Fish Swimming Behavior and Bypass Acceptance at Curved-Bar Rack Bypass Systems

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Abstract

The present study deals with the hydraulic and fish-biological performance of an innovative curved-bar rack bypass system (CBR-BS). CBR is a mechanical behavioral fish guidance structure typically combined with a BS, that was developed at VAW of ETH Zurich for safe downstream fish passage at hydropower plants. A hydraulically optimized CBR with a full-depth BS was tested with six European fish species, namely, spirlin, nase, barbel, Atlantic salmon parr, brown trout and European eel in an ethohydraulic laboratory flume. The approach flow velocities were 0.50 and 0.70 m/s and the velocity ratios (*VR*) of mean bypass inlet velocity to mean approach flow velocity were 1.2 and 1.4 for each flow velocity, resulting in four different hydraulic conditions. The flow field around the CBR-BS was numerically simulated for each hydraulic condition with a CFD model. The simulation results show that the velocity gradients between the curved bars and up to ~40 mm upstream from the rack are high. The live-fish tests showed that such high velocity gradients triggered an avoidance reaction of spirlin, nase, barbel, salmon parr and partly brown trout, but not of eel. Fish guidance and protection efficiencies of the CBR-BS were higher than 75% for spirlin, barbel, nase and Atlantic salmon parr, whereas they were lower than 75% and 50% for brown trout and European eel, respectively. Increasing *VR* from 1.2 to 1.4 significantly decreased the number of bypass passages underlining the importance of bypass design. Recommendations for an optimized and economic CBR-BS design are given.

Keywords: Downstream fish migration; Fish protection and guidance; Curved-bar rack, Bypass system, Hydropower plant

1. INTRODUCTION

Hydropower is the largest source of renewable electricity generation worldwide, with 16% of the total electricity generated in 2017 (Ritchie & Roser, 2020). In Switzerland and Norway, hydropower accounts for 56% and 97% of the annual electricity production, respectively, and hence is the backbone of both countries' grids. However, hydropower plants (HPPs) and dams in regulated rivers are deemed among the main threats for fish fauna sustainability. They may block or delay up- and downstream fish movements and cause damage or mortality when fish pass turbines, weirs or spillways (Larinier & Travade, 2002; Courret & Larinier, 2008; Silva *et al*., 2018). For an efficient restoration of water bodies, the European Water Framework Directive (WFD) and the revised Swiss Waters Protection Act (WPA) and Waters Protection Ordinance (WPO) were introduced in 2000 and 2011, respectively. For HPPs, fish passage facilities and connections to adjoining water bodies must be upgraded or newly erected. Whereas upstream fish passage technologies are well developed, downstream fish passage still poses greater challenges to HPP operators, authorities, engineers, and scientists due to the lack of design standards and related basic information on the behaviour of various fish species. Most downstream fish passage technologies target salmonid species, and therefore cannot be directly transferred to other geographical regions where fish species have different behavioural, ecological and biomechanical requirements. Among others, fish guidance racks (FGRs) with an adjacent bypass system (BS) constitute promising technological mitigation measures for HPPs, because they facilitate safe downstream

passage for a range of fish species and hydraulic conditions and are robust and less vulnerable to sediment and driftwood loadings.

For small-to-large HPPs with a design discharge, Q_d < 120 m³/s, FGRs with narrow bar spacing between 10 mm ≤ s_b ≤ 30 mm such as vertically inclined bar racks (Courret and Larinier, 2008) or horizontal bar racks (Ebel, 2016, Albayrak et al., 2020b; Meister et al., 2020a, b; Meister, 2020) with a BS are the state-of-the art fish guidance and protection technologies and widely prescribed by authorities (Boes et al., 2016). However, these FGRs are debated to be applied at medium to large HPPs because of their velocity limitation to avoid fish impingement, narrow bar spacing causing relatively high clogging and hence operational problems, and large investment cost. For these HPPs, FGRs with wider bar spacing of 100 mm ≥ s_b ≥ 25 mm and vertical bars such as Louvers, angled bar racks, Modified angled Bar Racks (MBRs) and recently developed Curved-Bar Racks (CBRs) present promising alternatives (Albayrak *et al.*, 2018, 2020a; Beck et al., 2020a, b, c). They are classified as mechanical behavioural fish protection barriers and may partly function as physical barriers, depending on fish size and bar spacing. Louvers are made of vertical straight bars placed at an angle $β$ = 90° to the flow direction mounted in a rack. The rack is placed across an intake canal at an angle to the flow direction of typically $α$ = 15° to 30° so that the rack parallel velocity V_p is higher than the rack normal velocity V_n for effective fish guidance (Courret and Larinier, 2008). Furthermore, V_n should be smaller than the sustained swimming speed of fish, $V_{sustained}$, which is around 0.5 m/s for many fish but can be lower for small fish or eels to avoid fish impingement against the rack. Sustained swimming speed refers to the swimming activity that can be maintained by the fish over several hours (typically 200 min) without fatigue (Hoover et al., 2017). Angled bar racks function similar to louvers but their bars are placed at 90° to the rack axis so that $β$ varies with the main angle $α$, i.e. $β$ = 90°−$α$. MBRs have an independent variation of $α$ and $β$ with $β$ ≠ 90°−$α$ (Albayrak *et al.*, 2018, 2020a). Based on the design of MBRs, the authors have developed CBRs which consist of a series of curved bars with $β$ = 45° to 90°. The out flow angle at the downstream end of the bar is typically parallel to the flow direction, i.e. $δ$ = 0° (Beck et al., 2020a, b, c, Figure 1). These four similar FGRs create flow separations around the bar tips, and changes in flow velocities, directions, and pressure so that fish can sense them and react with behavioural avoidance (Amaral, 2003, Albayrak et al., 2020a and Beck et al., 2020c).

