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A Low Head Turbine for Microhydropower

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ABSTRACT

A low head propeller turbine of simplified construction is described. The electrical power output from the generator is 3.7 kW, 230 V, 50 Hz, single phase from a turbine head of 2.8 m. The equipment was designed and installed to match the domestic needs of a typical isolated, one-family New Zealand farm house. The geometry of the machine, the controls, the civil works and the experiences of a year's operation are described.

INTRODUCTION

As the name implies, microhydropower embraces hydroelectric power generation on a very small scale. The exact size range is not defined but customarily includes all sizes of installation up to about 100 kW. They can be autonomous or they may feed into an electricity supply network. There are various ways of classifying the schemes within this size range and one classification is concerned with the justification for professional supervision. Many aspects of hydroelectric schemes are complex and require expert knowledge to design and to supervise the construction so that they may be effective and safe. The cost of this professional involvement becomes excessive as the schemes become smaller and, generally speaking, precludes this approach for the supply for only one family. Another classification concerns ownership. This distinguishes the very small privately owned scheme, where the initial capital cost is of prime importance, from the small corporately owned community scheme, where a long term approach to the method of financing can be taken.

MICROHYDROPOWER RESEARCH AT THE UNIVERSITY OF CANTERBURY

Over recent years, a continuing research programme at the University of Canterbury has been concerned with the problems of establishing a suitable technology to enable any remote one-family farm, with a suitable water resource, to have its own individual microhydro scheme. The objective has been to produce a set of designs in which each one (a) is a properly engineered system requiring no further professional involvement in the installation and (b) has a cost of the energy produced that compares favourably with any of the alternatives.

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Standardisation has helped in this work. The only variations between different sites are in the civil works and the type of water turbine. The generator has been standardised together with the control and protection equipment. The standardised output is 5 kW, single phase, 50 Hz from a 2-pole brushless synchronous generator and the control of frequency is effected with an electronic load-diverting governor and dummy load bank. A disc flywheel is matched to the electronic governor. Both the normal and emergency stopping procedures are by a caliper brake that operates on the flywheel disc and brings the equipment to rest and holds it stalled without interrupting the flow. The generator is sized for a power factor of 0.8.

The programme has developed a set of solutions for the medium head range using centrifugal pumps in the reverse mode as water turbines [1,2]. A study at present proceeding in the Mechanical Engineering Department of the University of Canterbury is developing a small Pelton wheel for the high head range of operations. This paper describes a simplified low head turbine that has been developed, under the same auspices, to explore solutions for the low head range [3].

The design philosophy was to match the technology to the capabilities of rural commercial and industrial resources and the needs of remote farming areas in this country. Remoteness usually means many kilometres from assistance and, for that reason, the installation needs to be extremely reliable with maintenance and repairs as far as possible within the means of the consumer. Private financing implies that the initial cost is of prime importance and the challenge is to minimise costs without compromising the quality of the complete system. The design approach has been to use the best of technical resources to produce the simplest of solutions. It is hoped that the technology will, in due course, be transferable to sites in developing countries.

LOW HEAD TURBINES

The classical approach to turbine selection is to use a machine of the highest practicable specific speed. This leads to the smallest and fastest machine. For the low head application, the result would be an axial flow machine – a turbine based on the propeller. The Kaplan turbine is discouragingly complex in shape and the axial flow pump, which suggests itself in the reverse mode for this application, is not readily available in this country. The cross-flow turbine tends to be favoured for its simplicity but, being an impulse turbine and not a reaction turbine, runs relatively slowly with the consequent transmission problems involved in increasing the speed to a synchronous generator speed.

THE SIMPLIFIED LOW HEAD TURBINE

Selection

One of the advantages of the method of governing – using the load-diverting governor – is that the turbine runs at constant load and this obviates the need for any adjustable guide vanes or a feathering propeller. For these reasons it was decided to opt for a simple, vertical shaft, propeller turbine. This arrangement also complied with another design constraint that the turbine could easily be opened up for maintenance purposes by the owner.

Simplicity was taken to mean a design that could be produced in relatively unsophisticated workshops and, most importantly, could be maintained and serviced with typical farm facilities. A site was available to prove the design and the owner was enthusiastic to support the project. The design was evolved from first principles but the simplified shapes meant there was a limit to the appropriateness of the existing theory or experience curves and much of the development had to be done experimentally.

