

A low-cost water pumping windmill using a sail type Savonius rotor

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Abstract. A water pumping windmill which can be built largely with materials and skills available in rural areas has been designed and fabricated. The windmill uses a Savonius rotor and incorporates a novel sail-type construction. The pump is of a positive displacement type using the casing of a pneumatic tyre for the pumping chamber. Two prototypes have been constructed and these have indicated a reasonable performance and reliability.

Keywords. Windmill; Savonius rotor; water pump; low cost technology.

1. Introduction

For centuries wind energy has been exploited in many parts of the world, but to this day windmills are a rare sight in India. In the 1950s and early 1960s, the National Aeronautical Laboratory tried vigorously to introduce windmills into India by erecting more than sixty windmills of the horizontal axis, multi-bladed type in various parts of the country (Sen Gupta 1966), but they have not gained acceptance.

An important reason for this lack of interest in wind energy must be that winds in India are relatively low and vary appreciably with the seasons. For example, data quoted by Ramakrishnan & Venkiteshwaran (1961) indicate that during November about half the country experiences mean winds of less than 5 km/hr and almost nowhere are they higher than 20 km/hr; during July, on the other hand, more than half the country has mean winds exceeding 15 km/hr, and about a sixth has wind speeds higher than 20 km/hr. These low and seasonal winds imply a high cost of exploitation of wind energy. Calculations based on the performance of a typical windmill (Sivaraman & Venkiteshwaran 1963) have indicated that a unit of energy derived from a windmill will be at least several times more expensive than energy derivable from electric distribution lines at the standard rates, provided such electrical energy is at all available at the windmill site.

The above argument is not fully applicable in rural areas for several reasons. First, electric power is not and will not be available in many such areas due to the high costs of generation and distribution to small dispersed users. Secondly, there is a possibility of reducing the cost of the windmills by suitable design. Lastly, on small scales, the total first cost for serving a felt need and low maintenance costs are more important than the unit cost of energy. This last point is illustrated easily: dry cells

provide energy at the astronomical cost of about Rs 300 per kWh and yet they are in common use in both rural and urban areas.

This raises the question of what the felt needs are that a windmill might satisfy. While large scale energy production at some favourable sites in India is a possibility that needs to be explored, there appears to be a definite need for small sources of mechanical energy in rural areas. For example, even casual polls among villagers quickly reveal that their first concern is invariably water—for drinking, washing and irrigation; and lifting water is a task which a windmill can perform. For such a task, a windmill should produce about 100 W, considering that a pair of bullocks, often used for lifting water in villages, typically provides about 250 W power.

These considerations define the problem of designing a windmill for use in rural India: it must work efficiently at relatively low winds in the 10–20 km/hr range and must provide about 100 W typically. For individual ownership to be possible, it must have a low first cost (closer to Rs. 10³, which is the cost of a pair of bullocks, rather than around Rs. 10⁴ which is the cost of currently available windmill designs), and it should be simple and easy to build and maintain.

This paper describes one design that appears to meet these requirements and to merit further study.

2. Design principles

The requirements set out above appear to be best satisfied by a design that can utilise an appropriately low technology; the principles that characterise such technologies have been set out at length by Reddy (1975). In general, such a design should be labour- rather than capital-intensive, and use local materials and skills to the fullest possible extent. This suggests wide use of wood and fabric, both of which have been handled with considerable skill in Indian villages for ages and can be worked easily using handtools. Sophisticated controls and safety devices of the kind suggested for high technology windmills are obviously out of place in such a design. Thus, the windmill should start and operate reasonably well without attention and should have simple safety devices built into its design. Any maintenance or repairs that may be needed should be within the skill of the villagers themselves.

The use of such a low technology calls for a change in the engineer's usual attitude to design. Materials in their natural state exhibit large variations in dimensions as well as other properties, and it is not possible to adapt them to a standard design with fixed dimensions unless one processes them—and this calls for a technology which is, in general, energy-intensive and is therefore to be avoided as far as possible. Thus, for example, the windmill should use available timber even avoiding conversion to standard sizes wherever possible. This implies that a large number of design details (joints, location and type of fixtures for support of bearings etc.) will have to be determined by the quality and type of timber available. But such a design should still incorporate sound engineering in the sense that it should develop the necessary performance at the least possible cost. We may call this approach 'soft design'—something that is sound in principle but adaptable to local circumstances with modest variations in dimensions, materials and skills. Bullock carts and traditional housing are examples of such design.

Use of the soft design approach imposes certain constraints on admissible design solutions in any specific context. For example, a windmill using aerofoil blades demanding precise blade forms and excellent surface finish is inconsistent with the concept. This is so not because of any inherent limitations to attainable precision. A look at the carvings in ivory and metal made by the cottage industries in India will convince one of the extreme precision attainable. But such precision is achieved at enormous labour cost and will be uneconomical.

It is not obvious that satisfactory design solutions consistent with the above principles always exist. What follows is the description of one attempt to find such a solution for a device that could extract wind energy in sufficient quantity to make a significant contribution to energy use in rural areas.

3. The Savonius rotor

A horizontal axis windmill rotor requires mounting on a turntable or equivalent for orienting it into the wind at all times. This complexity is avoided in a vertical axis windmill which was therefore considered more suitable for rural application.

Among vertical axis machines the Darrieus rotor has good aerodynamic efficiency but suffers from poor starting torque, and, without complex starting devices, is unsuitable for pumping water. Further, the rotor is not easily constructed or maintained using low technology.

Windmills operating solely on drag differences (like the cup anemometer) usually have such poor efficiency that they tend to be uneconomical.

