Case Study – Lydia Mill Hydro, South Brent, Devon EJC Chapman 21/6/11

Summary

Lydia Mill is the second oldest mill site in South Brent, Devon. Originally a grist mill, the site was converted from its last commercial use as a wheelright's shop to residential use in the early 1960s. In 2006 the owners and tenants agreed that the 12' overshot waterwheel should be re-instated for the purpose of generating electricity. Following investigation into the options for refurbishment or replacement, a new wheel was custom made and installed over the winter of 2009/10. Based on a design by the Pedley Trust, the wheel makes use of a "surcharged" inflow to ensure water lands smoothly in the buckets. The new wheel is rated at 1.8kW and generated 8254kWh in its first year of operation.

Definitions

H = total head under flow conditions (water surface in headrace to water surface in tailrace)

h = head in launder to surcharge "jet" emerging under control gate at end of launder

S = surcharge factor, typically 1.2 to 1.25 (i.e. 120 to 125%)

Vj = surcharge jet velocity

Cv = Velocity coefficient of jet from launder (between 0.8 and 1.0 depending on design)

r = wheel radius

b = bucket (shroud) depth

ω = angular velocity, radians/s

g = acceleration due to gravity, $9.81ms^{-2}$

Introduction

Figure 1 shows the general arrangement of the site. The old mill building now forms a single story dwelling and, sadly, other than the old wheel nothing remains of the earlier mill machinery. Figure 2 shows the condition of the wheel in 2007, overgrown with weeds and heavily silted up. The cast iron rims had cracked in several places and repaired with gusset plates. Several of the flanges for the buckets and floors had broken. Although restoration may have been possible, no consensus could be found as to the most appropriate materials to use – heartwood oak, French elm and tanalised Douglas fir being suggested. Following a discussion with Paul and Ingrid Bromley of the Pedley Trust in Cheshire, and a visit to their wheel, the decision to install a new wheel specifically for electricity generation was taken.

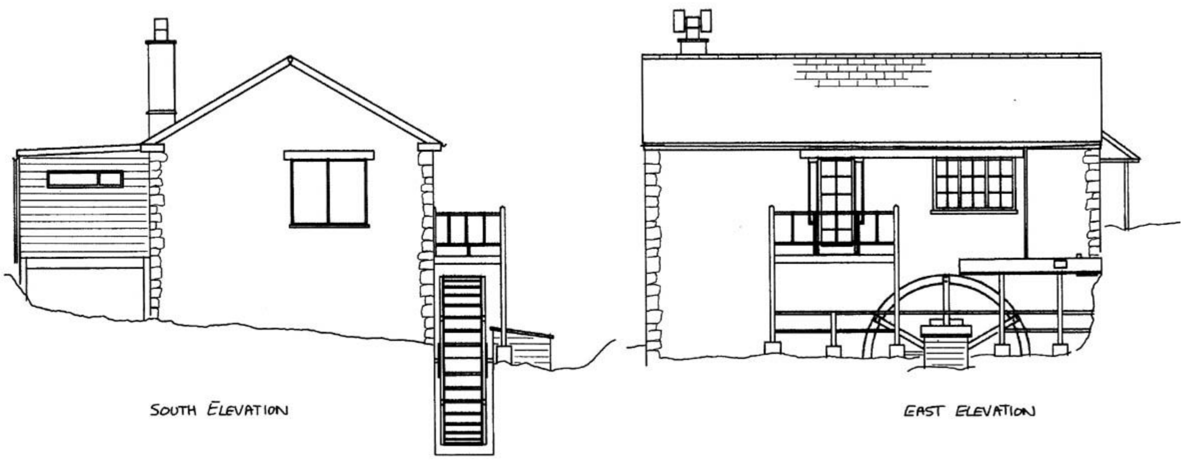

Figure 1 – Lydia Mill

Design considerations

The gearing required to drive a 4 or 6 pole alternator from a relatively slow turning wheel is often given as a reason for not considering traditional waterwheels. Running an overshot wheel "fast" typically produces a lot of splashing: try pouring water from a jug into a glass that is sweeping past at 2m/s and you'll see the problem. Figure 3 – Belsford Mill in Harberton shows what happens if you run a 12' wheel at 16 rpm – in this case a flap is employed in an attempt to keep the water on the wheel.

