

Performance Optimization of Overshot Water Wheels at High Rotational Speeds for Hydropower Applications

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2 Performance Optimization of Overshot Water Wheels at 3 1 High Rotational Speeds for Hydropower Applications

4 Emanuele Quaranta¹ and Roberto Revelli²

5 **Abstract:** Overshot water wheels are hydropower converters generally employed for head differences up to 6 m and maximum flow rates of
6 150–200 L/s per meter width. The hydraulic efficiency (80%–85%) is constant for rotational speeds below the critical speed, whereas the
7 efficiency linearly decreases at higher rotational speeds due to the increase of water losses at the inflow. To improve the efficiency when the
8 rotational speed is above the critical speed, an improved geometric design was investigated by implementing a theoretical model validated
9 using experimental results. The new geometry consists of a circular wall around the periphery of overshot water wheels. The wall redirects
10 into the buckets the water flow that is lost at the inflow, improving the efficiency up to 1.5 times at high rotational speeds. DOI: 10.1061/
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12 **Author keywords:** Low head; Hydropower; Microhydro; Overshot water wheel; Water mill.

13 4 Introduction

14 5 In irrigation canals and near old mills there is a great potential of
15 6 low-head hydropower (ESHA 2004), in which head differences of a
16 few meters and flow rates of few cubic meters per second are avail-
17 able. The installation of low-head hydroturbines could be a viable
18 option to generate clean renewable energy below 100 kW (micro-
19 hydropower) at these sites, with beneficial effects on the local
20 economy and on the electrification of remote areas. In rural and
21 decentralized areas, the installation of microhydro plants is consid-
22 ered one of the most economical options for rural electrification,
23 especially when existing hydraulic structures are used to reduce
24 7 infrastructure costs (Paish 2002; Bozhinova et al. 2013; ESHA
25 2004; Quaranta and Revelli 2018).

26 In this context, water wheels are considered more environmen-
27 tally friendly and cost-effective than Kaplan and Francis turbines,
28 due to their low rotational speeds, large buckets, and free-surface
29 working behavior. Water wheels can be divided into stream water
30 wheels and gravity water wheels; stream water wheels exploit the
31 kinetic energy of flowing water (Quaranta 2018), whereas gravity
32 wheels mainly use the water weight to generate energy (Quaranta
33 and Revelli 2018). Among gravity water wheels, undershot, breast-
34 shot, and overshot water wheels can be identified. In overshot
35 wheels (analyzed in this paper) the water enters the buckets from
36 the top of the wheel; overshot wheels generally are employed for
37 2.5–6-m head and flow rates below 0.2 m³/s per meter width, with
38 8 maximum efficiencies of 85% (Williams and Bromley 2000; Dubas
39 2005; Pellicciardi 2015; Quaranta and Revelli 2015). Some existing
40 9 overshot water wheels are shown in Fig. 1. Breastshot (Müller and

41 Wolter 2004; Quaranta and Revelli 2016, 2017) and undershot
42 water wheels (Von Harten et al. 2013; Quaranta and Müller
43 2018) generally are employed at sites with heads below 4 and
44 1.5 m, respectively, and have maximum hydraulic efficiency of be-
45 tween 75% and 80%.

46 The first systematic experiments on water wheels were carried
47 out in the nineteenth century (Fairbairn 1864; Bach 1886; Chaudy
48 1896; Garuffa 1897; Weidner 1913; Meerwarth 1935), whereas the
49 most recent hydraulic theory of overshot water wheels was pre-
50 sented and validated by Quaranta and Revelli (2015).