The Savonius rotor, invented around 1930, has moderately good efficiency and a satisfactory starting characteristic, the latter being particularly important for use with a positive displacement pump. A small windmill for pumping water was in fact designed by the Brace Research Institute (Anon 1973) many years ago using halves of oil drums for rotor buckets. Though this work indicated that a moderate efficiency of about 15% was attainable by such a rotor, the windmill itself was too small to be generally useful. Being related to the sizes of oil drums, the above rotor cannot be easily scaled up. It was therefore decided to design a rather larger windmill using fabric for the rotor surfaces.

Some wind tunnel experiments (Govinda Raju *et al* 1976) were first conducted on small Savonius-type rotors of 100 mm diameter to study the effect of the end plates and the bucket shape on performance. The results of some other test programmes on this class of rotors have also recently become available (Shankar 1976, 1979; Manser & Jones 1976; Blackwell *et al* 1977).

To test the feasibility of sail-type construction a windmill of about 0.2 m² sail area was first fabricated. Here, the sails were supported by wires strung between end plates fixed to the shaft. Tests in the 14 ft × 9 ft wind tunnel at the Indian Institute of Science showed that the scheme was feasible and gave satisfactory performance.

Two windmills, designated prototypes 1 and 2 respectively, each of roughly 8 m² projected sail area, have since been designed and fabricated. They are largely similar, but prototype 2 uses a slightly different sail profile and rotor support structure. The descriptions to follow apply to both with the differences noted.

4. Support structure for the rotor

Each windmill consists of two A-frames spaced apart by two connecting beams with the rotor supported between the beam centres. The lower parts of the A-frames are triangulated by diagonal members. Guy wires are used to add strength and stiffness to the structure. Figure 1 (Plate 1) and Figure 2 show the details of prototype 2. Both prototypes utilise the same structural concept, but the sizes of members are different. The first prototype used cut timber of 5 cm × 10 cm nominal size and boards of 2.5 cm nominal thickness. The second prototype uses casuarina poles. These poles were obtained by felling and trimming standing trees, purchased near the erection site. The trees were 20 to 25 cm diameter near the base tapering to about 15 cm diameter at a height of 10 m. All joints in wood are by mild steel bolts of 12 mm diameter. The guy wires are made of galvanised mild steel of a commercial grade.

The support structure receives the forces exerted by the rotor at its bearings. These forces have a significant periodic component with the period corresponding to the rotational speed of the rotor. To avoid excessive vibrations, the natural frequencies of the structure must be sufficiently above the frequency corresponding to maximum expected rotor speed (around 100 rev/min). The observed frequencies of the structures were 160 cycles/min for prototype 1 and 250 cycles/min for prototype 2 and are thus adequately above the rotor revolutions per minute. (These frequencies were obtained by counting the resonant oscillations of the structure excited by pulling periodically on a length of rope tied to a suitable part of the structure.)

Experience shows that the natural frequencies of structures considered above are strongly dependent on the flexibilities at the joints between various members. The frequencies given above were obtained with good matching at the lap joints in the structure, the bolts and turnbuckles being tight. Looseness of bolts or guy wires reduces the frequencies alarmingly and hence due care is necessary in making joints and in keeping the bolts tight.

5. The rotor

The rotor, based on the Savonius type indicated in § 3, consists of a vertical shaft in the form of a galvanised steel pipe with suitable welded end fittings; the shaft is supported by a simple self-aligning brass bush at the top and by a ball bearing at the bottom. The bottom end of the shaft can carry a brake/power-take-off drum and an end-crank for driving a pump.

Near the ends of the shaft are welded fittings to which can be bolted wooden end plates of built-up construction using planks of 12 mm and spars and ribs of 25 mm nominal thickness. As shown in figure 3, these end plates each have a central structural part to resist loads exerted by wires strung vertically between them. Extensions to the central parts in the form of plywood sheets supported by ribs complete the end plates. Bamboo matting may conveniently replace the plywood sheets and this possibility will be tried in the future.

The wires strung between the end plates (16 in all) form the support system for the two sails of jute canvas which form the aerodynamic surfaces of the rotor. The wires

