WATER WHEELS AS A POWER SOURCE

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Abstract: Water wheels have been known since antiquity. With the industrial revolution, hydraulic sciences were developed and new materials such as wrought iron became available allowing for a rational analysis and improved strength and geometry of water wheels. Contrary to common perception, water wheels did not disappear with the advent of steam engines and water turbines but evolved further so that even at the beginning of the 20th Century tens of thousands of water wheels were in operation, predominantly in Central Europe. Virtually all water wheels disappeared in the 1950's and 60's and little knowledge is available from current text books regarding their design or performance. A detailed study of the available literature covering the engineering design of water wheels was conducted. The design of water wheels was dominated by the requirement for a geometry which would minimize losses, and retain the water as long as possible in the machine. Reports of experimental investigations on the efficiencies of overshot and undershot wheels were also found. Well designed water wheels can reach efficiencies of 71 (undershot) to 85% (overshot). Some small companies are again manufacturing water wheels for electricity production.

Introduction

Water wheels are one of the oldest hydraulic machines known to man and have been used since antiquity, see e.g. Viollet (2003). Then, water wheels were built of wood and, since the difference between potential and kinetic energy was unclear, the efficiencies were not very high. With the development of hydraulic engineering, and with new materials, the shape, power output and efficiency of water wheels improved substantially. Even after the advent of steam engines and water turbines, water wheels were developed further, in particular in Germany and Switzerland. This technology reached a high point of technical perfection at the beginning of the 20th Century. Water wheels remained in wide spread use until the 1950's after which they disappeared virtually completely. Today, very little is known about the stage of development reached then.

The development of modern water wheels

Even today, water wheels are considered as an empirical technology belonging to the pre-steam era. In reality however, scientists and engineers paid a great deal of attention to this hydraulic energy converter. The British engineer John Smeaton was the first to determine the efficiency of water wheels using a series of model tests in 1759. He found that over shot wheels had efficiencies of more than 60%, whereas undershot wheels only reached 30%. The development of hydraulic engineering in combination with a new material – wrought iron, which was much stronger and allowed hydraulically more favourable shapes - resulted in a further evolutionary step of water wheels into rather efficient energy converters for very low heads. During the industrial revolution and in the 19th and early 20th Century, water wheels were subsequently important hydraulic energy converters, Reynolds (1983). Even after the advent of the water turbines after approximately 1850, e.g. Smith (1980), the steam engine

and the electric motor, water wheels remained in service as prime movers in large numbers on the European Continent. In the 1850's, an estimated 25-30,000 water wheels were operated in England alone, McGuigan (1978). The total number of water wheels recorded for operation on Germany as late as 1925 amounted to 33,500, Kur & Wolf (1985). In Baden-Württemberg, a German province of 35,000 km² area, 3,554 water wheels were counted to be in operation in the same year. Their numbers had dramatically reduced to only 18 operational wheels reported in the most recent count in 1977, Neumayer et al. (1979).

Water wheels were used as mechanical power sources for flour and mineral mills, textile and tool making machines, wire drawing and hammer works, oil mills or water supplies, to generate electricity and for other purposes. The main reasons for the use of water wheels were their comparatively low costs compared with steam engines, and reportedly high efficiencies for a wide range of flow rates, where water wheels compared favourably with turbines, Müller & Kauppert (2003). During the late 19th and early 20th Century, the design of water wheels was part of the syllabus of mechanical and civil engineering courses at University level, Albrecht (1900), and engineering textbooks covering the design of water wheels appeared in print until 1939. In the time up to the 1950's and 60's however virtually all water wheels disappeared and with them the knowledge about their design and performance characteristics.
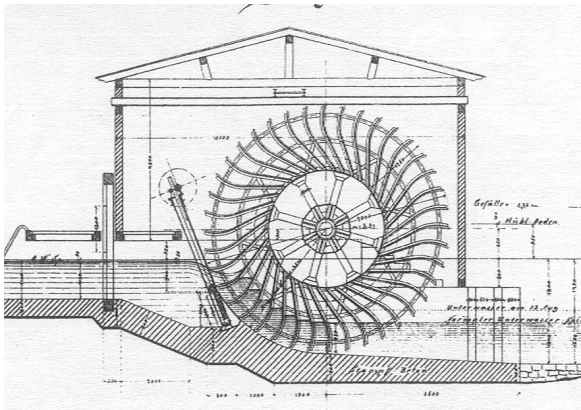
Types of water wheels

In order to be able to utilize the head differences from 0.5 to around 12m, three basic types of water wheels were developed. Most wheels employed only the potential energy of the water.