High fish guidance efficiency (FGE) of Louvers, angled bar racks and MBRs are reported for a large range of fish species by Bates and Vinsonhaler (1957), Ducharme (1972), EMRI & DML (2001) and Albayrak et al. (2020a). The latter reported an interspecies average FGE of MBRs with $α$ = 15° and 30° of 80% and 65%, respectively, for five European freshwater fish species, namely common barbel (*Barbus barbus*), spirlin (*Alburnoides bipunctatus*), European grayling (*Thymallus thymallus*), brown trout (*Salmo trutta*) and European eel (*Anguilla anguilla*).

The novelty of the CBR is the curved cross-sectional shape of the vertical bars (Fig. 1). By placing the bar with an outflow angle of $δ$ = 0°, a flow straightening effect is created leading to significantly reduced head losses and quasi-symetrical downstream flow conditions as compared to other bar rack types (Beck et al., 2020a, b). Beck et al. (2020a, b) recommended a CBR configuration with $α$ = 30°, $β$ = 45°, $δ$ = 0° and s_b = 50 mm. The goals of this study are to report fish-biological performance of the recommended CBR configuration with a full depth open channel bypass system for various European fish species under different hydraulic conditions, the governing parameters affecting the fish protection and guidance, and to give recommendations for engineering application of the study results. Ultimately, the present results will contribute to improve the sustainable, efficient and fish-friendly usage of hydropower.
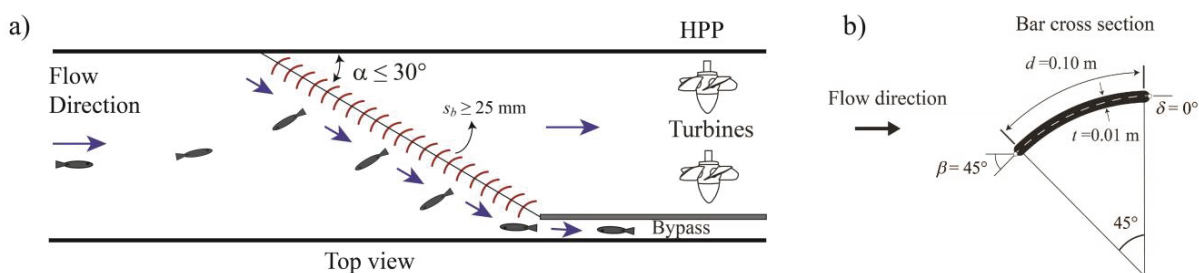

Figure 1. (a) Illustration of Curved-Bar Rack (CBR) and (b) curved-bar cross section.

2. MATERIALS AND METHODS

2.1 Test set-up and hydraulic conditions

Live-fish tests were conducted in a 30 m long, 1.20 m deep and 1.5 m wide open channel flume with a horizontal concrete bed at the Laboratory of Hydraulics, Hydrology and Glaciology (VAW) of ETH Zurich

(Figure 2a and b). The side wall of the flume was equipped with glass for lateral observation. The flume was connected to a closed water circuit with a cooling system. The 1:1 scaled section model of the hydraulically optimized CBR configuration with α = 30°, β = 45°, s_b = 50 mm (Figure 1a, b) was placed in the flume center with an adjacent full-depth open channel bypass of width w_{by} = 0.25 m. The discharges in the downstream and in the bypass channel were controlled separately with a flap gate at the end of each channel. The discharge in the flume was controlled with a frequency-controlled pump and measured with a Magnetic Inductive Discharge-meter (MID) of ±0.5% accuracy. The water depth h was measured using Ultrasonic Distance Sensors (UDS) of ±0.5% accuracy.

