Design & performance of a hydraulic micro-turbine with counter-rotating runners

Daniel Biner | Vlad Hasmatuchi | François Avellan | Cécile Münch-Alligné
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Introduction

Hydroelectricity in Switzerland

56% of annual electricity production: 36'031 GWh
Small hydro (<10 MW) exploited: 3'400 GWh
Maximal small hydro potential: 2'200 GWh

Source: OFEN, 2015
Picture: www.zoomvertical.com
Introduction

Hydraulic energy of drinking water networks

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Hydraulic design

Technical specifications

$N^A = 3000 \text{ min}^{-1}$

$N^B = -3000 \text{ min}^{-1}$

$\varnothing 100 \text{ mm}$

$\varnothing 80 \text{ mm}$

$P_h = 2.6 \text{ kW}$

$P_m \geq 2.1 \text{ kW}$

$\eta_h = \frac{P_m}{P_h} \geq 80\%$
Hydraulic design

Runner geometry

Skeleton-line

Thickness distribution

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Design method

• Specific energy

\[ E = \frac{p_1 - p_{\bar{I}}}{\rho} + \frac{C_1^2 - C_{\bar{I}}^2}{2} + g(Z_1 - Z_{\bar{I}}) \]

pressure energy \hspace{1cm} potential energy \hspace{1cm} cinematic energy

• Euler equation applied to a given streamline

\[ E_t = U_1 C_{u_1} - U_{\bar{I}} C_{u_{\bar{I}}} = \eta_h \cdot E \]
Hydraulic design

Velocity triangles

\[ C = \vec{U} + \vec{W} \]

absolute flow velocity  \hspace{1cm} \text{peripheral runner velocity} \hspace{1cm} \text{relative flow velocity}

\[ U_I^A \quad \beta_I^A \quad W_I^A \]

\[ U_I^B \quad \beta_I^A \quad W_I^B \]

\[ C_{mI}^A \quad C_{mI}^B \]

\[ C_{uI}^A \quad C_{uI}^B \]

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Summary

\[
E = \frac{p_1 - p_I}{\rho} + \frac{C_1^2 - C_I^2}{2} + g(Z_1 - Z_I)
\]

\[
E_t = U_1 C u_I - U_I C u_I
\]
Fluid simulation

Numerical setup

- Finite volume method
- Steady state
- SST turbulence model
## Fluid simulation

### Meshing

<table>
<thead>
<tr>
<th>Domain</th>
<th>Domain motion</th>
<th>Nodes</th>
<th>Elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Runner 1</td>
<td>Rotating</td>
<td>546'864</td>
<td>1'458'718</td>
</tr>
<tr>
<td>Runner 2</td>
<td>Rotating</td>
<td>571'559</td>
<td>1'491'680</td>
</tr>
<tr>
<td>Stator 1</td>
<td>Stationary</td>
<td>475'084</td>
<td>1'193'490</td>
</tr>
<tr>
<td>Stator 2</td>
<td>Stationary</td>
<td>557'981</td>
<td>1'415'510</td>
</tr>
<tr>
<td>Full domain</td>
<td></td>
<td>2'151'488</td>
<td>5'559'398</td>
</tr>
</tbody>
</table>

*Unstructured tetrahedral cells*

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## Fluid simulation

### Results

<table>
<thead>
<tr>
<th>$\eta_h$ [%]</th>
<th>$Q$ [l · s$^{-1}$]</th>
<th>$P_h$ [W]</th>
<th>$P_m$ [W]</th>
<th>$\Delta p$ [bar]</th>
</tr>
</thead>
<tbody>
<tr>
<td>78.86</td>
<td>7.0</td>
<td>1'210</td>
<td>953</td>
<td>1.81</td>
</tr>
<tr>
<td>83.08</td>
<td>7.9</td>
<td>2'142</td>
<td>1'779</td>
<td>2.76</td>
</tr>
<tr>
<td>81.29</td>
<td>9.6</td>
<td>4'762</td>
<td>3'871</td>
<td>4.96</td>
</tr>
<tr>
<td>83.14</td>
<td>8.7</td>
<td>3'311</td>
<td>2'753</td>
<td>3.80</td>
</tr>
</tbody>
</table>

| $\geq 80$   | 8.7                  | $\geq 2'610$ | $\geq 2'090$ | 3.0 |

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Machining

• Prototyping for experimental tests
• CAM tool path generation
• 5 axis milling

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Performance measurements

Hydraulic test rig

- Max. pressure: 16 bar
- Max. discharge: 45 m³·h⁻¹
- Power/pump: 5.5 kW
- Total volume: 5'000 l

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### Performance measurements

#### Test results

<table>
<thead>
<tr>
<th>( \Delta p ) [bar]</th>
<th>( Q ) [l\cdot s(^{-1})]</th>
<th>( \alpha ) [-]</th>
<th>( N^B ) [min(^{-1})]</th>
<th>( \eta_h ) [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>3.95</td>
<td>1.0</td>
<td>1010</td>
<td>50</td>
</tr>
<tr>
<td>1.0</td>
<td>5.63</td>
<td>1.0</td>
<td>1493</td>
<td>51.5</td>
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<tr>
<td>1.3</td>
<td>6.77</td>
<td>1.18</td>
<td>1749</td>
<td>50.5</td>
</tr>
<tr>
<td>2.0</td>
<td>7.90</td>
<td>1.0</td>
<td>2003</td>
<td>52.8</td>
</tr>
<tr>
<td>2.5</td>
<td>9.22</td>
<td>1.0</td>
<td>2499</td>
<td>52.9</td>
</tr>
<tr>
<td>3.0</td>
<td>9.80</td>
<td>1.18</td>
<td>2257</td>
<td>53</td>
</tr>
</tbody>
</table>

\[
\alpha = \frac{N^A}{N^B}
\]

- **Mechanical losses**
- **Blade clearance gap**

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Conclusion

• New counter-rotating micro-turbine for drinking water networks has been developed
• Runners have been designed based on a simplified flow model
• Hydraulic efficiency of > 80% has been verified by fluid simulations
• Prototype runners have been machined and tested
• Measured efficiency is lower due to unconsidered mechanical losses
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