by the nature of their occupation would put cross beams on the top stone of their grindstones and erect vertical poles on the ends for the masts for four sails. If each sail had a boom, it would tack and gybe around the circle, thus driving the top millstone. I have never seen any picture or drawing of such a mechanism.

Used as a windmill, it is called a 'Vertical axis windmill.' As a windmill, it starts to generate electricity in winds of 10 m.p.h. whereas the more efficient conventional windmill only start about 14 mph. Its fault is that its drag is greater and there can be no protection in gales with the usual applications. This windmill might just work to propel a land vehicle directly to windward, especially if the tail end had a streamlined fairing. The section would also have to be altered to be used on the two tacks on each of which the rotation would have to be in the opposite direction.

THE VOIGHT SCHNEIDER PROPELLOR

This was a propellor which consisted of three or four symmetrical hydrofoils spinning around in a circle. At different points on the circle, the angles of attack varied and could be controlled in different ways. By appropriate adjustments, this propellor could drive the boat forwards, backwards or sideways all with equal efficiency. Moreover, it was claimed to be more efficient than a conventional propellor. I think that it never came into common use because of the vulnerability of the blades. The ordinary propellor can be chipped, bashed, hit flotsam, etc., and still function. If a similar thing were to happen to this propellor, it would cease to function altogether.

The Voight-Schneider propellor might not have been useful as a propellor, but it might make the ideal windmill for a yacht or land vehicle application. In effect, it is similar to four little yachts, on the ends of cross beams on a single axle, tacking and gybing with sailing on all points.

A Voight-Schneider windmill, for utmost efficiency, would need four aerofoil sails, like those of 'Miss Nylex' or even 'Patinet Lady', the C Class catamarans. Optimum slat and flap angles would have to set around the circle of rotation. The rotational speed would, it is hoped, be great enough for gybing never to occur, as with ice boats. Even then, a complex mechanism would be needed to make the thing work. From what I have read, however, the effort to get such a windmill going would be well worthwhile. A certain amount of Magnus effect would also occur which would increase still further the value of this windmill when used on a land or water vehicle. If the Magnus effect turns out to be relatively powerful, however, rotation in opposite directions would be obligatory. i.e. Twin Rotors.

SUMMARY

An efficient windmill of conventional pattern will drive a boat directly to windward, if connected to a propellor of fairly large size and conventional pattern, Its efficiency on other courses is not as good as conventional sails.

A vertical axis windmill is likely to drive a boat or land vehicle directly to windward, if connected to a propellor or wheels. This might be increased on other courses by the Magnus effect, but this means having a mechanism to alter the direction of rotation of the rotor. The aerodynamic drag of the vertical axis windmill might be greater than that of a conventional windmill, and if so, this would appear in sailing trials, as a limitation of the concept. Some improvement might be possible by streamlining the tail of the rotor.

A Voight-Schneider windmill might well be the most efficient windmill of all, but, if some asymmetry of the aerofoil is built in, a complex mechanism would be necessary to activate it. If Magnus effect is apparent, alternation of rotation would be necessary for change of tack.

CONTRIBUTORS

Simon H. Sanderson.

Interests include models of windmills, windmill boats, full size hydrofoils, Starting University to study physics.

Kenneth R. May.

Pioneer experimenter on model vehicles and boats propelled by windmills. References are included in this publication to his previous contributions. One of his model windmill vehicles was a working model on the A.Y.R.S. Stand at the London Boat Show.

Reg Frank

Engineer. Interested in what flows. Gases, liquids, molten metals, beer, Humber tides.

Dr. Peter Musgrove.

Pioneer in developing wind power devices and in particular the vertical axis windmill at Reading University, England.

James L. Amick of Ann Arboc.

We don't know much about James, but hope to hear more.
They also sent the A.Y.R.S. descriptions of his arrangements for water surface skimming aircraft.

Dr. John Morwood

A.Y.R.S. Honorary Editor. Pioneer of Pioneers in amateur studies and experiments connected with all kinds of sailing craft.

George Webb.

Inventor, engineer, sculptor. His windmill catamaran should demonstrate the advantages and limitations of windmill propulsion for small marine craft.

Readers who would like to go further, will find useful information in the publications listed below:–

AMATEUR YACHT RESEARCH SOCIETY PUBLICATIONS

No. 61 Sailing Analyses.

No. 66A Foils, Ice Yachts and Sails.