The approach flow water depth was kept at a constant value of 0.90 m. The live-fish tests were conducted at two different cross-sectionally averaged approach flow velocities of U_o = 0.50 and 0.70 m/s with bypass entrance velocities of (i) $U_{by,in}$ = 0.6 and 0.7 m/s, and (ii) $U_{by,in}$ = 0.84 and 0.98 m/s, respectively. The resulting cross-sectionally averaged bypass inflow to mean approach flow velocity ratios (VR) were $VR = U_{by,in}/U_o$ = 1.2 and 1.4 for each approach flow condition. These ratios were chosen based on the findings and recommendations in the literature [**Error! Reference source not found.**,**Error! Reference source not found.**]. A few tests were conducted for U_o = 0.50 m/s and VR = 1.1, and for U_o = 0.30 m/s and VR = 1.2 (Table 1). For the main tests, velocity measurements using Acoustic Doppler Velocimetry (ADV) and high-resolution numerical simulations were conducted (Beck, 2020; Beck et al., 2020c).
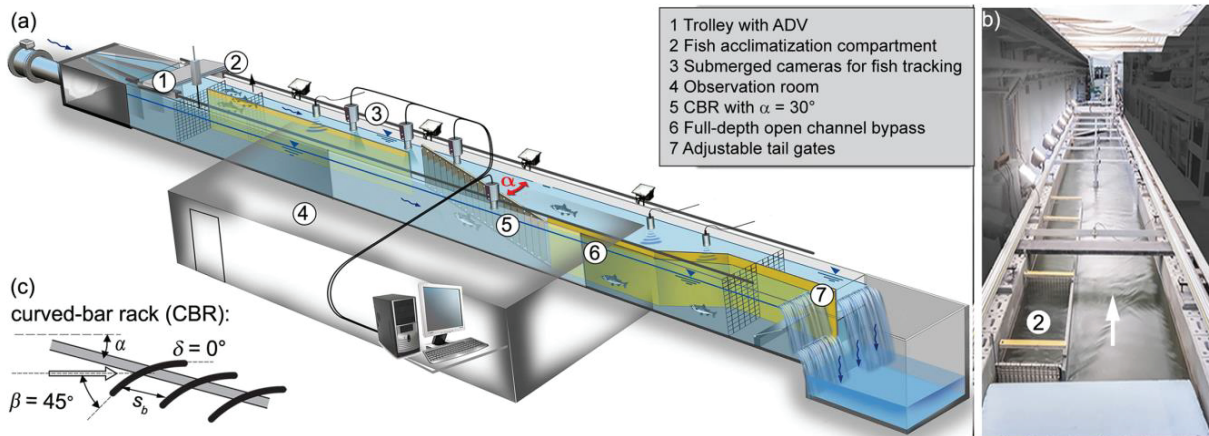

Figure 1. (a) Schematic 3D view and (b) photo of the ethohydraulic model flume, and (c) CBR definition sketch; adapted from Kriewitz (2015) and Beck et al., (2020c).

2.2 Live-fish tests and data analysis

Six fish species typically found in Swiss plateau rivers were tested with the recommended CBR configuration in autumn 2018 and in spring 2019. These were spirlin, common barbel, nase (*Chondrostoma nasus*), European eel, Atlantic salmon parr (*Salmo salar*) and brown trout (*Salmo trutta*). Wild fish were caught by electrofishing and transferred to fish holding tanks in the laboratory for a maximum of 7 days without feeding (Beck et al., 2020c). According to the river water temperature, the water temperature in the tanks and the flume was adapted to 12-16°C. The water quality (e.g., temperature, pH, oxygen concentration and turbidity) in the holding tanks and the flume were recorded daily. After the tests, all fish were brought back to the same river reach of the source river.

Three fish were used for each run. Each fish was photographed to measure their total length and then placed in a 1 m long, 0.5 m wide adaptation and starting compartment near the flume inlet at the left flume wall in flow direction (Figure 1b). In this compartment, the fish acclimatized to the flow conditions for 15 minutes in accordance with Albayrak et al. (2020). After the acclimatization phase, the downstream fence was raised and the three fish were free to swim downstream and interact with the CBR-BS. Their movements were recoded using five synchronized high-resolution cameras slightly submerged from top simultaneously recorded the fish movements at 50 Hz (Figure 1a, b). The videos were later analyzed with a fish-tracking software using Matlab [**Error! Reference source not found.**]. The duration of each test was 30 minutes after the starting compartment was opened. To reduce the total number of fish for the tests, each fish was used up to three times but with different hydraulic conditions, on different days and within another group of three fish. The minimum, mean and maximum fish total lengths TL_{min}, TL_{mean} and TL_{max}, respectively, are listed in Table 1 for all live-fish tests conducted in this study. The table lists the total number N of fish per species and the number of fish n leaving the starting compartment, actively swimming downstream, and interacting with the CBR-BS.