51 The tested water wheel was a 1:2 scale model of an existing
52 overshot water wheel sited in an irrigation canal in North Italy
53 [Fig. 1(b)]. The scale wheel was 1.46 m in diameter and 1 m wide,
54 and had 24 blades that were 0.153 m deep [Fig. 2(a)] (Quaranta and
55 Revelli 2015). A power loss model was developed and validated on
56 experimental results with an average discrepancy between pre-
57 dicted and experimental power output of 8% [Fig. 2(b)]. Beyond
58 a certain rotational speed, called the critical rotational speed, N_{cr} ,
59 the experimental power output P_o and the efficiency decreased lin-
60 early with the speed N . The efficiency decrease was due to the flow
61 rate that was lost at the inflow (i.e. at the top of the wheel) when
62 the flow impacted on the blades, forming splashes and water drop-
63 lets [Figs. 1(a) and 3]. The critical speed was estimated as $N_{cr} =$
64 $31.3/\sqrt{D}$, where D is the wheel diameter, in agreement with results
65 reported by Williams and Bromley (2000). The results of Williams
66 and Bromley (2000) and Quaranta and Revelli (2015) highlighted
67 the importance of the inflow design of overshot water wheels, as
68 also suggested for hydrodynamic screws (Lubitz et al. 2014;
69 Straalsund et al. 2018) and breastshot and undershot water wheels
70 (Quaranta and Revelli 2016; Quaranta and Müller 2019), both of
71 which are classified as low-head hydraulic machines.

72 With the aim of reducing volumetric losses, Wahyudi et al.
73 (2013) proposed converting volumetric losses from the buckets
74 and from the channel into a high-velocity water jet by a nozzle,
75 and squirting the jet on the lowest blade using a ram pump system.
76 The efficiency increased from $\eta_o = 61.6\%$ to $\eta_{new} = 73.5\%$,
77 i.e., $\eta_{new}/\eta_o = 1.2$.

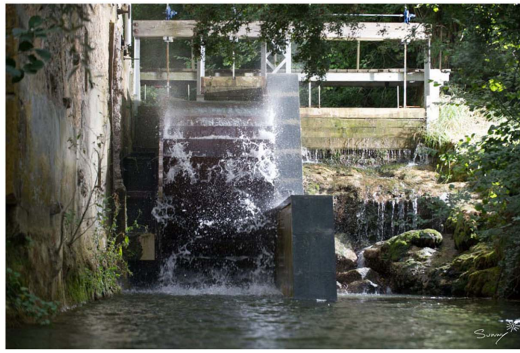
78 The present study improved the performance of overshot water
79 wheels at $N > N_{cr}$ by converting volumetric losses into potential
80 energy, rather than kinetic energy, by means of a wall installed
81 around the periphery of the wheel. The theoretical model developed

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(a)



(b)



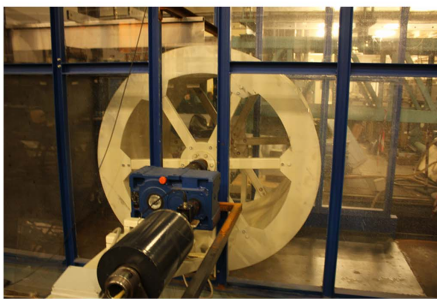
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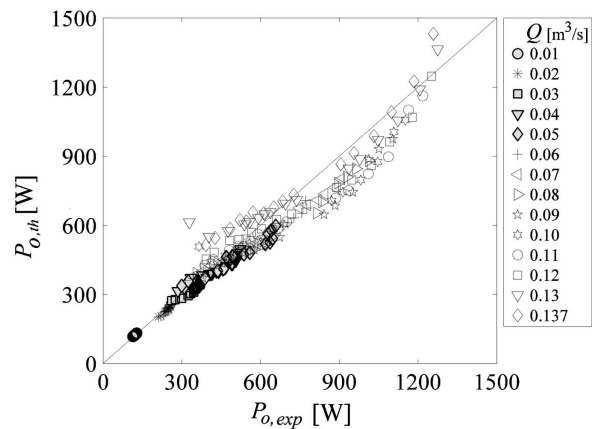
(d)

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Fig. 1. Overshot water wheels, with the conveying channel at the top: (a) overshot wheel of Gratia Hydro, 2.5 m in diameter and 1.5 m wide (image courtesy of Martin Eillebrecht); (b) wheel in Ciconio, 3 m in diameter and 2 m in width (image courtesy of Marco Gatta); (c) wheel in Judenburg, 4 m in diameter and 0.75 m wide (image courtesy of Helmut Mitterfellner); and (d) wheel in Bobbio Pellice, 2.6 m in diameter and 0.9 m wide (image courtesy of Emanuela Genre, Mulino di Bobbio staff).