Description

The turbine that was developed, built, installed and operated is a vertical shaft propeller turbine as shown in cross-sectional elevation in Fig. 1, with the plan of the guide vane assembly superimposed on the tripod stand.

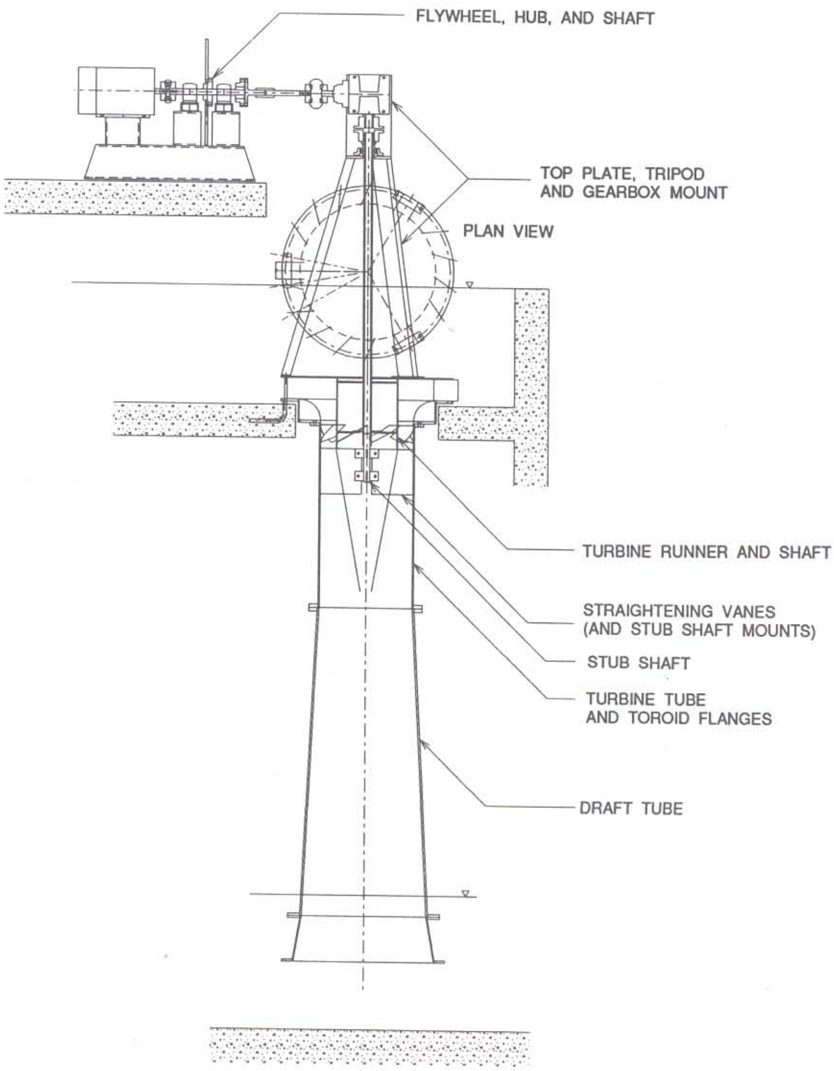
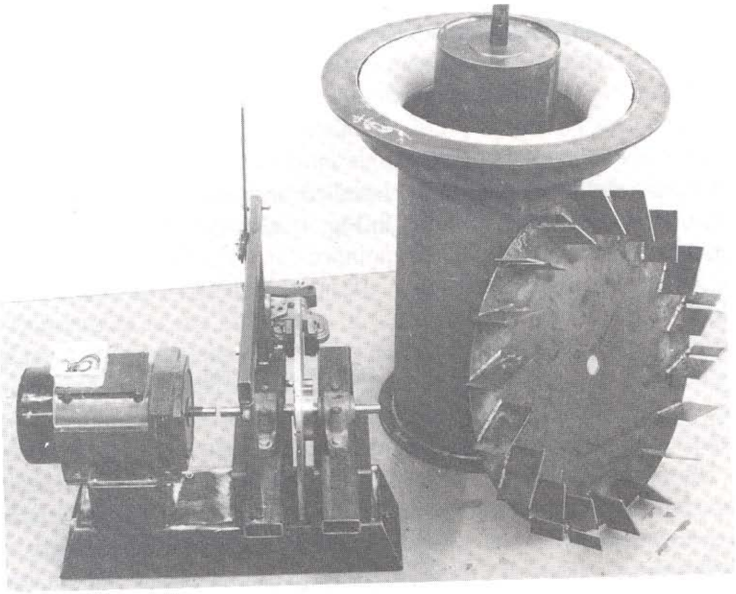