The number of active fish per hydraulic condition was above 21 except for two tests highlighted in red in Table 1 due to a limited fish number (Beck et al., 2020c).

Table 1. Test program for the live-fish tests with N = number of tested fish, and n = number of active fish, which were used for the further analyses.

Fish species	Spirlin	Trout	Nase	Barbel	Salmon	Eel
TL_{min} - TL_{max} (TL_{mean}) [cm]	8.4-11.9 (9.9)	9.5-20.4 (14.3)	6.5-8.9 (7.2)	9.7-22 (15)	7.9-15 (11)	50.4-80.9 (67.1)
N	150	189	33	102	60	16
n	142	117	33	84	60	14
Hydraulic conditions						
No rack test (U_o = 0.5 m/s, VR =1.2)	X					
U_o = 0.3 m/s, VR =1.2		X (n = 9)				
U_o = 0.5 m/s, VR =1.1			X			
U_o = 0.5 m/s, VR =1.2	X	X	X	X	X	X (n =14)
U_o = 0.5 m/s, VR =1.4	X	X		X	X	
U_o = 0.7 m/s, VR =1.2	X	X		X		
U_o = 0.7 m/s, VR =1.4	X	X		X		

Each fish was counted as an individual data point in the data analysis and performed one of the following four possible actions during the tests:

1. Bypass passage: the fish swam downstream, did not pass through the CBR, but swam at least 1.5 m into the bypass ("bypassed", subscript *by,all*)
2. Bypass passage with rack interaction: the fish swam near the CBR (a 15 cm wide corridor parallel to and upstream of the rack) during the test before finally swimming at least 1.5 m into the bypass ("bypassed with rack interaction", subscript *by,red*)
3. Rack passage: the fish swam downstream and eventually passed through the CBR ("rack passage", subscript *rack*)
4. Refusal: the fish swam near the rack, did not pass through the rack, and also refused to swim into the bypass within 30 minutes ("refusal", subscript *ref*)

Bypass passages were classified into two categories as with rack interaction ($N_{by,red}$) and without rack interaction ($N_{by,all}$). From four different listed actions, four parameters were defined to evaluate the performance of the CBR-BS: the fish guidance efficiency (FGE) and the fish protection efficiency (FPE) of the CBR-BS including only bypass passages with rack interaction (Eqs. [1,2]), respectively, the total system fish guidance efficiency (FGE*) (Eq. [3]) and the total system fish protection efficiency (FPE*) including all bypass passages (Eq. [4]):

$$FGE = N_{by,red} / (N_{by,red} + N_{rack} + N_{ref}) \qquad [1]$$

$$FPE = (N_{by,red} + N_{ref}) / (N_{by,red} + N_{rack} + N_{ref}) \qquad [2]$$

$$FGE^* = N_{by,all} / (N_{by,all} + N_{rack} + N_{ref}) \qquad [3]$$

$$FPE^* = (N_{by,all} + N_{ref}) / (N_{by,all} + N_{rack} + N_{ref}) \qquad [4]$$

2.3 Numerical model

The flow field around the curved bars was simulated using a 3-D computational fluid dynamics (CFD) model of the CBR-BS in the ethohydraulic flume in OpenFOAM® (v1812) based on the work of Leuch (2019). For turbulence modelling, the Shear Stress Transport (SST) k-ω model was used for the present application. The four main flow conditions listed in Table 1 (light grey highlighted) were simulated. The average mesh resolution in the domain up- and downstream of the CBR was 20 x 20 mm^2 with a refined mesh of 5 x 5 mm^2 around the CBR and three additional grid layers of 1 mm width around the bars (Beck, 2020). The simulation time was 200 s.

3. RESULTS

3.1 Flow field near bars and bypass of CBR-BS

The spatial velocity gradients in streamwise direction ($SVG_x = \partial U/\partial x$) in the vicinity of the downstream (d/s) rack end and at the bypass entrance are shown in Figure 3 for the four main flow conditions. The computation of SVG_x allows to identify areas of flow acceleration as well as deceleration. The cut-off value of | SVG_x | = 1 m/s/m (s^{-1}) is chosen since values equal to or above this value are known to trigger an avoidance reaction in salmonid species, which is therefore important for interpretation of fish behavior around the rack and in the bypass (Enders et al., 2012). Due to flow separation at the upstream bar tips, the SVG_x values are high between the bars and approx. 40 mm in front of the bars with values $SVG_x > 1$ s^{-1} and $SVG_x < -1$ s^{-1} indicating regions of a strong velocity increase and a strong velocity decrease, respectively. The alternating regions of high positive and negative SVG_x values contribute to the behavioural barrier effect of the CBR as a FGR.