1. Overshot water wheels, Fig, 1a: the water enters the wheel from above. This wheel type was employed for head differences of 2.5 to 10m, and flow rates of 0.1 to 0.2 m³/s per m width.
2. Breast wheels, Fig. 1b: the level of the upstream water table lies at approximately the level of the wheel's axis. This wheel type was used for head differences of 1.5 to 4m, and flow rates of 0.35 to 0.65 m³/s per m width.
3. Undershot or *Zuppinger* wheels, Fig. 1c: the water enters the wheel below its axis. This wheel type can be used for very small head differences of 0.5 to 2.5m, and large flow volumes ranging from 0.5 to 0.95 m³/s per m width.

Between these wheel types, a large number of intermediate forms existed. All ‚modern' wheels have in common that they employ the potential energy of the water, and that they are built in steel. Fig. 1d shows a stream wheel. These impulse wheels, which employ the kinetic energy of flowing water, were also occasionally built, although it was well known that their efficiencies were too low to be used economically in large numbers, see e.g. Müller (1899).
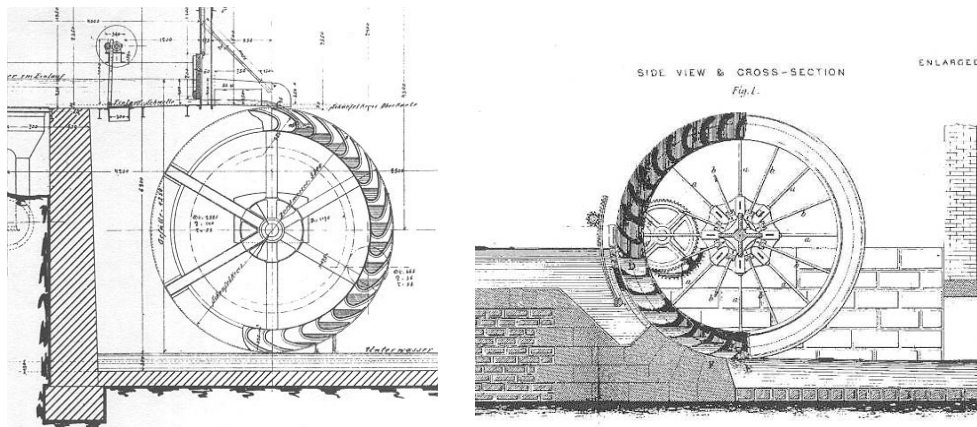
a. Overshot wheel, Müller (1899)   b. Breast wheel, Fairbairn (1876)
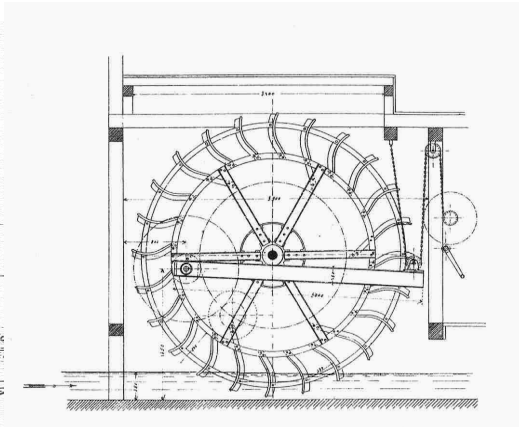
c. Undershot (*Zuppinger-*) wheel, Müller (1899)   d. Stream wheel, Müller (1899)

Fig. 1: Types of water wheels

The overshot wheel

Principles

'Modern', i.e. engineered, overshot water wheels are made of steel and feature a very distinctive geometry of the cells as well as a specially designed inflow detail.