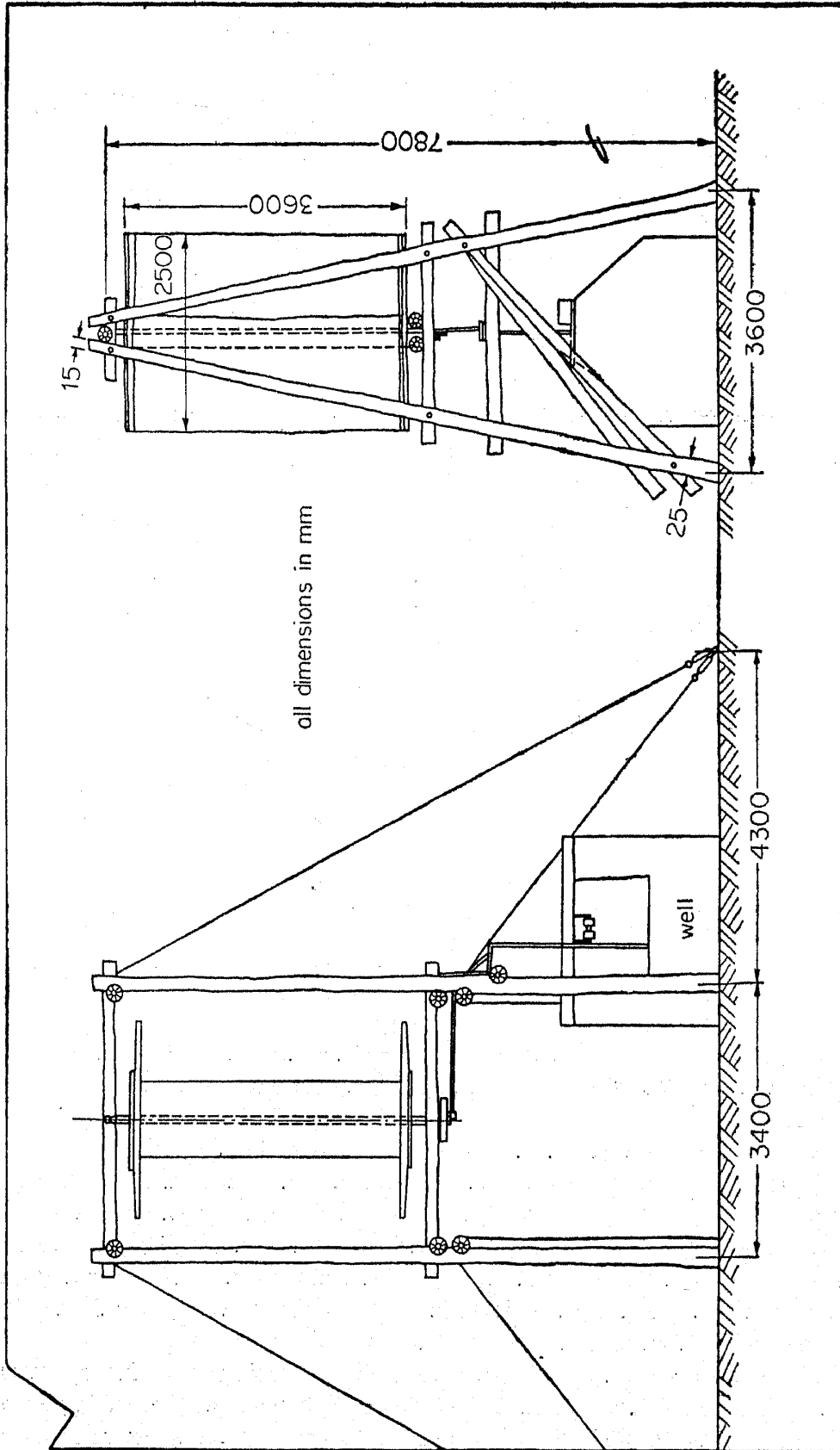


Figure 2. Configuration and major dimensions of prototype.

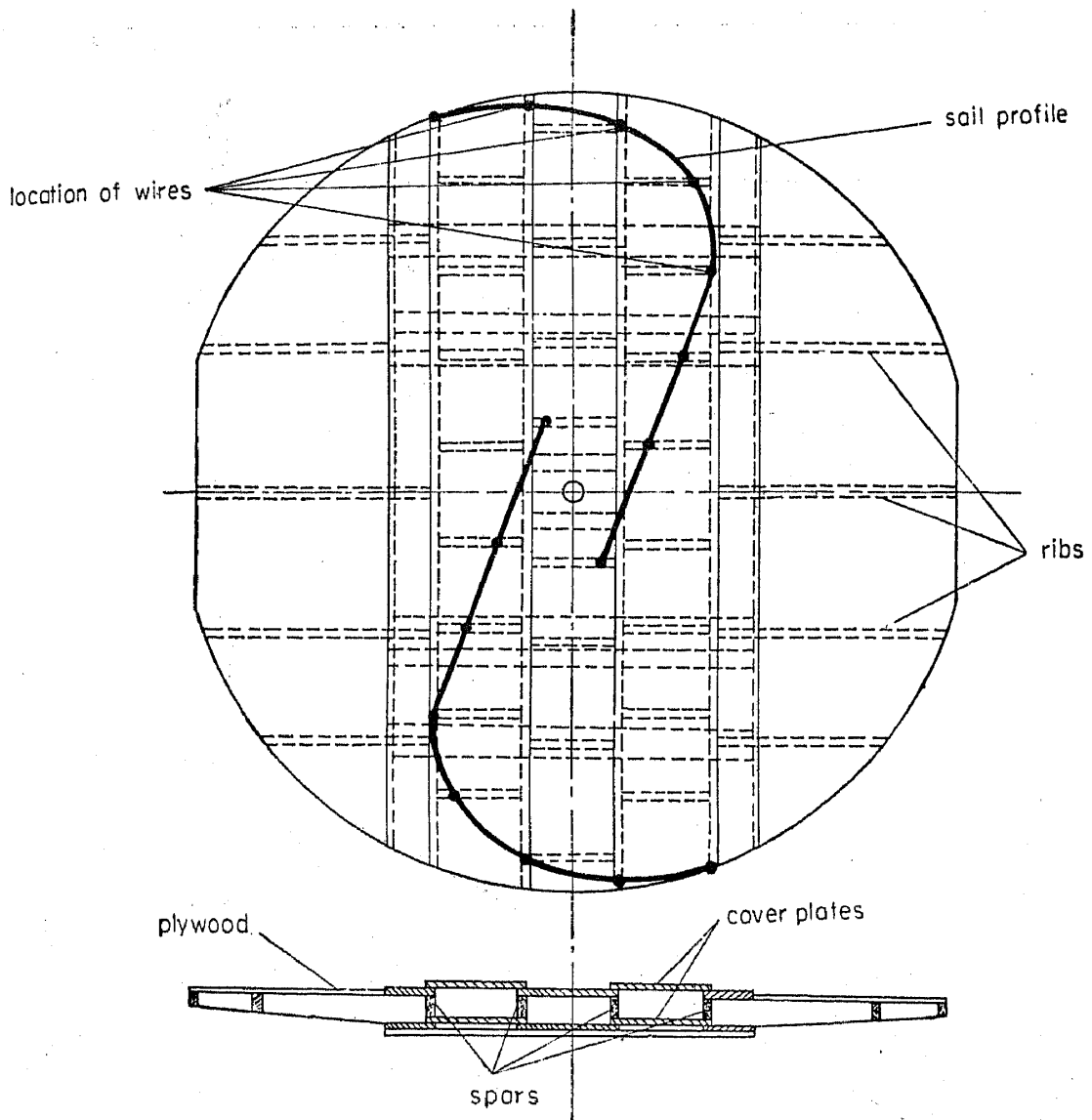


Figure 3. End-plate assembly, showing also sail geometry.

pass through ribs in the end plates from one side and are clamped on the other side. During installation, the wires are so clamped that there is a play at their midpoint of about 15 cm.