Figure 2 – Lydia Mill Feb 2007

Figure 3 – Belsford Mill at 16rpm

The solution the Bromley's had hit upon, following their extensive travels to mill sites across Europe and beyond, was to "surcharge" the water emerging from the launder to a speed equal to, or slightly above, the peripheral speed of the wheel. In this way water lands smoothly in the buckets at top dead centre, ready to work on the wheel for half a revolution, even though the wheel is operating faster than for a traditional grinding mill. However, so far as this author could tell, the underlying mathematics had not been documented, so the following was drawn up which provided a key input to the design process.

The Maths

An assumption is made that the waterwheel runs at half its free speed, and the bottom of the wheel is just clear of the water surface in the tail race. The launder has a controlled sluice gate at its end with a head of water behind to provide a jet into the wheel (Figure 4).

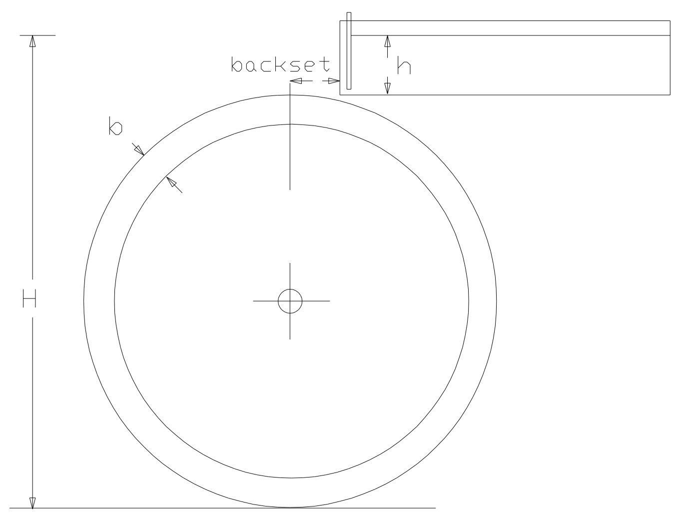

Figure 4

For the purpose of this analysis, the wheel free speed (no load) is taken to be limited by the ability of water falling under gravity to catch up with the bucket at top dead centre:

$$r\omega^2 = g$$

Therefore the angular velocity of the wheel under no load is

$$\omega = \sqrt{\frac{g}{r}}$$

If, from a rule of thumb, maximum power output is at half this speed:

$$\omega = 0.5\sqrt{\frac{g}{r}}$$

But

$$r = \frac{H - h}{2}$$

so the angular velocity of an overshot waterwheel delivering power is given by

$$\omega = 0.5\sqrt{\frac{2g}{H - h}}$$

The peripheral speed of the wheel is simply rω.

Surcharge jet velocity is given by

$$Vj = Cv\sqrt{2gh}$$

where h is the head in the launder just upstream of the control gate, and Cv depends on the precise shape of the bottom of this gate.

For best operation, the surcharge jet velocity should be slightly higher than the wheel's peripheral speed, by a factor S, the Surcharge factor. Thus we have the equality:

$$Vj = Sr\omega$$

or

$$Cv\sqrt{2gh} = \frac{S}{2}\sqrt{\frac{g(H - h)}{2}}$$

Solving for h:

$$h = H\frac{(S/2Cv)^2}{4 + (S/2Cv)^2}$$

Taking S = 1.2 and Cv = 0.9 gives

$$h = H\frac{0.444}{4.444}$$

or

$$h = 0.1H$$

At Lydia Mill the total head available is 4.2m. Therefore the surcharge head should be 0.42m and the wheel diameter 3.78m.

The working speed of the wheel is then

$$\omega = 0.5\sqrt{\frac{2g}{3.78}}$$

$$= 1.139$$

Since there are 2π radians in a circle and 60 seconds in a minute, the speed in rpm is given by

$$\omega\frac{60}{2\pi}$$

$$= 10.9\, rpm$$

Finally, the peripheral speed of the wheel is

$$1.139\frac{3.78}{2} = 2.15 m/s$$

In practice, the speed of the wheel was to be dictated by the gear ratios available in standard industrial motor-drives and the induction generator speed, taken to be 1540rpm. Together with the advice from the Bromleys that the peripheral speed should be no more than 2m/s, the closest gear ratio was 154.82:1 for a Pujol-Muntala DXC compact 3-stage helical unit. After re-working the maths and allowing for adequate clearance under the wheel, the finally adopted design figures were:

Diameter: 3.81m over buckets (3.86m over rims)
Rotational Speed: 9.95rpm
Peripheral speed: 1.98m/s
Surcharge head: 0.35m

Whilst it is true that for most regular sized waterwheels the working peripheral speed is around 2m/s, it should be proportional to the square root of wheel diameter – the larger the wheel the larger the peripheral velocity. Thus, to maintain a surcharge jet velocity ~20% faster, the depth of water in the launder will also need to increase with wheel diameter. As shown in the equations above, the surcharge head h is only dependent on the required surcharge factor and the velocity coefficient (i.e. efficiency) of the surcharge jet. A model waterwheel's launder will therefore scale correctly. (If the peripheral velocity of waterwheels was fixed at 2m/s regardless of diameter, the model wheel would require a ridiculously deep launder).

<u>Position of launder</u>

It is assumed that water from the launder should land in the bucket at or just after top dead centre (TDC). The jet of water emerging from the launder describes a parabolic path with a horizontal component given by the jet velocity Vj and a vertical component due to acceleration due to gravity. If the water is allowed to fall half bucket depth b at TDC (imagine the jet striking the middle of the bucket when at TDC), a particle of water is in flight for time determined by

$$\frac{b}{2} = 0.5gt^2$$

$$t = \sqrt{\frac{b}{g}}$$

The tip of the launder should, therefore, be a distance upstream of the wheel's TDC given by

$$Launder\ backset = Vj\sqrt{\frac{b}{g}}$$

For this wheel the buckets are 0.15m deep, so this works out at 0.29m. Being back set gives space for the launder's bottom to have finite thickness! (It is assumed that the inside bottom of the launder is level with the top of the wheel).

Other design factors

The volume flow rate available had been determined from measurements over 2007 and by comparison with long term data. A figure of 70 litres/s was used, which together with the rotational speed determined the bucket depth. The width of the wheel was limited to just over 1m by the width of the existing wheel pit.

The launder had to be able to carry the surcharge depth of water plus, when shut down, it had to allow water to spill over safely. Additionally, it had to be sufficiently adaptable to allow for a range of surcharge head and lip position relative to the wheel, to "fine tune" water entry to the buckets. To meet these requirements, it was built in three sections: an upstream section of lower sidewall height (to act as a spillway), a middle section spanning the upstream half of the wheel, and the control gate/lip section.

Implementation

Following planning permission and abstraction licensing, the new wheel was commissioned from Pedley, manufactured by Congleton Engineering and collected from their works in September 2009. The wheel is of modular construction, with 8 segments each with 5 buckets, supported by a "spider" of spokes and braces made from standard steel strip and angle. The gearbox is shaft-mounted so that there are only three points of contact from the wheel/gearbox/generator assembly to the ground: the two main bearings and the end of a torque arm, manufactured from stainless steel by Exeline Engineering. The induction generator and control system is from Sustainable Control Systems.

The launder was made like an inside-out dinghy: marine ply with stiffening stringers, lined with glass reinforced plastic. The control gate runs in PTFE slides, moved by a low cost satellite dish actuator modified with change-over limit switches to interface with the SCS controller. The supporting timber framework is tanalised Douglas fir from Rattery Sawmill.