The Fig.'s 1a and 2 show typical overshot cell wheels. It can be seen that the water is caught in 'buckets' or cells. The cells are formed in a way so that the water jet from the inflow can enter each cell at its natural angle of fall. The opening of each cell is slightly wider than the jet, so that the air can escape. The cells are kept as narrow as possible so that the weight of the water can become effective almost immediately. In order to avoid an early loss of water, each cell should only be filled with up to 30 - 50% of its volume. The inflowing water enters the cells as a fast and thin sheet; the outflow only starts at a very low level. The peculiar shape of the cells retains the water inside of the cell until the lowermost position, when it finally empties rapidly, as is illustrated in Fig. 1a. No water is carried over the lowermost point.
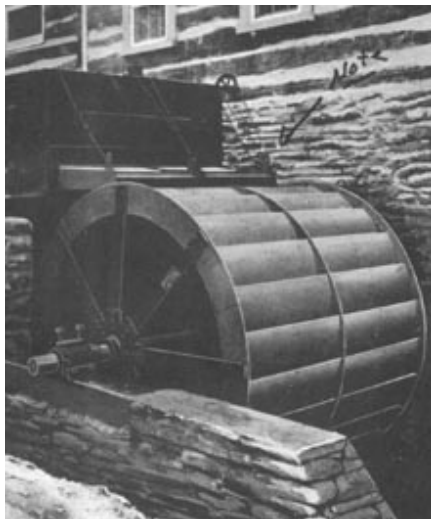
a. Overshot cell wheel,   b. Overshot wheel 8.88m diameter, paper mill,
   USA , ca 1900   Pfulllingen / Southern Germany ca. 1900

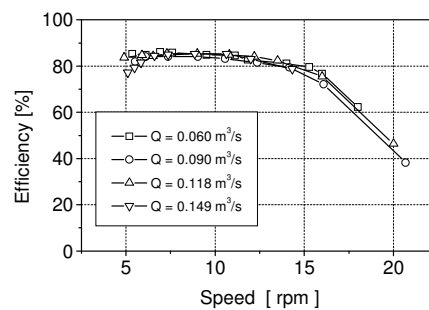Fig. 2: Typical overshot water wheels

Hydraulic design

Water wheels are designed for a given application, head difference and flow volume. For the design of an overshot water wheel, the diameter is determined by the head difference, although it has to be decided whether the wheel will be operated with free or regulated inflow (i.e. constant or variable speed) since this affects the available head. The wheel speed and the number, depth and shape of the cells then has to be determined as well as the width of the wheel for a given design flow volume and wheel speed. The inflow detail with or without a sluice gate has to be designed so that the design flow volume can be guided into the wheel. Engineering textbooks covering all aspects of the design calculations and giving empirical factors e.g. for losses or wheel speeds were published until 1939, see e.g. Fairbairn (1874), Bresse (1876), Bach (1886), (1886a), Müller (1899), (1899a), Frizell (1901), Müller (1939).

Performance characteristics

Although a large number of overshot water wheels were in operation in the last century, only three series of tests where the efficiencies were determined were performed. Most of the test results were never published in hydraulic engineering textbooks or journals and are only available in not widely known articles and reports, see Weidner (1913), Staus (1928) and Meerwarth (1935), whereby the experiments conducted in Germany remained unknown in the USA and vice versa. The efficiency against flow rate curve displays one of the main characteristics of any turbine. Fig. 4 shows a typical efficiency curve from one the reported tests. The efficiencies reach around 85% even for very small ratios of Q / Q_{max} of 0.3, and remain at this level up to $Q = Q_{max}$, so that the water wheel (when well designed) can be regarded as a rather efficient energy converter with the additional advantage of having a broad performance band width.
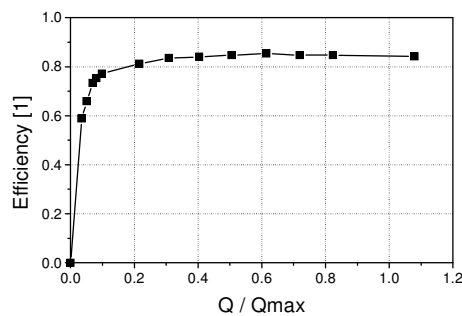
a. Efficiency, Staus (1928)   b. Efficiency as a function of speed