Fig. 1. General arrangement of turbine, transmission and generator.



The photograph shows on the left the generator/flywheel/brake assembly and on the right the turbine tube with propeller installed and the guide vanes. The gearbox, tripod and conical draft tube are not shown.

The turbine head and available discharge were decided by a site survey. The head is 2.8 m with a discharge of approximately 400 L/s, the turbine shaft speed 612 rpm, the electrical output is 3.7 kW. The efficiency of the installed turbine has not been measured due to a lack of resources to measure the discharge and torque. The model performance gave a maximum efficiency of 57% and an efficiency at the best power point, for the same head, of 50%. The turbine was designed to operate at the best power point and, for manufacturing reasons, shows small departures from the model geometry. Further development work to increase the turbine output power but retain the simplicity is continuing.

The turbine was built of mild steel sheet. It has no inlet scroll casing. It has a flat upper surface to the vortex chamber and a cylindrical hub. The guide vanes are straight and vertical and inclined at 30° to the radius. The 8 propeller blades are cut from flat sheet and arranged as described in detail below. The draft tube is parallel, in the vicinity of the propeller, and is fitted with flow straightening vanes which also support the lower shaft bearing and a fixed conical streamlining below the rotating hub. Below this section the draft tube itself (salvaged from another application) is conical.

The upper bearing is supported clear of the water by a tripod and comprises a self-aligning ball thrust bearing. The lower bearing is a water lubricated rubber journal running on a stainless steel sleeved stub shaft with the lubricating water being supplied from the head water through the hollow shaft.

The right-angle, speed-increasing gearbox increases the shaft speed from 612 rpm to 3000 rpm. A hoist is provided to lift the assembly comprising the gearbox, tripod, guide vanes, shaft, propeller and rubber journal for maintenance purposes.

The leading dimensions are as follows:-

Guide vanes – 18 vanes, outer diameter 860 mm, inside diameter 590 mm, height 95 mm, set at 30° to the inner radius.

Runner – hub diameter 270 mm, tip diameter 408 mm, 8 blades with straight radial leading and trailing edges, 3 mm thick.

Draft tube, cylindrical section – 410 mm diameter, 820 mm long; conical section – inlet diameter 410 mm, outlet diameter 600 mm, length 1470 mm, bottom floor clearance 200 mm.

Water depths – inlet 500 mm, outlet 300 mm.

The dimensions were optimised in the laboratory with the use of a scale model with a linear scale ratio of 1:2.38. A clear plastic draft tube enabled flow visualisation. Some uncertainty is associated with the measurements of the model power, which was very small for the size of dynamometer available, and difficulties in assessing the model transmission losses also contributed to this uncertainty.

Propeller Blade Geometry

The design of the propeller blades took advantage of the properties of the intersection of an inclined plane with a vertical cylindrical annulus.

Consider the intersection of an inclined plane with a vertical circular cylinder. The line of intersection is an ellipse. Consider the tangent to this ellipse and the angle that this tangent makes with the horizontal. It is to be noted that this angle varies with position around the ellipse. It is zero at the highest and lowest points of the inclined ellipse and a maximum, equal to the angle of the inclined plane, at the half height of the ellipse.

The propeller blade, cut from flat sheet, lies in the inclined plane and the cylindrical annulus is the space between the cylindrical hub and the cylindrical draft tube. By this means, the blade is effectively "curved" with respect to the flow through the turbine. The blade inlet was set at the point of maximum slope, i.e. the inlet blade angle was the same as the angle of the inclined plane, from which it followed that the blade outlet was set at a point of reduced angle. This enabled the inlet angle of the blade to be set by adjusting the slope of the inclined plane and the outlet angle of the blade to be set independently by adjusting the length of the blade.