No. 82 Design for Fast Sailing.

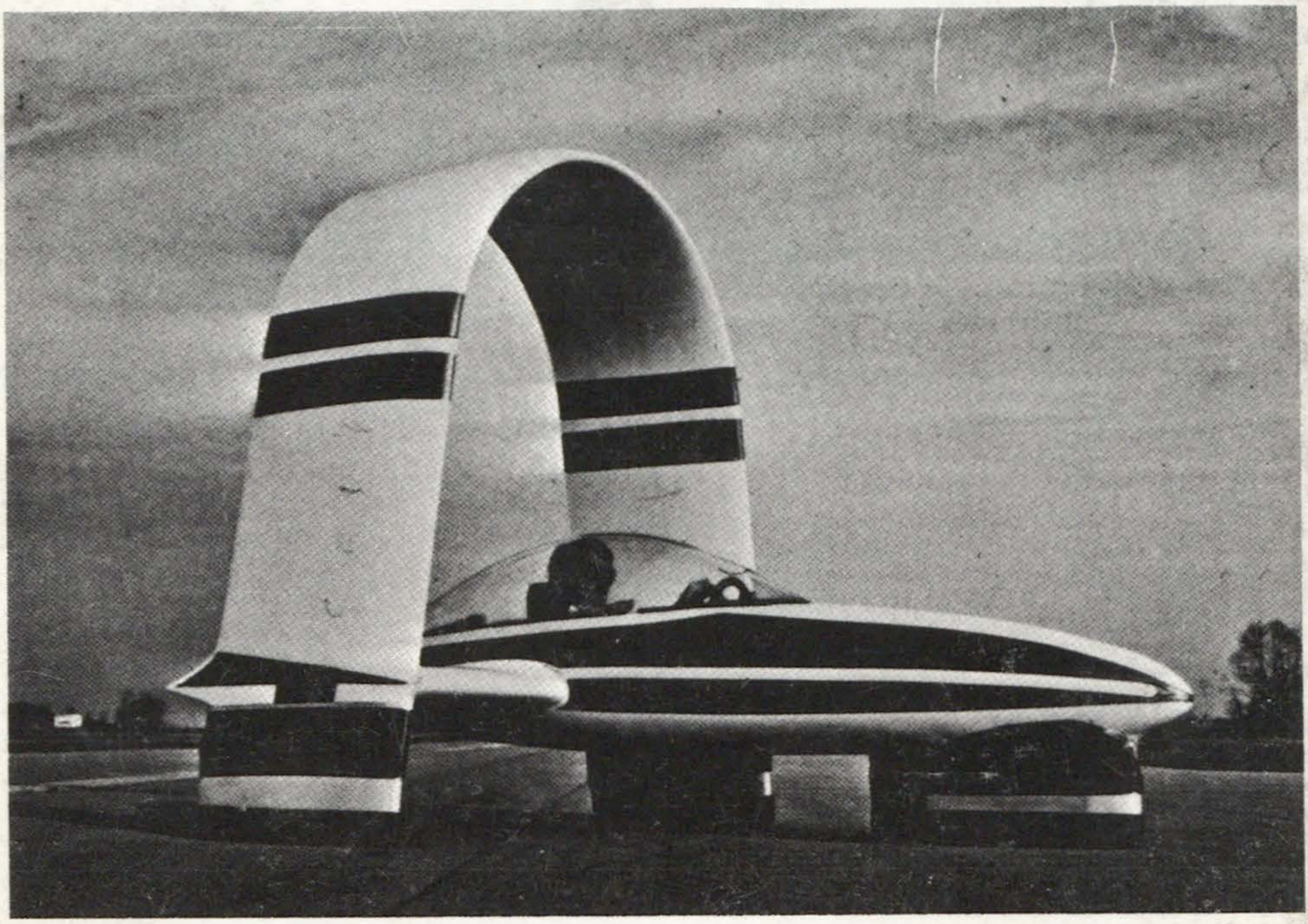
'Theory of Flight' – Richard von Mises.

'Theory of Wing Sections' – Iva H. Abbott, and Albert E. von Doenhoff.

Both published by: Dover Publications Inc.

For guidance on the mechanical aspects:–

Energy; power; mass; momentum – consult text books used in College of Technology and University Engineering courses.



The Windmobile – James L. Amick of Ann Arboc. – Page 55.

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