Fig. 4: Efficiency curves for an overshot water wheel, (from: Müller & Kauppert, 2003)

The breast wheel

Breast wheels receive their water approximately at the level of the wheel axis. These wheels were developed for head differences of usually 1.5 to 4 m. Fig. 6a shows a breast wheel with ventilated buckets. This wheel type was particularly popular in Britain, see Fairbairn (1876). A detailed description of the design procedures for such wheels is given in Bach (1886), together with design examples. In Fig. 6b and c, the design requirements for breast wheels are illustrated. The water enters the wheel with a rather steep angle, to ensure a rapid filling of each cell. The buckets are shaped so that the resultant force acts in the direction of the wheel's

motion, and so that the cell walls exit the water downstream at a right angle, to avoid losses at this point. The weight of the water constitutes the driving force on the wheel. The cells are ventilated in order to let the air escape during inflow, and to let air into the cell when the cell starts to rise again above the lowermost point. Just like overshot wheels, it appears that the designers intended the wheel to operate with constant speed of the inflowing water.
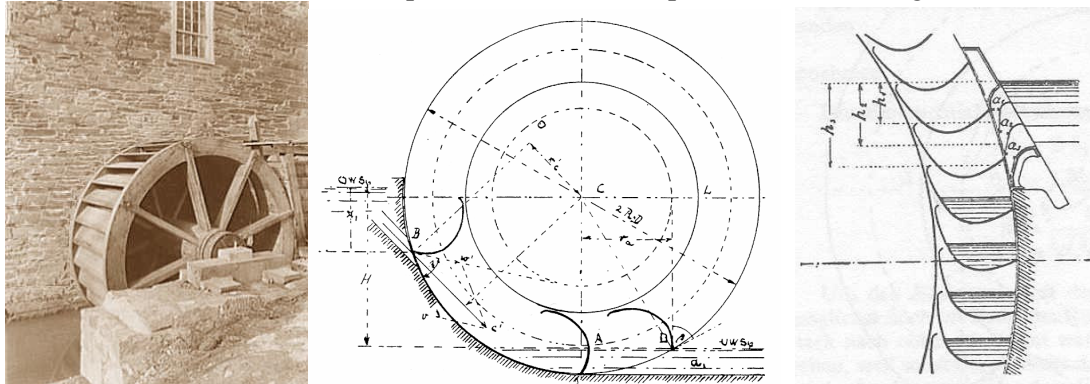
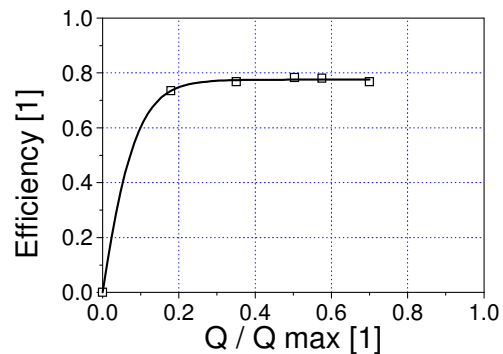|		
a. Typical breast wheel, 4.8m dia., 1.5m width,	b. Side elevation with design parameters, Bach (1886)	c. *coulisse* – type inflow detail, Bach (1886)

Fig. 6: The breast shot water wheel

Fig. 6c shows a typical inflow detail which directs the water into the cell. In this case, it has three slit-type openings which are opened or closed depending on the flow volume so that the upstream water level remains constant. Efficiencies were estimated at 80 – 85%, making them nearly as efficient as overshot wheels, Bach (1886).