Correctly, the blades of a propeller turbine reveal 3-dimensional curvature or twist. This was ignored with the consequent misalignment of the flow along the leading and trailing edges of the blades. It was expected that this would lead to secondary flows and shock losses. Examination of the flow, in the perspex model used to develop the turbine, suggested that the propeller worked better than might have been expected. Figure 2 shows the propeller design.

For a plane inclined at 30° to the horizontal, Fig. 3 shows how the blade angle varies with the angle subtended at the centre of the ellipse in the plane of the ellipse from the leading edge of the blade when this is located at the point of maximum slope. It is noticeable, in Fig. 3, that the blade angle is less sensitive to variations in the subtended angle at the leading edge of the blade, when the subtended angle approaches zero.

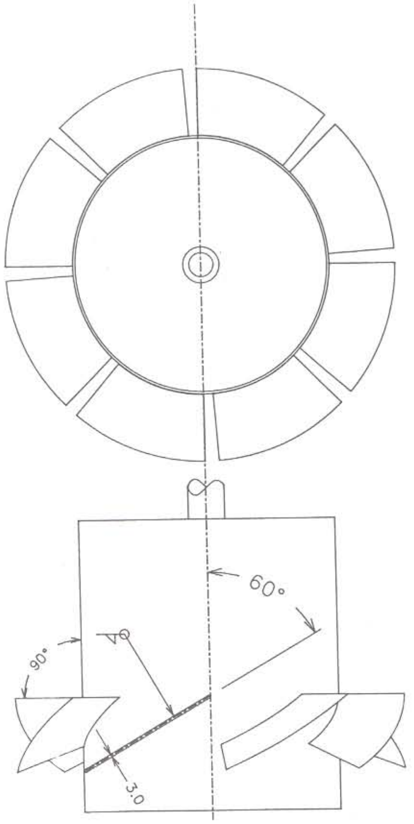


Fig. 2. Plan and elevation of the 8-bladed propeller.

Operational Experiences

Leaves

In practice it was found that the performance of the turbine was seriously affected by the small leaves suspended in the flow. The most common leaves were beech, about 40 mm in diameter, but other leaves and stalks occurred from water-cress. It seemed that the leaves wrapped themselves around the leading edge of the blade and so upset the flow that the output would gradually drop to about 30%. There were sufficient leaves to make their removal by the cleaning of passive screens impracticable – it would have meant cleaning at hourly intervals, at times of heavy leaf transport. The provision of automatic rotary screens was considered to be undesirably complicated. Clearing was simple – the machine was stalled and restarted. The disturbed flow, with the propeller stalled, cleared the leaves. However, the gradual unpredictable reduction in output and the interruption of the power supply for leaf clearing were unacceptable.

A solution was found by adding a blade extension in the plane of the blade, in the form of an equiangular spiral with a constant angle of 60° to the radius, to the leading edge of the blades. Conveniently, this was situated in the location where the blade angle varies little with the sub-