A foam space-holder was placed between the last bar of the CBR and the separation wall dividing the bypass from the main channel to avoid large separation zones and to ensure a gradual velocity increase from the downstream rack end into the bypass. Nevertheless, a flow deceleration with values down to $SVG_x = -0.3$ s^{-1} is observed at the d/s rack end caused by the separation wall. High $SVG_x > 1$ s^{-1} are observed directly at the bypass entrance close to the separation wall due to the arrangement of the bypass parallel to the downstream channel for all flow conditions. This leads to a reduction of the available flow cross section with $SVG_x < 1$ s^{-1}. Downstream of the transition from the foam space-holder to the separation wall, a small separation zone with negative SVG_x values occurs. Otherwise, SVG_x remains positive inside the bypass indicating that there are no areas of flow deceleration. The different flow conditions lead to slightly different SVG_x distributions near the bypass entrance. Figure 3 shows that the velocity increase starts further upstream and reaches higher SVG_x values over the entire bypass width at higher VR and higher U_o. This means that the same VR values can lead to different SVG_x values at different U_o, thus triggering a different avoidance reaction of fish, which are sensitive to velocity gradients. More information on the turbulent flow characteristics around the CBR-BS can be found in Beck (2021).
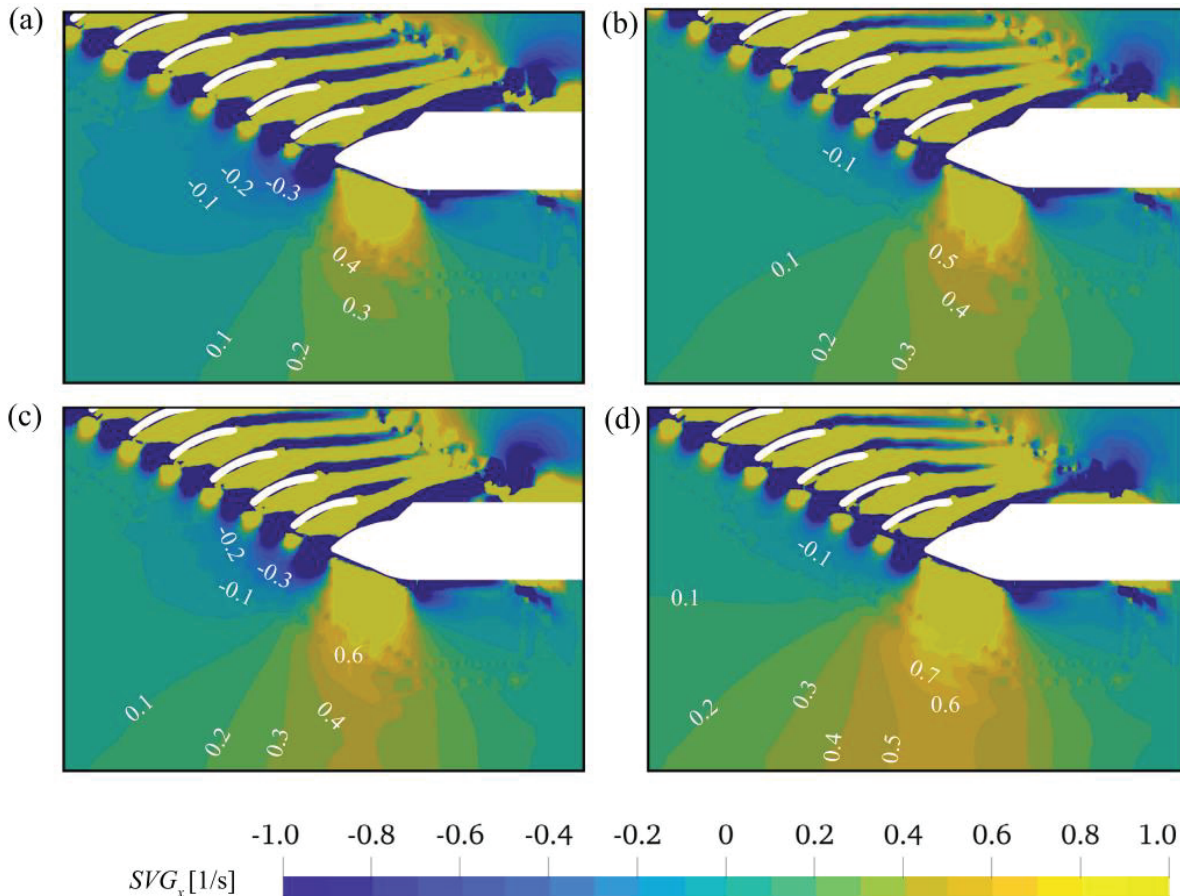
Figure 3. Spatial velocity gradients in streamwise direction (SVG_x) near the bypass entrance resulting from the numerical simulation at a normalized vertical distance from the bed $z/h_o = 0.14$ for (a) $U_o = 0.5$ m/s, $VR = 1.2$, (b) $U_o = 0.5$ m/s, $VR = 1.4$, (c) $U_o = 0.7$ m/s, $VR = 1.2$, and (d) $U_o = 0.7$ m/s, $VR = 1.4$ (source: Beck, 2020).

