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Optimization of breastshot water wheels performance using different inflow configurations

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ABSTRACT

Breastshot water wheels are gravity hydraulic machines employed in low head sites. The scope of this work is to test the performance of a breastshot water wheel with two geometric inflow configurations: a sluice gate at different openings and two vertical overflow weirs. With the sluice gate, the maximum efficiency of the plant is 75%, constant over a wide range of flow rates, while the efficiency with the weir is increasing in the same flow rate range. Therefore, the wheel with the weir can exploit higher water volumes, and also it performs better at high power input. In practical applications, the inflow configuration can be effectively controlled to optimize the operative working conditions of breastshot water wheels, depending on the external hydraulic ones. The experimental results are also discussed in dimensionless terms, in order to support engineers in the design of similar breastshot water wheels.

1. Introduction

The wheel has been one of the most ancient technology used by mankind to produce energy. The first vertical water wheel was the *stream* water wheel, still used nowadays in flowing water [1]. The water interacts with the blades below the wheel and the kinetic energy of streams drives the wheel. In *gravity* wheels (*overshot*, *breastshot* and *undershot* water wheels) the weight of water is mainly employed for the generation of energy, in sites where a geometric head difference exists (the difference of the channel's bed elevation upstream and downstream of the wheel). In overshot water wheels the water enters into the cells from the top of the wheel. They are generally used for head differences between 2.5 and 10 m and at low flow rates (approximately from 0.2 to 1.0 m^3/s per unit width). In breastshot wheels the water enters into the buckets near the rotation axle. These wheels are usually employed for head differences lower than 4 m and at flow rates from 0.5 to 2.0 m^3/s per unit width. When the geometric head difference is very low (e.g. 1/8 ÷ 1/10 of the diameter, although there not exists a precise limit), breastshot water wheels can be called *low* breastshot wheels, or undershot wheels: the water fills the buckets in the lowest part of the wheel and these wheels are generally used at flow rates from 1 to 3 m^3/s per unit width.

During the Eighteenth and Nineteenth century, some experimental tests and theoretical estimations for the determination of the efficiency of water wheels were developed [2–8]. However, the previous studies generally were not totally satisfactory, since theoretical analyses were not supported by experimental tests, and comparisons among different geometric configurations under the same hydraulic conditions were generally not presented. Therefore, the most of the available engineering and scientific information is ancient, with uncertainty and often published in not well known text-books.

At the beginning of the Twentieth century, the rising demand of energy, the economic development and the rapid improvement in the engineering knowledge (especially the design of big hydroelectric plants and the transmission of electricity), led to the introduction and diffusion of modern turbines, employed in big hydroelectric plants with heads of tens/hundreds meters. Therefore, the classical water wheels, used in low head sites especially for self sustainment, were replaced and by then considered ancient and bygone machines.

In the last years, due to their numerous purposes, quite high efficiency, low payback periods, low environmental impact and simplicity of construction [9], water wheels are regarded again as interesting hydraulic machines for the production of decentralized energy, especially when combined with a mill for grinding wheat.

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Indeed, it is a general view that bread made by water mill's flour is tastier than that produced by electric engines and it has also a finer quality and higher nutritive value [10]. When installed in old water mills, water wheels may also contribute to the preservation of the cultural heritage, the development of tourism, the promotion of local manufacture and the creation of employment. Hence water wheels may become a profitable industry, especially due to the wide diffusion on the territory of sites suitable for water wheels [11]. These machines may be also an interesting investment in rural areas, since their payback periods are low ($7 \div 14$ years with respect to 30 years for a Kaplan installation) [9].

Therefore, thanks to the previous motivations, the interest of the scientific community in water wheels is starting to increase. For example, recent scientific studies on undershot and stream wheels can be found in Refs. [1,12–15]. In Ref. [16] a study of an overshot water wheel is presented. Concerning breastshot water wheels, in Refs. [17,18] theoretical and dimensional analysis, respectively, have been performed for a breastshot wheel equipped with a sluice gate.

2. Breastshot water wheels

Since this work will investigate different inflow configurations of a breastshot water wheel, it is worthwhile to cite the book of *Garuffa* [7], where breastshot water wheels are classified as *fast* and *slow*. Fig. 1 shows a *fast* breastshot wheel, where the inflow configuration is constituted of a sluice gate. Fig. 2 depicts a *slow* breastshot water wheel, where the inflow configuration is constituted of an overflow weir. In this book, the previous terminology is inspired by the fact that in fast breastshot wheels the flow accelerates passing under the sluice gate. The flow velocity to the wheel is hence faster with respect to the flow velocity in *slow* wheels, where the water passes over an overflow weir just upstream of the wheel, entering into the buckets from higher elevations. This means that, considering the same flow rate, head difference and wheel rotational speed, the torque contribution of the water weight in *slow* wheels is higher with respect to the torque contribution of the water weight in *fast* breastshot wheels. In *slow* breastshot wheels the torque due to the kinetic energy of water is lower with respect to *fast* wheels.