The sails of jute canvas are attached to the wires by threading the wires through loops stitched to the canvas. Each sail incorporates a total of five loops, four for the first four wires counting from the leading edge and the last one at the trailing edge. This leaves three wires touching but unattached to each sail. Skirts, about 10 cm wide at the edges near the end plates, provide a seal there and allow for any errors and/or shrinkage of the fabric after installation. After installation, the sails and skirts are painted with coal tar to make them weatherproof.

The above scheme of attaching sails to their supporting wires incorporates an important element of safety in excessive winds. The wires at the trailing edges of the sails incorporate twisted joints just below the top end plate as shown in figure 4. Each twisted joint unwinds at a definite and predictable tension in the wire and in the event of this happening in a high wind, the corresponding sail opens out, being in

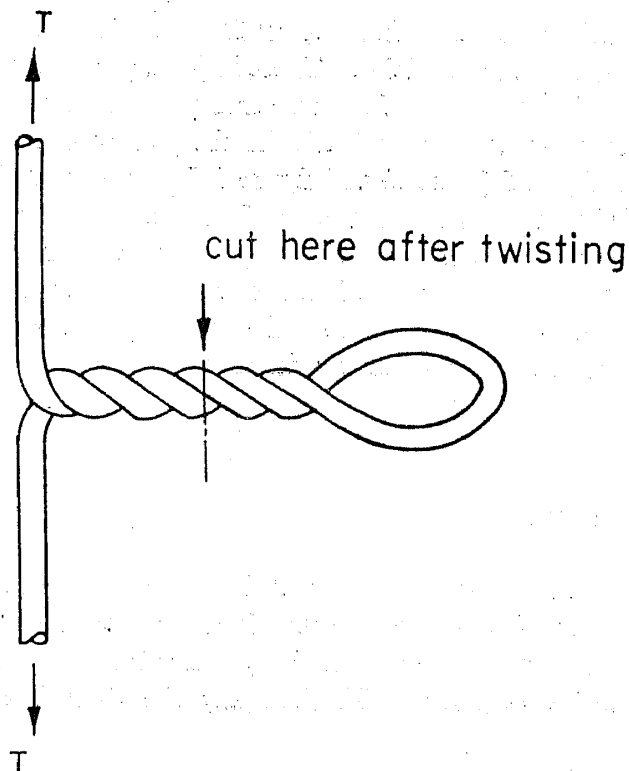


Figure 4. Safety wire.

that case held only by the four wires near the leading edges, thus reducing the rotor speed as well as unloading the structure. The scheme has worked well in actual practice.

6. The pump

One of the major uses of the windmill is expected to be lifting water from wells for domestic use or for minor irrigation. In such applications, the head against which water is to be lifted is generally 3 to 15 m with seasonal variations of 5 m. For this type of application only positive displacement pumps appear suitable because they can be directly coupled to the windmill and can be adapted to varying head conditions easily. It may be noted here that one or more of the well-known devices for lifting water (like the Archimedean screw, chain and bucket elevator, persian wheel etc.) can be used for this type of duty. But they appear non-competitive in comparison with the pump designed here.

Among the positive displacement pumps, the one suggested by Papanek (1972) appeared to be particularly suitable in the present context. The pump consists of the casing of a pneumatic tyre blocked by two discs (one at each bead) thus creating an enclosed volume. Relative displacement between the discs changes the enclosed volume and can be used as the pumping chamber of a positive displacement pump by adding a pair of non-return valves and pipes. Because the pneumatic tyres are generally designed for operation at an internal pressure of around 2 kg/cm^2 which corresponds to about 20 m of water, a pump using tyre casing can be used to pump against a head of up to this height.

Available pneumatic tyres range from about 35 cm in diameter for small scooters to more than a meter on heavy vehicles. These imply a pump displacement of about 1 litre per cm of stroke for the smallest tyre and progressively more for the larger sizes. The smallest tyre was found suitable for the present application and a pump using it is shown in figure 5 (plate 2) and figure 6. It is seen that the relative motion between the discs is imparted through a lever of ratio about 10 to bring the forces in the transmission between the windmill and the pump to a comfortable level.

For use with the windmill, the pump incorporates an unloading device in the form of a small leak and a check valve in the delivery pipe just after the delivery valve. This eases starting of the windmill as it reduces the torque demand of the pump at low rotor speeds.

7. The power transmission

The windmill power take-off point which is at the bottom of the rotor is typically 4 m above the ground level while the level of water in an open well is typically 10 m below ground level. The pump, whose suction is typically limited to 3 m, is thus to be located not much above water level. Horizontally, the windmill shaft is about 2.5 m