(a)



(b)

F2:1
F2:2

Fig. 2. (a) Tested water wheel in the laboratory (image by Emanuele Quaranta); and (b) predicted power output $P_{o,th}$ versus experimental power output $P_{o,exp}$ at different flow rates for the original configuration.

82 and validated by Quaranta and Revelli (2015) was implemented. As
83 previously discussed, the model was proven to be reliable and ac-
84 curate, and hence it can be used to explore different geometries in
85 similar hydraulic configurations. The new design does not affect
86 the upstream conditions (the upstream hydraulic depths and pro-
87 files do not change), which is an essential requirement in irrigation
88 canals. The proposed method is expected to be more cost-effective
89 than the conversion of water losses into kinetic energy.

Method

The theoretical model described by Quaranta and Revelli (2015), based on the estimation of power losses, was implemented. The model was based on the following assumptions:

1. The hydraulic behavior of overshot water wheels is very complex, because splashes, water droplets, and jets arise in the buckets during rotation. Such turbulent phenomena are neglected, so

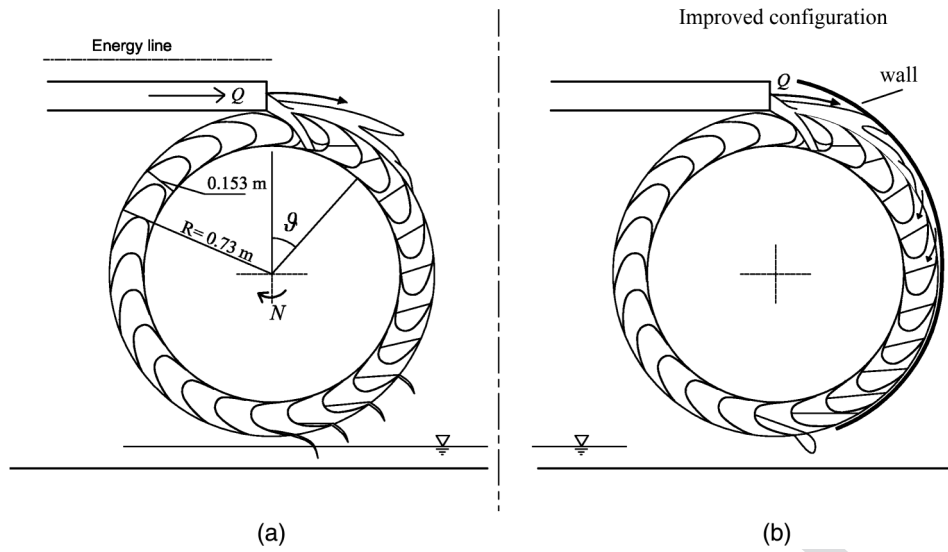


Fig. 3. (a) Original water wheel; and (b) modified configuration on the right, with additional wall to recover and direct the water into the buckets.

- 97 that the water jet is considered as a continuum and water in the
 98 buckets was considered to be at rest.
 99 2. The flow behavior of water wheels is two-dimensional,
 100 i.e., velocity components parallel to the rotation axis are negli-
 101 gible and the water depth inside each bucket is uniform along
 102 the direction of the rotation axis. This assumption is well sat-
 103 isfied observing well designed water wheels.
 104 3. The kinetic energy of the water flow which is redirected into the
 105 bucket is lost when the flow enters the bucket, because for most
 106 of the time the water flow impacts on the water volume already
 107 inside the bucket, dissipating its kinetic energy. Therefore, the
 108 additional impulsive force of the water impact is neglected.