Recently, model tests on a 1m diameter 1:4 scale model of a breast wheel were conducted at Queen's University Belfast. Fig. 7a shows a side view of the model, with the friction brake. In Fig. 7b the efficiency is given as a function of the flow rate. The wheel was design after Bach (1886). It was found that efficiencies reach 79% for a broad range of flows. Observations led to the conclusion that significant energy losses occur at the in- and outflow, leading e.g. to the fact that the wheel can only absorb 10% of its design flow rate of 15 l/s. A further increase of efficiency is expected after the optimization of both in- and outflow.
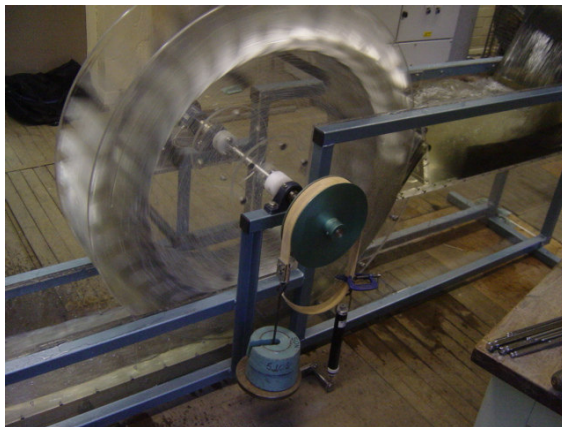
a. 1m diameter model (QUB)	b. Efficiency as a function of flow rate

Fig. 7: The breast shot wheel – model tests

The undershot or *Zuppinger*-wheel

The undershot wheel for the exploitation of very small head differences was originally used as an impulse wheel, employing the kinetic energy of the flow. The French engineer Poncelet however noticed that the potential energy of the slow moving water masses in small rivers was appreciably larger than the kinetic energy, and designed the first wheel for very low head differences which employed the potential energy only. Another French engineer, Sagebien, improved the original design. The most efficient shape for these wheels was finally developed by the Swiss hydraulic engineer Walter Zuppinger. Fig. 1c shows a side elevation of a *Zuppinger* wheel with the typical 'backwards' inclined blades and with a weir type inflow.

The wheel employs only the potential energy of the flow as the principal driving force. Fig. 8a shows the cross section of a wheel and illustrates the inflow conditions as well as the geometry required for efficient operation. The water enters the wheel over a weir, so that the cells can be filled rapidly. Fig. 8b illustrates the working principle of the wheel. The blades are arranged in a way so as to avoid losses at the water entry, then to gradually reduce the head of water in each cell and finally to discharge the water, again with a minimum of losses.

a. Side elevation and inflow   b. Working principle
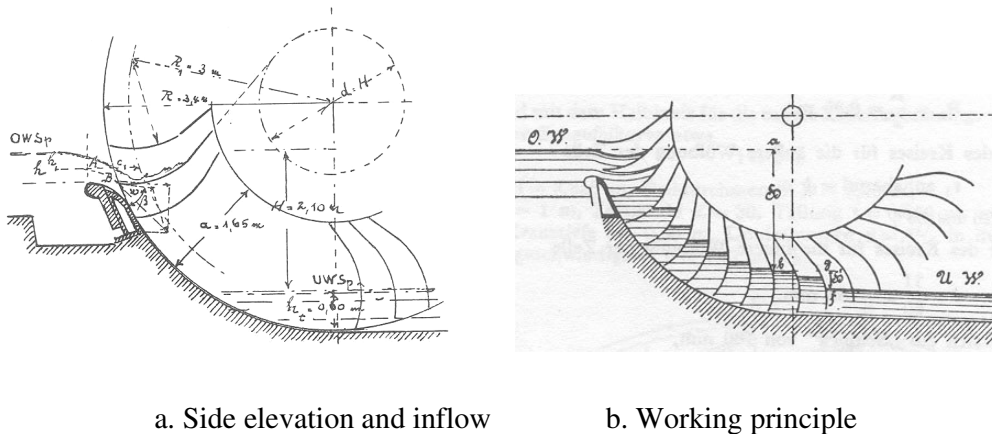
Fig. 8: Design principles of undershot or *Zuppinger*-wheels, Müller (1899)