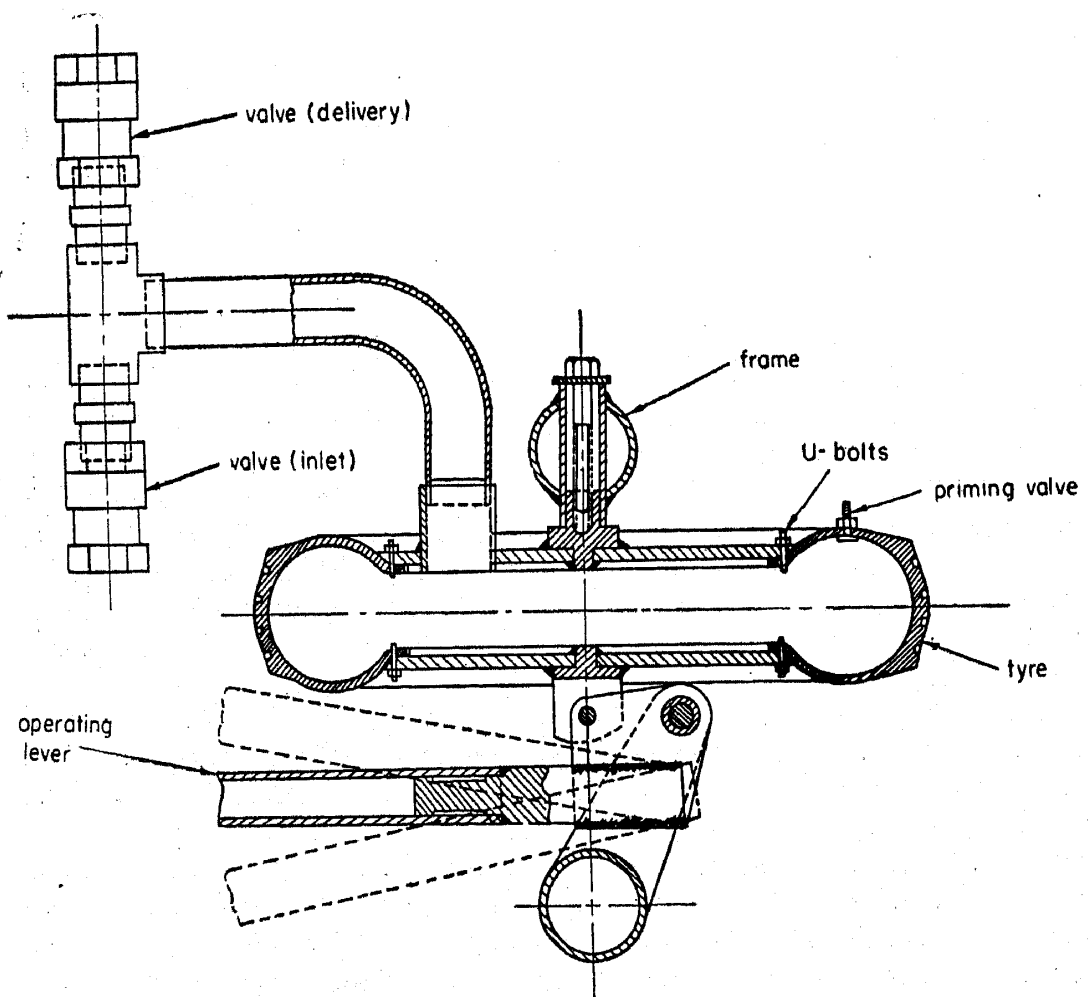


Figure 6. Cross-section of pump.

removed from the nearest point of the well. The transmission, which has to handle the problem of conveying power from the rotating shaft below the rotor to the oscillating pump operating lever at the pump, has thus to convey power over a distance of 15 m or more.

The transmission adopted is schematically shown in figure 7. It consists of a variable arm end crank at the shaft and a bell crank at a position vertically over the pump operating lever and horizontally at the level of the end crank. A connecting rod, with a ball bearing at one end and a ball-joint at the other, connects the end crank and the vertical leg of the bell-crank. An operating rod (roughly 11 m long in the second prototype), in the form of a GI pipe of 12 mm nominal size, connects the horizontal leg of the bell crank and the pump lever. Two supports, in the form of wooden blocks with holes drilled for the passage of the rod, are located at two points along the operating rod to prevent induced oscillations and /or buckling of the operating rod. Also, it is arranged so that the delivery stroke of the pump corresponds to a tensile load on the operating rod so that compression in the rod (corresponding to suction) is small.

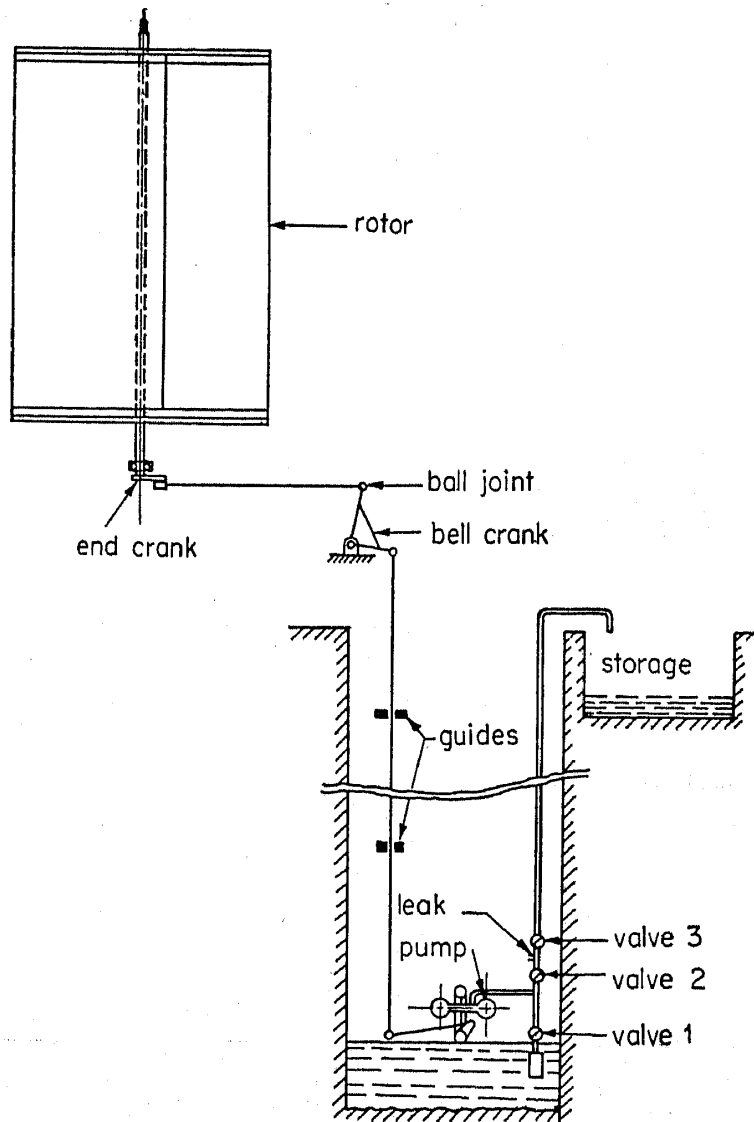


Figure 7. Schematic layout of wind-pump at Ungra.