Although it is not mandatory to install one of the previous hydraulic structures upstream of a water wheel, they are useful. These inflow structures allow to regulate and to optimize the operative working conditions. Sluice gates and weirs are usually present in irrigation canals, where suitable conditions for breastshot water wheels exist. Due to the higher flow velocity, in fast breastshot wheels the kinetic energy of the flow can contribute significantly to the driving torque of the wheel. In order to exploit efficiently the kinetic energy of the flow, the inclination of the blades surface has to be parallel to the flow relative velocity ($\overrightarrow{w}$) at the entry point, as shown in Fig. 1. The relative velocity is defined as the vector difference between the absolute entry velocity of water ($\overrightarrow{v}$) and the tangential velocity of the wheel ($\overrightarrow{u}$). The opening (a) of the sluice gate can be regulated to control the absolute velocity of the flow to the wheel, hence the relative velocity.

No complete and detailed experimental comparisons on the performance of slow and fast breastshot wheels have been found in modern literature, under the same hydraulic conditions. Therefore, in order to shed light on this issue, the aim of the present paper is to perform experimental tests on a breastshot water wheel, investigating its performance with an inflow weir and a sluice gate. In practical operative conditions, the inflow configuration can be managed depending on the external hydraulic conditions, optimizing the efficiency of the hydro plant. Scope of the present paper is thus to determine in which conditions it is more advisable to use the weir, and when it is better to regulate the flow to the wheel acting on the opening of the sluice gate.

3. Method

3.1. Experimental equipment and procedure

An experimental channel has been installed in the Laboratory of Hydraulics at Politecnico di Torino with the aim of testing different kinds of water wheels; in this work the results of a breastshot water wheel are presented. The diameter of the wheel was $D = 2R = 2.12$ m, the width was $b = 0.65$ m and the number of the blades was 32 (Fig. 3).

The flow rate Q to the wheel was set acting on a pump and a gate valve installed in the supply pipe of the channel (flow rates $Q = 0.02 \div 0.1\ m^3/s$ were investigated). The flow rate was detected by an electromagnetic flow meter, whose accuracy was $\delta Q = \pm 0.5 \cdot 10^{-3}\ m^3/s$. A brake system, constituted of a generator and a resistor, was connected at the wheel's shaft. An electrical energy analyzer and a control of the electrical resistance were installed to

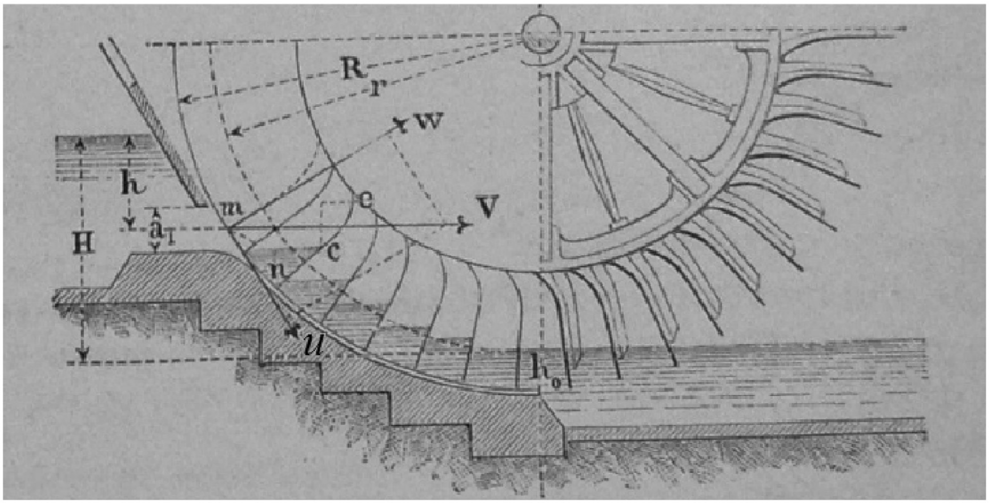

Fig. 1. Classical configuration of a fast breastshot wheel equipped with a sluice gate of opening a (Garuffa, 1897 [7]). The relative flow velocity $\overrightarrow{w} = \overrightarrow{v} - \overrightarrow{u}$ is oriented as the blades in the impact point, where $\overrightarrow{v}$ is the absolute flow velocity and $\overrightarrow{u}$ is the tangential velocity of the wheel.