109 With the previous assumptions, the mechanical power output P_o
 110 of a generic overshot water wheel can be estimated by the following
 111 equation (Quaranta and Revelli 2015):

$$P_o = P - \sum \text{Losses} = P - L_{\text{imp}} - L_t - L_g - L_{Q_u} - L_{Q_r} \quad (1)$$

112 where L_{imp} = kinetic power loss occurring at inflow; L_t = impact
 113 loss of blades on tailrace (if blades are submerged in tailrace); L_g =
 114 mechanical friction loss at shaft supports; L_{Q_u} = volumetric loss at
 115 inflow; and L_{Q_r} = volumetric loss during rotation, due to the em-
 116 ptying process of the buckets. Inflow volumetric losses were quan-
 117 tified by the following equation:

$$\frac{L_{Q_u}}{P_{\text{in}}} \approx 0 \quad \text{for } N < N_{\text{cr}}$$

$$\frac{L_{Q_u}}{P_{\text{in}}} = 2.2 \cdot \left[\frac{N}{N_{\text{cr}}} - 1 \right] \quad \text{for } N > N_{\text{cr}} \quad (2)$$

118 where L_{Q_u} = volumetric power loss; and $P_{\text{in}} = \gamma QH$ = power in-
 119 put, where $\gamma = 9810 \text{ N/m}^3$ = specific weight of water, Q = total
 120 flow rate (m^3/s); and H = head difference (m).

121 This model was implemented and applied to the new geometric
 122 configuration depicted in Fig. 3. The new design consists of a wall
 123 located around the periphery of the wheel, used to redirect into the
 124 buckets the water which is lost at the inflow. No additional moving
 125 part is added, and thus the modification is cost-effective. A similar
 126 geometry was suggested (but not tested, neither experimentally nor
 127 theoretically) by Weisbach (1849), but with some conceptual differ-
 128 ences. In our design, the water above the wheel and at the inflow is

129 at atmospheric pressure; otherwise, the gravity wheel would be-
 130 come a pressurized turbine, which would be beyond the purpose
 131 of the present study. The diameter of the wheel is almost equal
 132 to the head difference, and the wall does not affect the upstream
 133 conditions (Fig. 3). In Weisbach (1849), the headrace was dammed
 134 at its end by a weir, creating a water basin above the wheel, up-
 135 stream of the weir. The pressurized water entered into the wheel
 136 at high velocity through a nozzle on the bed of the basin. Therefore,
 137 a portion of the potential head was converted into kinetic energy.
 138 This solution can be useful for head differences above 6 m to avoid
 139 very large wheel diameters, and where the increase in the upstream
 140 water level (due to backwater propagation) is not a problem; this
 141 design was used in the last century in the Black Forest and in the
 142 Swiss Alps in Europe (anonymous reviewer, personal communication,
 143 2020). A similar idea also was tested by Ikeda et al. (2010),
 144 although it must not be confused with the wall investigated herein,
 145 because in Ikeda et al. (2010) the role of the wall was to direct the
 146 water of a waterfall into an action turbine, with the aim of control-
 147 ling the flow direction at variable flow rates.