8. Performance

The performance of a windmill-pump system depends on the individual characteristics of the windmill and the pump. The characteristics of a positive displacement pump can be analytically worked out to fair accuracy using data on hydraulic losses (Davies 1969). The characteristics of Savonius-type rotors are known fairly accurately and it is possible to estimate the performance of the wind-pump for any given combination of wind, head of water and pump displacement.

Such estimates of performance of the wind-pump of present design indicate the following. For a given head of water and pump displacement, there is a minimum windspeed below which steady operation is not feasible. As the wind speed rises above this value, the rate of water pumped increases rapidly at first and more slowly later. The efficiency of the system (defined as the ratio of the useful power delivered in lifting water to the power available in the wind crossing the rotor) is zero below the minimum speed, rises rapidly with further increase of wind-speed, reaches a maximum and then decreases monotonically. Thus it is possible to extract energy from the wind efficiently only over a narrow band of wind-speeds; and therefore careful adjustment of the pump displacement (i.e. stroke) is needed to maximise the water delivered for any given wind spectrum. For this reason, the present design incorporates a variable arm crank at the windmill to facilitate changing the pump stroke, which may be done from time to time to cater to changing wind and/or head of water. Figure 8 shows the performance of the first prototype windmill as estimated and as

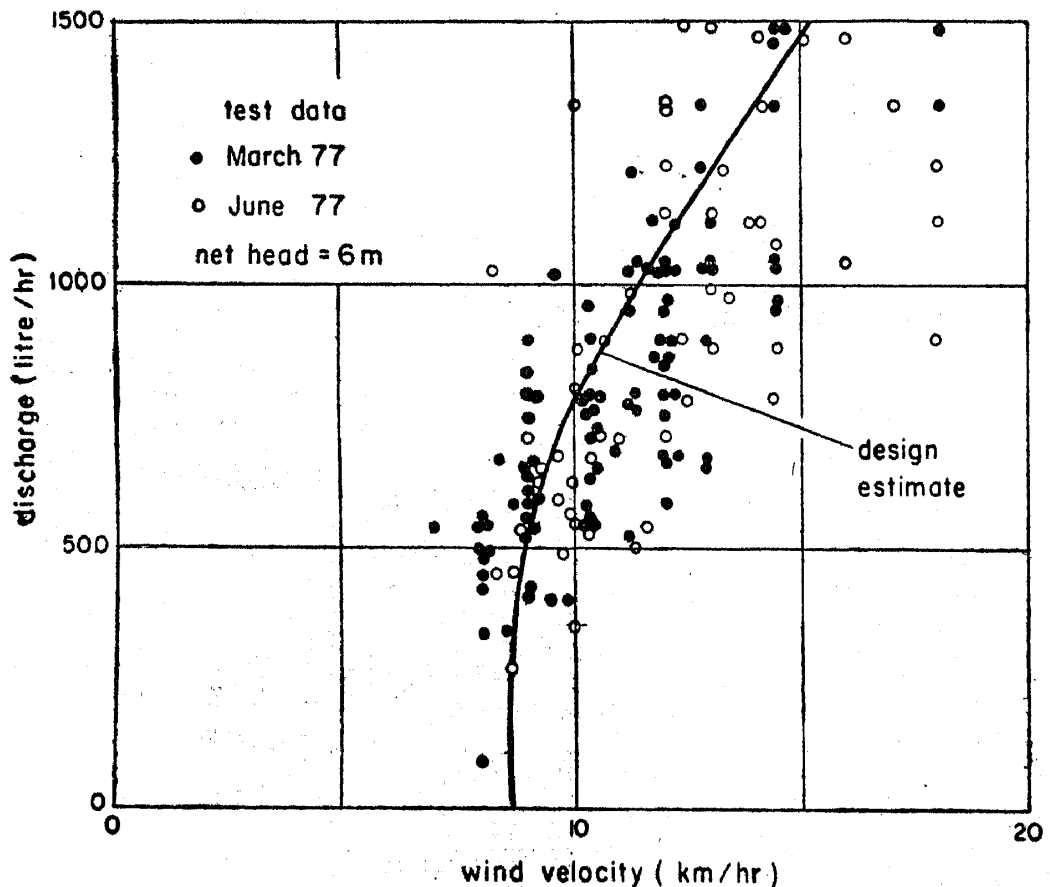


Figure 8. Performance of IISc windmill (prototype 1):

measured for one value of pump stroke and head of water. There is some scatter in the measurements because it was not possible to obtain perfectly steady conditions during the tests. However, the agreement between the estimates and measurements is seen to be satisfactory, indicating that design estimates can be relied on for any other stroke and head of water.

It can be noted here that, for the conditions represented in figure 8, the best efficiency of the system is about 12% at a windspeed of 10 km/hr. As indicated earlier, this efficiency is sustained only over a narrow windspeed range and there is a rapid fall-off with increase of windspeed. For example, the efficiency at 16 km/hr is only 6% and consequently the net pumping power is only 25 W. By an increase of pump displacement, the same system can deliver a net power of up to 40 W at 16 km/hr; but this will lead to a higher starting speed and reduced utilisation of lower winds. Thus, an optimal variation of pump displacement with windspeed over a range can result in a substantial increase of net energy output besides improving starting performance. Manual setting of crank arm to achieve this is not fully satisfactory because of the frequent attention such a scheme calls for. At present, an automatic variable arm crank to effectively do this, at a first cost of only a few hundred rupees, is being designed, and this device when installed is expected to yield a substantial increase in the output of the windmill-pump combination.