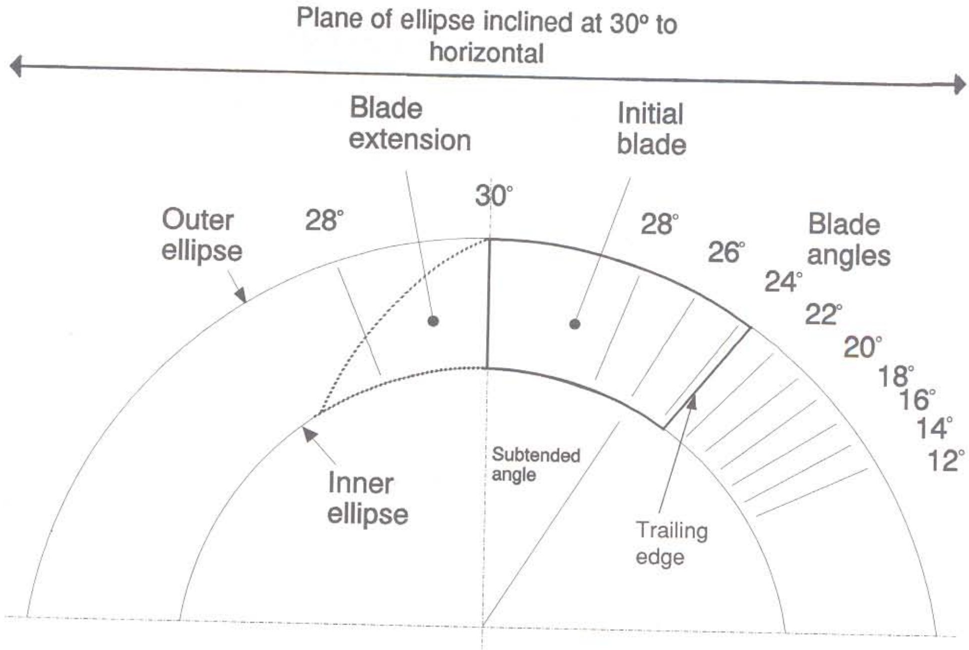


Fig. 3. The shape of the flat blade in the plane of the blade.

tended angle of the blade. This has effectively prevented the leaves from lodging on the leading edge and has obviated the need for removing them by screening. The machine now passes the leaves with no loss in power and only coarse screening of the flow is necessary.

Operating Point

One field test for the performance of a water turbine is to measure its runaway speed. The point of maximum efficiency is expected to occur at about half the runaway speed and, in the case of a propeller turbine, the maximum power point is expected to occur at about 60% of the runaway speed. In this case, the point of maximum power is required to occur at 612 rpm which would give a runaway speed of about 1020 rpm. The measured runaway speed is about 910 rpm which suggests a reduction in blade angle is necessary. This can be done by simply changing the length of the blade, to adjust the outlet angle, or changing the slope of the inclined plane to change the inlet angle.

It is seems that the conventional methods of calculating blade angles are not good predictors of the required blade angles for this particular flat blade case and the adjustment to the blade angle to improve the runaway speed, and hence efficiency, will be dealt with largely empirically.

Inlet Geometry

In the interests of simplicity of construction and ease of withdrawing the turbine for maintenance, no inlet scroll casing was provided. The turbine is mounted centrally in a rectangular forebay with no special provisions to direct the flow into the guide vanes. The excess flow over the spillway, to maintain a constant inlet water level, passes over the turbine. There was a tendency for air-entraining vortices to occur but these were controlled by simple wooden baffle posts.

It is assumed that flow separation will be taking place off the relatively sharp entry provided by the flat top to the vortex chamber. Further attempts will be made to improve the flow geometry at the entry.

LOAD MANAGEMENT CONTROLS

The installation is now operating continuously providing 3.7 kW with very little need for attention. The consumer load management equipment monitors the load being used by the consumer and sounds an audible warning if an inadvertent overload occurs. It allows time for the consumer to reduce load to within the limit before isolating the consumer from the supply if no action is taken. This approach avoids nuisance tripping of the generating plant and is quite acceptable to the consumer.

CIVIL WORKS

The general arrangement of the civil works is shown in Fig. 4.

The river level at the position of the intake can vary in excess of 1 metre, from low flow to high flow. Consequently, the inlet structure was designed to make the flow relatively insensitive to variations of inlet river level by providing a submerged rectangular orifice with the opening area manually controlled with vertical stoplogs. These were arranged in a hit and miss fashion across the opening and served as a coarse primary screen. This was an inexpensive and effective control process. The kinetic energy of the discharge from the orifice was controlled by energy dissipating baffles and blocks.

The flow had to pass through a culvert under the road and the capacity of the culvert placed a restriction on the maximum discharge. A control structure, similar in design to the inlet structure, was provided to protect the culvert. A side spillway obviates any risk of the road being washed away due to flows exceeding the culvert capacity. The canals were excavated by digger and, although the material was coarse alluvially deposited gravels, it was found unnecessary to line the canals. The power house was designed with sufficient weight to resist the forces of the backfilling and was fitted with drain-holes in the walls to prevent any additional hydrostatic loading due to seepage.

COSTS

It is difficult to be specific about a representative overall cost because, in this case, part of the costs were inflated due to the development work but the general impression is that, taking all factors into account, the cost of energy supplied would probably be less than for a diesel electric alternative over which it has a number of advantages. Firstly, it operates continuously whereas diesel sets are usually operated for only a few hours each day to control fuel costs. Secondly, it is quiet in comparison with the diesel engine.