148 To avoid backwater propagation, the wheel and the wall at the
 149 inflow should not interact with the upstream water flow; hence
 150 the distance between the wheel and the wall was set at 0.15 m
 151 at the inflow. In the lowest half of the wheel, the clearance between
 152 the wall and the wheel must avoid friction between the wall and the
 153 wheel, and must minimize the flow through the gap. The gap value
 154 of 0.01 m was chosen because this value generally is adopted be-
 155 tween undershot/breastshot water wheels and their curb and lateral
 156 shrouds for manufacturing considerations (Quaranta and Müller
 157 2018). Therefore, the curvature radius R of the wall in the lowest
 158 half of the wheel was $R_{\text{wall}} = R_{\text{wheel}} + 0.01 \text{ m}$. The wall in the
 159 upper part of the wheel was shaped to gradually connect the supe-
 160 rior part of the wall (where there is clearance of 0.15 m) to its
 161 inferior portion. The wall has to be interrupted at $\theta \leq \pi$ (Fig. 3)
 162 for a correct emptying process and to avoid counteracting torque
 163 due to residual water that may be carried out upstream of the wheel.

164 Considering the presence of the wall, the following assumptions
 165 have to be taken into account in the theoretical model:

- 166 1. The amount of water that cannot enter into the buckets runs
 167 through the gap between the wall and the wheel. When the flow
 168 reaches $\theta = \pi/2$, i.e. one-half the wheel diameter D (Fig. 3), it
 169 enters the bucket. This means that the water flow which is lost

170 from the top of the wheel does not lose the full hydraulic head H
 171 (as in the original configuration), but it loses a potential head
 172 equal to $D/2$. Therefore, the inflow power loss L_{Q_u} [Eq. (2)]
 173 must be multiplied by $(D/2)/H$ (generally in overshot water
 174 wheels, $D \approx H$). The position $\theta = \pi/2$ was chosen for two reasons:
 175 at lower values of θ , the water jet may impact on the outer
 176 surface of the blade (the downstream face), generating power
 177 losses; and at $\theta = \pi/2$, the tangent at the wheel circumference
 178 is vertical, and thus the wall is easier to build in practical
 179 applications.

- 180 2. Once the water is redirected into the bucket, it remains inside the
 181 bucket, acting by its weight. When the bucket water volume
 182 equals the maximum storable volume, the bucket starts to
 183 empty; the emptying process is not affected by the wall, as
 184 in the original theoretical model. Therefore, the calculation
 185 method for the power losses L_{Q_r} does not change (Quaranta
 186 and Revelli 2015). However, in this case the bucket is filled with
 187 a larger amount of water, because it also contains the water that
 188 is lost at the inflow.
- 189 3. The critical rotational speed N_{cr} is the same, and it depends only
 190 on the wheel diameter [Eq. (2)]. This is because the inflow volumetric
 191 losses start at the same rotational speed (i.e., N_{cr}), so the
 192 inflow is not affected.

193 Results and Discussion

194 The modified theoretical model was applied to 256 operative
 195 conditions: the flow rate was in the range $Q = 0.01\text{--}0.137 \text{ m}^3/\text{s}$
 196 13 and the wheel rotational speed was in the range within $N =$
 197 14 $0.5\text{--}3.5$ rads/s. The upstream flow velocity varied between 0.5
 198 and 1.5 m/s, whereas the water depth at the end of the conveying
 199 channel (i.e. just upstream of the wheel) varied from 0.02 to 0.09 m.
 200 The velocity of the water jet during the impact with the blade
 201 ranged between 1.5 and 2.4 m/s (Quaranta and Revelli 2015).
 202 The average discrepancy between theory and experiments was
 203 8% [Fig. 2(b)].

204 Fig. 4 depicts the efficiency in the original configuration η_o and
 205 the efficiency in the modified configuration η_w with the wall. The
 206 efficiency is defined as the ratio of the power output to the power
 207 input, i.e. $\eta_o = P_o/P_{in}$ considering the original configuration, and
 208 $\eta_w = P_w/P_{in}$ considering the modified configuration, where P_w is
 209 the power output with the wall.