3.2 Fish guidance and protection efficiencies

The average, minimum, and maximum fish protection and guidance efficiencies considering only the bypass passages with rack interaction (FGE, FPE) and considering all bypass passages (FGE*, FPE*) resulting from the live-fish tests were calculated by taking the weighted average efficiencies over all tested flow conditions for each fish species and are shown in Figure 4. The average FGEs and FPEs for spirlin, barbel, nase and salmon parr are higher than 75% and 80%, respectively. Compared to these species, FGE and FPE for brown trout are lower with below 75% and 80%, respectively, while they are lower than 50% for European eel. For nase, eel and salmon parr, the FPEs are only slightly higher than the FGEs, indicating that these fish species rarely refused the CBR-BS but swam either into the bypass or through the CBR. On the contrary, the average FPE is considerably higher than the average FGE for spirlin, barbel and brown trout, because these fish were sensitive to the hydraulic conditions around the CBR-BS, in particular to the SVG_x near the bypass inlet (Figure 3) and mostly swam back upstream if they did not swim through the CBR or into the bypass. Finally, the average FGE* and FPE* did not significantly differ from the average FGE and FPE, indicating that consideration of the rack interaction in the data analysis does not greatly affect the resulting protection and guidance efficiencies for most of the tested fish species.

Although not shown here, Beck et al., (2020c) demonstrated that the approach flow velocity U_o did not have a significant effect on the number of bypass passages, i.e., FGE, of the CBR-bypass system (CBR-BS) in the tested range (Beck et al., 2020c). However, it significantly affected FPE. Contrary to U_o, the ratio of the bypass entrance velocity to the approach flow velocity $VR = U_{by,in}/U_o$ did have a significant effect on the fish guidance efficiency in the tested range. The total number of bypass passages, i.e., bypass acceptance of the fish significantly decreased, while the number of rack passages increased for $VR = 1.4$ compared to $VR = 1.2$ (Beck et al., 2020c). Furthermore, our visual observations indicated that nase hesitated less at the bypass and accepted it quickly at $VR = 1.1$ (Table 1).
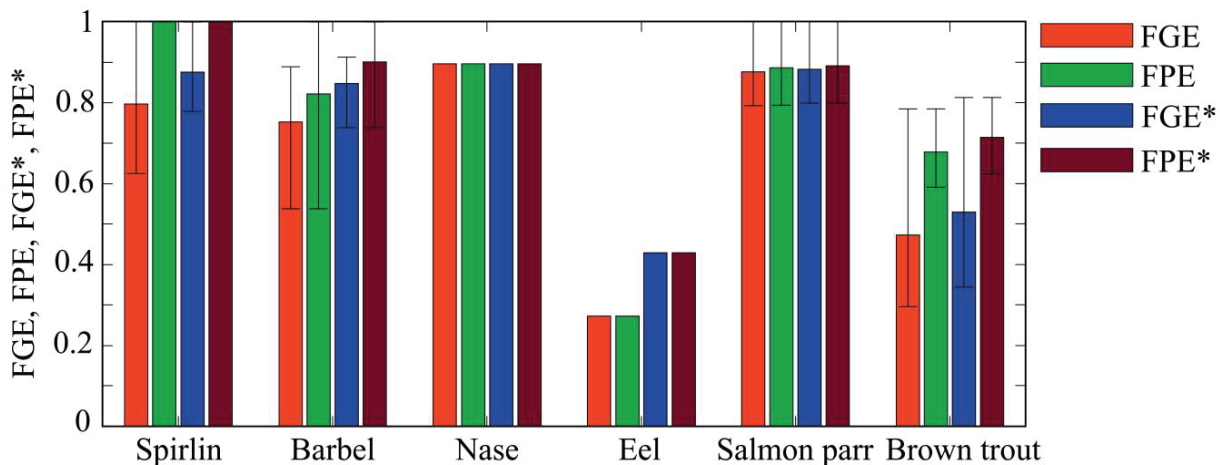
Figure 4. Fish guidance and protection efficiencies averaged over the tested hydraulic conditions by considering (i) the bypass passages with rack interaction (FGE, FPE) and (ii) considering all bypass passages (FGE*, FPE*) with additionally minimum and maximum values except for eel and nase (adapted from Beck et al., 2020c).