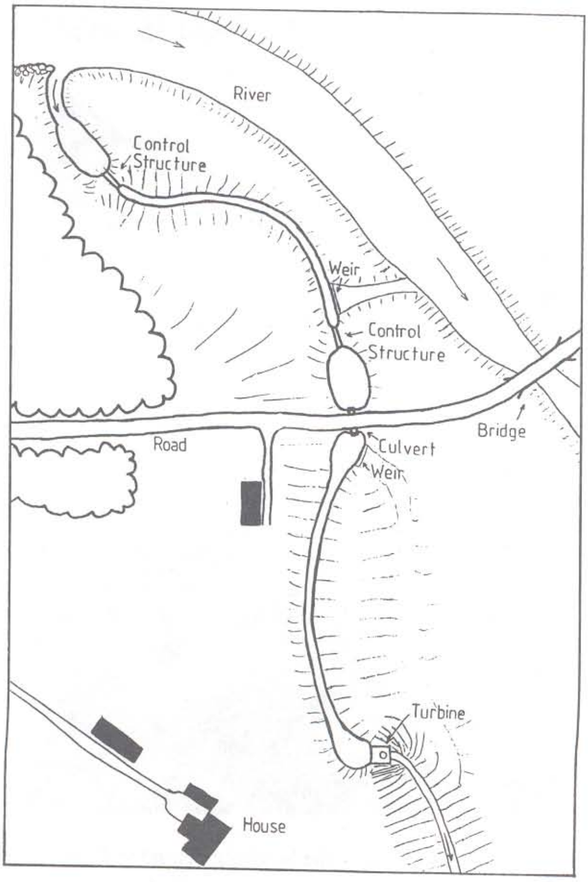
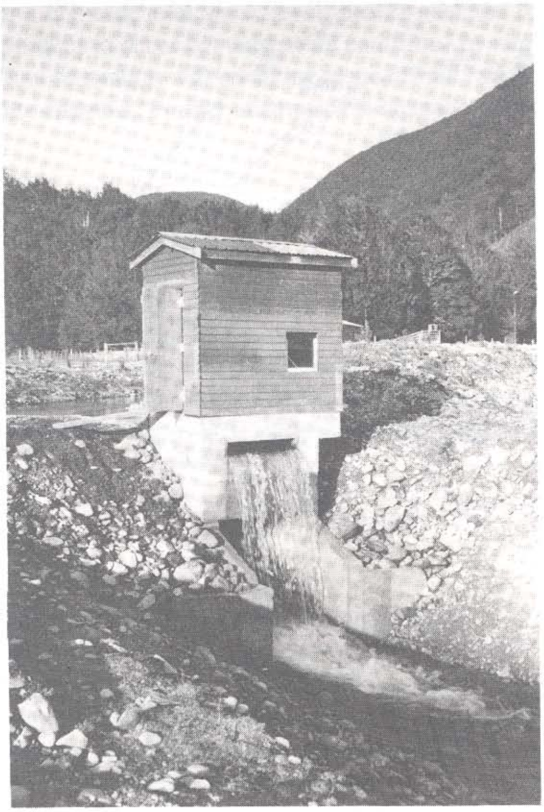


Fig. 4. Outline plan of the site.

The average domestic power needs of a New Zealand one-family home are equivalent to about 1.5 kW continuously. Normal brief peaks of up to about 12 kW can be expected and minimal consumption occurs for extended periods particularly at night. A realistic size of microhydropower scheme, operating at constant full load, is considered to be no more than 5 kW. This, together with provision for managing the connected load, is generous in average terms and sufficient when used in conjunction with demand-side load management. This particular system has now been operating for a year and measurements have shown that the useful consumption has been approximately half the energy generated, i.e. an average of 1.8 kW from a 3.7 kW supply, and the upper limit of 3.7 kW has proved to be adequate although a larger output would be preferred.



The photograph shows the power house with the headrace behind and the tailrace in the foreground. The excess flow to control the upstream water level is seen discharging to waste from the spillway.

ACKNOWLEDGEMENTS

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