210 When $N > N_{cr} = 2.7$ rad/s, η_o and η_w decrease due the the in-
 211 crease of volumetric losses at the inflow with N (Fig. 4). However,
 212 η_w is higher than η_o , because the inflow water losses are redirected
 213 into the bucket at the middle of the wheel. When $N \leq N_{cr}$, improve-
 214 ments are negligible, because inflow volumetric losses are negli-
 215 gible. The ratio $\eta_w/\eta_o = P_w/P_o$ increases with the rotational
 216 speed (Fig. 4) according to the following dimensionless equation:

$$\begin{aligned} \frac{P_w}{P_o} &\approx 1 \quad \text{for } N < N_{cr} \\ \frac{P_w}{P_o} &= 1 + \left(1.54 \cdot \left[\frac{N}{N_{cr}} - 1 \right] \right) \quad \text{for } N > N_{cr} \end{aligned} \quad (3)$$

217 Once P_w is estimated and normalized to P_o [Eq. (3)], the power
 218 output improvement G_w strictly related to the wall can be calculated
 219 as $G_w = P_w - P_o$. If G_w is normalized by P_{in} , it can be added to the
 220 power loss terms in Eq. (1) to theoretically take into account of the
 221 wall benefit (the other power loss terms can always be estimated as
 222 in the original configuration); G_w/P_{in} can be expressed as a func-
 223 tion of the normalized speed N/N_{cr}

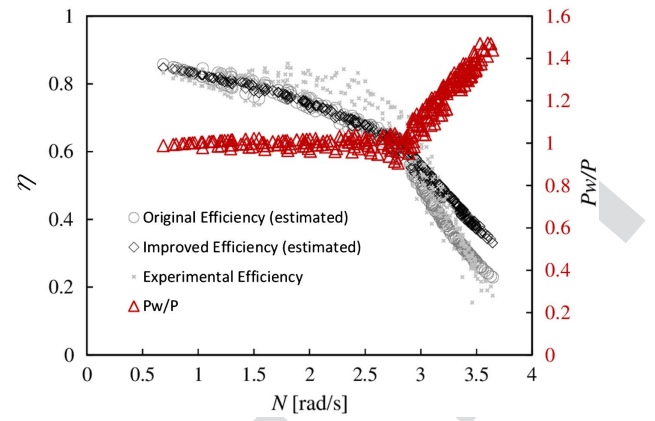


Fig. 4. Original efficiency (theoretically estimated and experimentally measured), η_o , improved efficiency, η_w , and $P_w/P_o = \eta_w/\eta_o$ versus rotational speed.

$$\frac{G_w}{P_{in}} = -0.94 \left(\frac{N}{N_{cr}} \right)^2 + 2.57 \left(\frac{N}{N_{cr}} \right) - 1.65 \quad (4)$$

Based on the investigated conditions, the terms calculated in Eqs. (3) and (4) are valid when $1 < (N/N_{cr}) < 1.35$, and can be applied in practical applications.

In our new configuration, water losses are converted into hydrostatic pressure, instead of velocity, generating a more effective [with η_w/η_o up to 1.5, whereas the ratio was 1.2 in Wahyudi et al. (2013)] and cheaper system. Furthermore, the additional cost of the wall is negligible with respect to the total cost of the installation, although some sediments may be trapped between the wheel and the wall, interfering with the rotation. A trash rack is required in this case, which, in any case, also is recommended for traditional water wheels.

Conclusions

A modified design of overshot water wheels was theoretically investigated with the intent of improving the performance at rotational speeds higher than the critical one. The modified design consists of a lateral wall around the width of the wheel. The wall recovers the inflow volumetric losses and redirects them into the wheel without affecting the upstream conditions. The modified design is a cost-effective improvement of overshot water wheels, and equations were proposed for use in practical applications to quantitatively estimate the benefits of the wall. This optimization can lead to the exploitation of higher discharges with higher efficiency. Future developments of this concept could lead to the increase of the operational speed of water wheels (with a consequent reduction of the electromechanics costs), improving the efficiency of the wheel up to 1.5 times with respect to the original efficiency.

Data Availability Statement

All data, models, and code generated or used during the study appear in the published paper.

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F4:3

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