3.3 Fish behavior

The results of the live fish tests show that spirlin swam actively with a positive rheotaxis (fish align with head facing the approach flow) during all tests in a strong schooling behavior. Spirlin generally avoided direct contact with the flume bed and walls, or the CBR. When first approaching the CBR, the spirlin kept a distance of approx. 15 to 30 cm to the rack and were quickly guided by the positive rack parallel velocity towards the bypass. The swimming behavior of nase was similar to spirlin. Compared to spirlin and nase, salmon parr swam in loose schools. They repeatedly approached and moved away from the rack and were thereby guided to the bypass. The video recording revealed that they reacted with burst swimming against the flow between the bars, i.e. zones with high SVG_x (Figure 3).

In general, brown trout were mostly inactive during the tests (see *n/N* ratio in Table 1). In most tests, they showed a weak schooling behavior and swam mostly with a positive rheotaxis towards the rack. They explored the flow between the bars with their caudal fins similar to salmon parr, often reacting with swimming upstream and repeatedly changing the rheotaxis along the rack.

Compared to spirlin, nase and salmon parr, the swimming behavior of barbel was different. They swam mostly with positive rheotaxis and were more passive, spending more time in the starting compartment and preferring the low flow velocity regions of the flume. They were permanently in contact with flume bed and walls or the rack (a strong thigmotactic positive behavior). Such behavior of barbel was also observed by Albayrak et al. (2020c) during MBR tests.

The European eels showed a completely different behavior compared to the other tested fish species. They often approached the CBR with negative rheotaxis, collided with the rack and passed it without hesitation. Overall, they had a weak reaction to the hydrodynamic cues created by the CBR (Figure 3), which led to a low FGE and FPE of 27% (Figure 4).

3.4 Engineering application of the results

The hydraulic head losses, the flow fields and the fish guidance efficiency of CBR-BS are affected by a large number of parameters. In the following, each parameter is analyzed for an adequate engineering application and design of a CBR-BS regarding the hydraulic performance, efficient fish guidance as well as operational and economic issues. A step-by-step guideline for the design of a CBR-BS is found in Beck (2021).

Bar attack angle *β*: The curved bars of CBRs with $\beta = 45°$ cause a flow straightening effect resulting in a quasi-symmetrical flow distribution downstream of the rack. In the present study, the fish guidance and protection efficiencies (FGE, FPE) were only evaluated for a CBR with $\beta = 45°$. According to Kriewitz (2015) and Albayrak et al. (2020c), the FGEs in ethohydraulic laboratory tests for five European fish species, namely spirlin, European grayling, common barbel, brown trout and European eel, are significantly higher for MBRs with $\beta = 45°$ than for louvers with $\beta = 90°$. Similar trends are expected for the CBR since the velocity gradients upstream of the CBR are more gradual and the maximum velocities at the d/s rack end are decreased for $\beta =$

45° compared to β = 90° (Beck et al., 2020b). Since the upstream velocity gradients are decreased, the downstream flow distribution is improved, the head losses are significantly lower (Beck et al., 2020a), and the FGE for most tested fish species is high, CBRs with β = 45° are recommended over those with β = 90°.

Clear bar spacing s_b: The bar spacing does not significantly affect the head losses of the CBR with β = 45° for a range of 50 mm ≤ s_b ≤ 230 mm as compared to β = 90° and therefore should be selected mainly based on the size of the target fish species or operational aspects. It is expected that the physical and behavioral barrier effect of the CBR decreases with increasing s_b as demonstrated by EPRI and DML (2001), Kriewitz (2015) and Albayrak et al. (2020c). To ensure a high degree of fish guidance, clear bar spacings of s_b ≤ 50 mm are therefore recommended.

Rack angle α: It should not be larger than 45° because of high head losses and a should not be smaller than 15° due to excessive rack length and thus cost (Beck et al., 2020a). Furthermore, the ratios of parallel to normal velocity components V_p/V_n are more favourable for fish guidance with decreasing α. Additionally, the V_n values decrease with decreasing rack angle α with $V_n \approx U_o \cdot \sin(\alpha)$. Consequently, a smaller rack angle might be suitable for HPPs with higher approach flow velocities U_o in order to decrease V_n. Regarding the FGE, EPRI and DML (2001) and Albayrak et al. (2020c) showed high FGE for milder rack angles, i.e., α = 15°, for the tested North American and European fish species, receptively. Therefore, CBR with α ≤ 30° is recommended for high FGE and FPE.