In order to investigate the efficiencies of undershot wheels, some measurements were conducted by the Technical University of Stuttgart/Germany in 1977. A *Zuppinger* wheel built in 1886, which was still in operation in a mill, was instrumented. The wheel was originally designed for a head difference of 1.36m and a flow rate of 3.0 m³/s. It had a diameter of 6.0 m with a width of 2.5m. The wheel was still in its original condition, except that some of the wooden blades had been replaced. Flow rates and power output were measured for a speed of 4.85 rpm and for two flow rates of 1.48 and 3.1 m³/s.
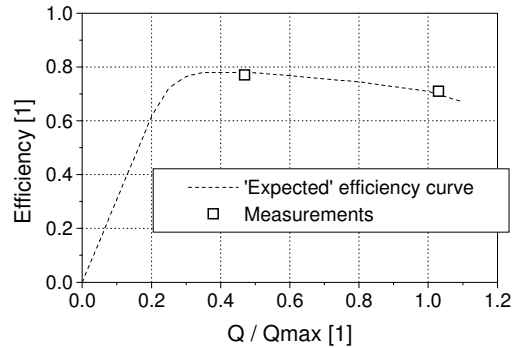
Fig. 9: Efficiencies measured at a 91 year old wheel, Neumayer et al. (1979)

Fig. 9 shows the efficiencies determined from the two measurements. An efficiency of 77% was reached for $Q / Q_{max} = 0.5$, and 71% for $Q / Q_{max} = 1$. These figures are surprisingly high, considering the facts that the wheel was still running on its original bush bearings, and that gaps of 50mm to each side wall and 30mm between blades and the bed exist now due to the wear on the wooden blades.

Water wheels for electricity generation

In the previous section it was shown that 'modern' water wheels have a surprisingly high efficiency for a wide range of flows. This has the great advantage that power can be generated even from low flow volumes without complex control elements as they are e.g. required for Kaplan turbines. The power/speed curves were also quite flat, indicating that speed control is not very critical as long as the wheel operates approximately at design speed.

The slow speed of water wheels means that gear boxes with transmission ratios of approximately 1:100 have to be employed. Although such gear boxes are available and do not cause significant energy losses (2-3%), they constitute a significant part of the costs (25-30% for undershot, 40-45% for overshot wheels) of a water wheel installation. The development of a slow speed multipolar generator which could be driven directly with a belt drive would constitute a major advance in this field.

Current situation

A small number of companies are currently manufacturing water wheels for electricity generation, see Fig. 10 and internet references. Overshot water wheels are today built for head differences of 2.9 – 6.0m, and flows of 0.1 – 1.2 m³/s, undershot wheels for head differences of 1.2 – 2.3m and flow rates of up to 3 m³/s. Payback periods can be estimated as 7.5 years for an overshot and 12- 14 years for an undershot wheel with expected life times of 30 years, Müller & Kauppert (2002, 2003). This compares favourably with Kaplan turbine installation, where payback periods of 25 – 30 years can be expected. Water wheels can therefore constitute an economically interesting investment even in industrialised countries.

a. 26 kW (el.) overshot wheel, Freiburg/Germany,   b. New *Zuppinger* wheel, 6.5m dia.,
   2.9m dia., 4m width (2000)   20 kW (el.) (1996)

Fig. 10: Recently built water wheels (Hydrowatt Ltd.)

Conclusions

A detailed study of the available literature on the design of 'modern' or engineered water wheels was conducted. It was found that in order to make optimum use of the available head differences, three different types of water wheels evolved: the overshot, breast shot and the undershot wheels for head differences of 0.6 to around 10m. Efficiency measurements conducted with overshot water wheels gave maximum efficiencies of 85-90% over a broad range of flows. Recent model tests of breast shot wheels gave efficiencies of 79%. Undershot wheels appear to be somewhat less efficient with 71 – 76%. Water wheels appear to be efficient and ecologically acceptable energy converters. For the cost-effective deployment of water wheels further development of the wheel itself and the generator unit (low speed generator) does seem nevessary.

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