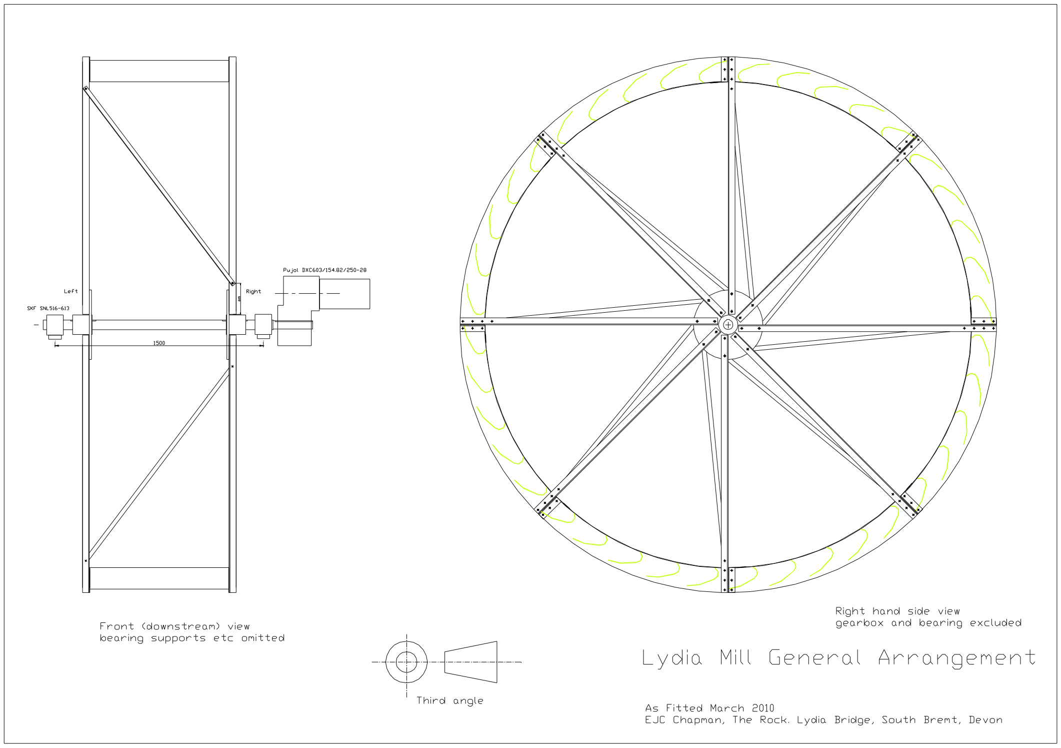

Figure 5 – The new wheel

Initial trials revealed a worrying noise problem: the steel wheel, mounted on resilient "Tico" pads, rang like a bell as the buckets slapped the underside of the jet of water. The solution was to fit a V-plate extension to the lip of the launder. This softened the impact, eliminating the ringing. An unexpected problem of gear noise being transmitted to the wheel is also quite noticeable, but being of relatively high frequency it is adequately attenuated, even through an open window, such that it does not cause a nuisance.

Figure 6 – Launder V-plate

From trial and error it was found that the optimum surcharge head, being defined as that which minimised splashing and noise, was proportional to flow rate. A compromise value of 0.39m has remained unaltered since July 2010.

The system was commissioned on 31st March 2010. It has more than halved the amount of electricity imported from the mains to the mill dwelling, but at the time of writing no FiT income has been received.

Figure 7 – Completed installation, splash-free (compare with Figure 3).

Efficiency

The approximate efficiency of the various components was estimated at the design stage to be:

Wheel: 0.85
Gearbox: 0.9
Generator 0.85

giving a system efficiency of 65% water-to-wire. Simple flow measurements in the launder suggest that at full power the overall efficiency is between 60% and 75%. At low flow the efficiency is believed to be higher because a higher percentage of water stays in each bucket as it approaches bottom dead centre. The system continues to generate usefully down to very low flows.

The ROO-Fit Transitional Process from a User's Perspective

This project was caught in the transition from the Renewable Obligation to the Feed-In-Tariff. As a non-MCS installation, it was necessary to follow the accreditation route specified in the government's response to the FIT consultation, published in February 2010 and complete installation, testing and commissioning by 1st April 2010. This target was met (with 12 hours to spare).

The scheme was accredited under the RO in autumn 2010 and (eventually) transferred to the FiT register in Spring 2011. It was clear that Ofgem had not been allocated the resources necessary to manage the transition.

Experience with the local electricity utility has also been mixed. Despite requesting that an appropriate import meter be installed prior to commissioning, EDF assured that the existing pre-payment token meter would be compatible with embedded generation. On the May bank holiday Monday 2010 the wheel shut down because the meter had not discriminated between import and export and had used up the token. 15 days (of lost generation) later an ordinary meter was installed.

As of June 2011, a total generation meter reading had been requested by, and submitted to, EDF, so in theory the first FiT payment should be due in September 2011 – 5 years after project inception, and 18 months after the plant first generated.

Acknowledgements

Many individuals have contributed one way or another but I am particularly grateful for the practical help from: Francis Macnaughton, Jon Cuming, Jamie Wood, Nick Brampton, Richard Pym, James and Jack Ford. Also Jane Kinross and Claire Roper for their initial environmental assessment. Last but not least Meg, Martin and Rachel for tolerating the disturbance.