Bottom and top overlays: Although overlays were not tested with fish in the present study, it is expected that fish guidance increases similarly as observed for louvers and MBRs with overlays (Odeh and Orvis, 1998; EPRI and DML, 2001; Amaral, 2003; Albayrak et al., 2020a). Ebel (2016) proposes a minimum height for top and bottom overlays of h_{To} = 1.0 m and h_{Bo} = 0.5 m, respectively. For approach flow depths $h_o >$ 5 m, the recommendation by Ebel (2016) can be applied to CBRs. For $h_o <$ 5 m, however, it is recommended to apply $h_v \leq (0.20...0.30) \cdot h_o$ to minimize the hydraulic head losses, where h_v is the total overlay height for both top and bottom (Beck, 2020).

Bar shape: the present curved bar shape of the CBR leads on average to 4.2-fold lower head losses than the straight, rectangular bars of the MBR (Beck et al., 2020a). Despite this, due to narrowing cross section of the current bar shapes in downstream direction, cleaning of the rack is difficult, which can lead to high clogging of the CBR. To mitigate this problem, the curved bar shape was further optimized and a foil-shaped bar (f-CBR) was developed (Beck, 2020). The f-CBR is expected to have a similarly high fish protection and guidance efficiency as the CBR and the application of the f-CBR is recommended.

Approach flow velocity U_o: Based on the present results, it is recommended to select the rack angle α to comply with the criteria $V_n \leq v_{sustained}$ proposed by Turnpenny and O'Keeffe (2005) and Ebel (2016) to enable fish of all sizes to react to the hydrodynamic cues of the mechanical behavioural barrier and avoid exhaustion.

Bypass design and operation: The main function of the bypass is to attract, safely collect and transport fish and to return them unharmed to the river downstream of an obstacle. The bypass must be easily found, quickly accepted, and passed by all fish species, while reducing energy expenditure, escape and exhaustion. The optimal position of a bypass is at the downstream end of a CBR. The ratio of bypass entrance to approach flow velocity VR is an important design criterion independent of the bypass design. Ebel (2016) recommends VR = 1.0...2.0 for all fish species, while USBR (2006) proposes VR = 1.1...1.5 for American fish species. To protect and guide fish of all species, life stages and sizes, VR = 1.1...1.2 are recommended according to the findings of this study. The recommended ratios should be maintained by bypass regulation for different flow discharges.

4. CONCLUSIONS and OUTLOOKS

The hydraulic performance and fish protection and guidance efficiencies of an innovative curved-bar rack bypass system (CBR-BS) were systematically investigated by means of numerical modelling and live-fish tests in the ethohydraulic flume at VAW of ETH Zurich, respectively. The hydraulically optimized CBR-BS configuration with a rack angle of α = 30°, bar angle of β = 45° and clear bar spacing of s_b = 50 mm was tested with six European fish species, namely, spirlin, nase, barbel, Atlantic salmon parr, brown trout and European eel. The average approach flow velocities were 0.50 and 0.70 m/s and the average bypass velocity to the approach flow velocity ratios, VR, were 1.2 and 1.4 for each approach flow velocity, resulting in a total of four different hydraulic conditions. In addition to those, three more different hydraulic conditions were tested.

The numerical simulation results show that the velocity gradients between the bars of the CBR and up to ~40 mm upstream of the rack are particularly high. The live-fish tests showed that such high velocity gradients triggered an avoidance reaction in most of the tested fish species in the tested range of fish total lengths and life stages. Partly brown trout and most of the European eel were exceptions as they reacted considerably less pronouncedly to the hydrodynamic cues of the CBR-BS than the other fish species. The approach flow velocity was found to have a negligible effect on the fish guidance efficiency of the CBR-BS. Increasing VR

from 1.2 to 1.4 significantly decreased the number of bypass passages and increased the number of rack passages. Therefore, *VR* = 1.1...1.2 is recommended for higher fish guidance efficiency. Overall, the CBR functioned as a mechanical behavioral barrier for spirlin, barbel, nase and Atlantic salmon parr with high fish protection and guidance efficiencies (> 75%) whereas it had low or no behavioral effect for brown trout and European eel, respectively. Recommendations for engineering applications are given.

Given the high fish protection and guidance efficiencies and improved up- and downstream hydraulic conditions compared to current fish guidance structure designs, CBRs offer a promising solution for the safe downstream fish movement for certain fish species at small-to-large hydropower plants and water intakes at reduced economic and operational impacts. A prototype CBR-BS is currently under construction at a pilot hydropower plant at the river Thur in Switzerland and its hydraulic and fish guidance and protection performance will be evaluated with a thorough monitoring study.

5. ACKNOWLEDGEMENTS

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