9. Field experience

The second prototype, constructed at the village Ungra (about 100 km from Bangalore), has been in operation since September 1977. The system has been delivering an average of around 2500 litres of water a day since that date. The problems of maintenance have been minimal. Apart from lubricating the rubbing parts, bolts and nuts had to be checked and adjusted occasionally for tightness because the timber frame has undergone some shrinkage. The rotor had to be lifted up (by using packing pieces at the supports) by a total of about 5 cm to take up the sagging of the support beams during the above period. The safety wire successfully operated thrice during this period and was reinstalled after every operation. During each operation of the safety wire, the windspeed exceeded 40 km/hr and the rotor was running on load. However, over the year, the sails of the windmill have been damaged. The damage is primarily due to the tears sustained by the sails when the safety wires snapped during development and during regular field trials. Recently, new sails, including rip stoppers and a slightly modified sail support system, have been installed.

Now some remarks about the durability of the windmill are in order. The largely metallic parts of the windmill including the mainshaft, the transmission and the pump appear to be in perfect condition after about one year of operation, and there should be little difficulty in their operating for several years more. The parts which employ solid wood—including the tower, which is unprotected, and the structural parts of the endplates, which are protected by a coat of coal tar—have shown little degradation, and a life of many years may be expected from them. The extensions to the end plates, which are of a weather-resistant type of plywood coated with coal tar, appear to be quite sound and a life of at least three years may be expected of them. Also, it may be possible to replace them later by inexpensive woven bamboo

matting. The sails of jute canvas, as mentioned already, had to be replaced within the year because of too many tears. With the improvements already incorporated, a sail life of upto two years may be achievable. The possibilities of using other materials for the sails to get a longer life are being considered.

10. Costs

The prototype windmills considered above were designed and constructed to establish the feasibility of building a windmill based on the novel sail-type Savonius rotor and using a comparatively low technology. Though costs have been held quite low, it is expected that they can be reduced further by careful redesign of components and optimisation of the geometry of the windmill. However, as an indication of the present state of development, table 1 gives a rough break-down of the costs incurred on the second prototype, which is shown in figure 1.

It may be noted here that the cost of a windmill of this type could be substantially lower than indicated here if built by the villagers themselves because they can procure timber more cheaply; and labour cost need not be accounted at the market rate if it is obtained on a mutual help basis. Many villagers who have seen the windmill have felt that the system would cost them only Rs. 2000.

11. Conclusions

It has been shown how a soft design, largely using materials and skills available in most Indian rural areas, could extract a reasonable amount of power from the wind for water pumping, at a first cost substantially lower than that of other designs with a comparable rating. Based on experience todate, it is felt that achieving a satisfactory life and scaling to larger sizes will not pose serious problems. Thus, this design appears to merit further study for use in a rural setting.

Table 1. Cost break-down of windmill and pump installation.

Item	Cost (in rupees)		
	Material	Labour	Total
Tower, including erection	350	250	600
Foundation	130	70	200
Rotor end plates, including painting	390	160	550
Sails with painting	120	80	200
Shaft, bearings, sail support wires and fittings	260	220	480
Pump	260	120	380
Transmission	190	90	280
Plumbing	150	—	150
Installation of rotor, transmission, pump and plumbing	—	150	150
Total	1850	1140	2990

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THE HISTORY OF THE UNITED STATES

The first part of the book is devoted to the early history of the United States, from the discovery of the continent to the establishment of the first colonies.

The second part of the book is devoted to the history of the United States from the establishment of the first colonies to the present time.

The third part of the book is devoted to the history of the United States from the present time to the future.

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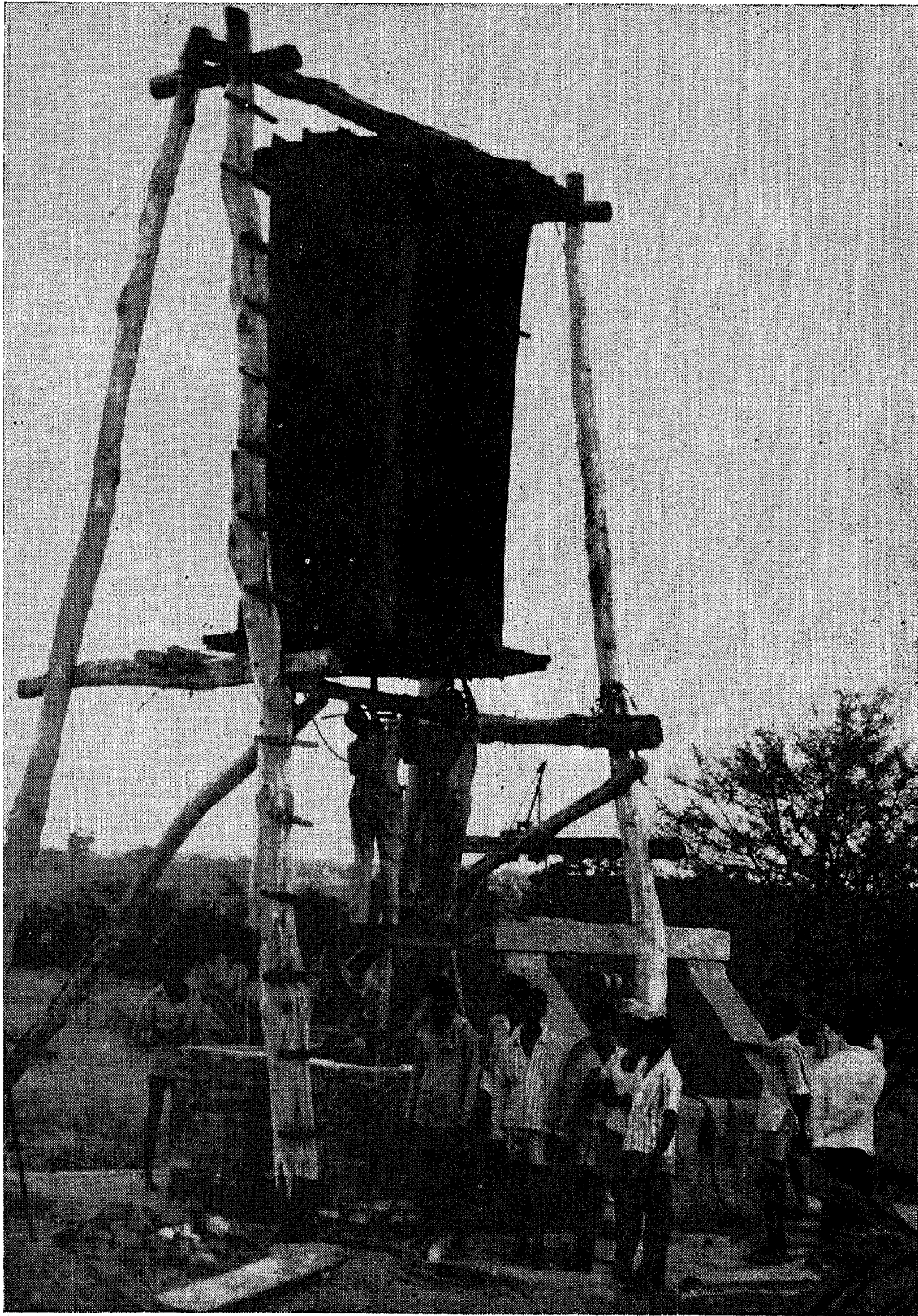


Figure 1. The windmill of the Indian Institute of Science (prototype 2), as set up at Ungra (Karnataka State).

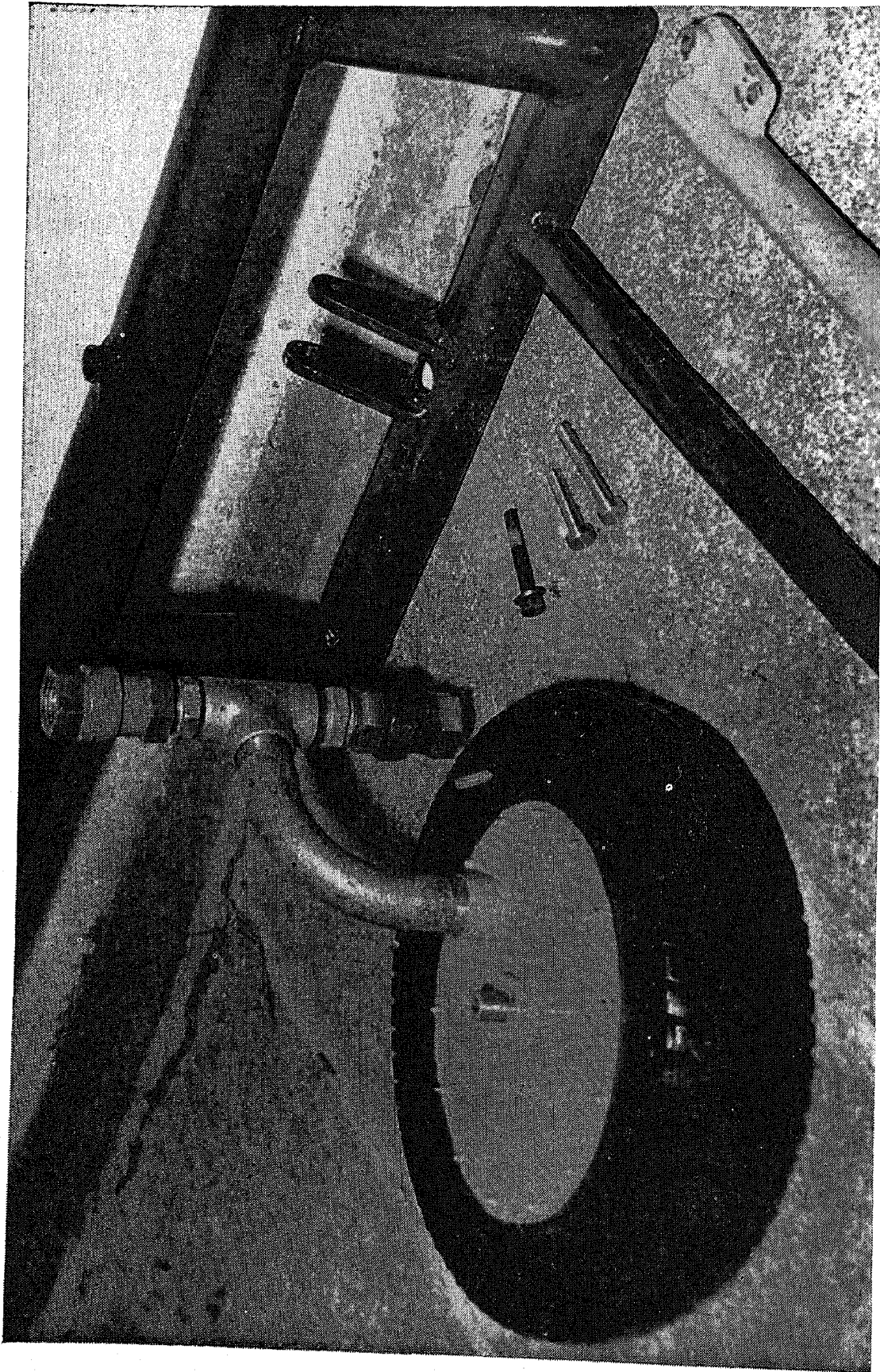


Figure 5. The tyre-pump.