Turbine Engineering for Hydropower Plants

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Scope

- Basic Concepts
- Turbine Specific Energy
- Specific Speed
- Specifications
- Pelton Turbines
- Francis Turbines
- Outlook

Turbine Engineering for Hydropower Plants
Hydroelectric Power Plant:
Storage or Run-of-River Power Station

1 Gates
2 Penstocks
3 Inlet valve
4 Turbine
5 Generator
6 Automation, control, protection
7 Medium-voltage switchgear
8 Power transformer
9 High-voltage switchgear
10 Transmission line

Turbine Engineering for Hydropower Plants
Hydropower: Turbine Driving an Electrical (Synchronous) Generator

- **Machine Power Output**
  \[ P = \bar{\omega} \cdot \bar{T} \quad (W) \]

- **Available Hydraulic Power**
  \[ P_h = \rho Q \times E \quad (W) \]

- **Turbine Efficiency**
  \[ P = \eta^T \times P_h \quad ; \quad \eta^T \leq 100 \% \]

- **Driving Power Defined as Positive**
  \[ P \geq 0 \]

\[
\begin{align*}
J \times \frac{d\omega}{dt} &= T + T_{el} \quad (N \cdot m) \\
\bar{T} &= \bar{\omega} \\
E &= gH_i - gH_I \quad (J \cdot kg^{-1}) \\
P_h &= \rho Q \times E \\
&= \rho Q \times (gH_i - gH_I)
\end{align*}
\]

**Basic Concepts**
Rotating train dynamics

- Rotating train angular momentum equation
  \[ J \frac{d\omega}{dt} = T + T_{el} \] (N·m)

  ✓ Synchronous conditions: \( T = -T_{el} \)

  ✓ Power failure: runaway speed \( T_{el} = 0 \Rightarrow \frac{d\omega}{dt} = T > 0 \)

- Synchronous speed relation:

  ✓ \( f_{grid} \) : Grid frequency
  ✓ \( z_p \) : Number of poles
  ✓ \( n \) : Rotating frequency

  \[ n = \frac{2 \times f_{grid}}{z_p} \] (Hz)
  \( f_{grid} = 16\frac{2}{3} \text{Hz}; 50 \text{ Hz}; 60 \text{ Hz} \)

Basic Concepts
Discharge - Head Chart of Hydropower Plant Capacity

\[ P_h = \rho Q \times gH \]
Definition of State Variables

- **Mean Flow Local Specific Energy**
  \[ h_t = \frac{\rho}{\rho} + g \times Z + \frac{\dot{C}^2}{2} + \text{Cste} \quad (\text{J} \cdot \text{kg}^{-1}) \]

- **Discharge: Extensive Variable**
  \[ Q \triangleq \int_{A} \dot{C} \cdot \vec{n} dA \quad (\text{m}^3 \cdot \text{s}^{-1}) \]

- **Mean Flow Specific Energy: Intensive Variable**:
  \[ gH \triangleq \frac{P_h}{\rho Q} = \int_{A} \left( \frac{p}{\rho} + gZ + \frac{\dot{C}^2}{2} \right) \frac{\dot{C} \cdot \vec{n}}{Q} dA \geq 0 \quad (\text{J} \cdot \text{kg}^{-1}) \]

**Basic Concepts**
Hydraulic System: Specific Energy and Discharge Budgets

- **Specific Energy Budget**
  - Steady Flow?
  - Straight Stream Lines, free of Secondary Flow
  
  \[ gH_1 = gH_2 + \sum_{1 \to 2} (gH_r)_j \]

- **Flow Budget**
  - Discharge \[ Q_1 = Q_2 \]
  - Discharge Velocity \[ A_1 \times C_1 = A_2 \times C_2 \]
Runner/Impeller Specific Energy Transfer

- **Traversing Discharge**
  \[ Q_t \quad \left( \text{m}^3 \cdot \text{s}^{-1} \right) \]

- **Transferred Specific Energy**
  \[ gH_1 - gH_{\bar{1}} = E_t \pm E_{rb} \quad \left( \text{J} \cdot \text{kg}^{-1} \right) \]

- **Power Transfer**
  \[ P_t = \rho Q_t E_t \quad (\text{W}) \]

  ✓ **Drive:** Turbines
  \[ P > 0 \]

  ✓ **Brake:** Pumps, Propellers
  \[ P < 0 \]

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Brilliant Extension Project, British Columbia, Canada, Kaplan Turbine CAD Model, PF2 EPFL Test Rig

**Turbine Specific Energy**
Specific Energy Transfer

\[ gH = \frac{p}{\rho} + gZ + \frac{C^2}{2} \quad \left( \text{J} \cdot \text{kg}^{-1} \right) \]

\[ E_t = \left( \frac{\rho_1 - \rho_{\text{II}}}{\rho} \right) + \left( \frac{C_1^2}{2} - \frac{C_{\text{II}}^2}{2} \right) + \left[ gZ_1 - gZ_{\text{II}} \right] \pm E_{rb} \quad \left( \text{J} \cdot \text{kg}^{-1} \right) \]

Turbine Specific Energy
Dimensional Analysis

- “Power Plant” Conditions
  - Discharge
    \[ [Q] = L^3T^{-1} \cdots (m^3 \cdot s^{-1}) \]
  - Specific Energy
    \[ [E \triangleq gH_i - gH_T] = L^2T^{-2} = \frac{ML^2T^{-2}}{M} \cdots (J \cdot kg^{-1}) \]
- Unit Characteristic
  - Angular Speed
    \[ [\omega] = T^{-1} \cdots (s^{-1}) \]
  - Turbine/Pump Dimension
    \[ [D] = L \cdots (m) \]

Specific Speed...
Dimensional Analysis (Contd)

- Dimensionless Angular Speed Condition

\[ [\nu] = \left[ \omega \times Q^\alpha \times E^\beta \right] = M^0 \times T^0 \times L^0 \]

\[ T^0 \times L^0 = T^{-1} \times L^{3\alpha} T^{-\alpha} \times L^{2\beta} T^{-2\beta} \]

- Yields Linear System

  ✓ Dimension of Time

  \[-1 - \alpha - 2\beta = 0\]

  ✓ Dimension of Length

  \[3\alpha + 2\beta = 0\]

- Solution

  \[ \alpha = \frac{1}{2}; \quad \beta = \frac{-3}{4}\]

  \[ \nu = \frac{\omega}{\pi^2 \frac{2^4}{3}} \times \frac{Q^{\frac{1}{2}}}{E^{\frac{3}{4}}} \]

  Specific Speed
Dimensional Analysis (Contd)

- **Discharge Coefficient**
  \[ \varphi = \frac{Cm}{U} \]

- **Energy Coefficient**
  \[ \psi = \frac{2E}{U^2} \]

- **Specific Speed**
  \[ \nu = \frac{\varphi^2}{3} = k_U \sqrt{k_{cm}} \]
  \[ \psi^4 \]

- **Unit Specific Speed**

  ✓ Rotating Speed \( N \) \( (\text{min}^{-1}) \)
  \[ n_Q = N \times \frac{Q^2}{3} = 157.7 \times \nu \] (S.I.)
Selecting Hydraulic Turbines

Head

Highest eff. $\approx 96\% \div 97\%$

Specific Speed

Head = $H$ (m)
Discharge = $Q$ (m$^3$·s$^{-1}$)
Speed = $N$ (min$^{-1}$)

$$n = \frac{2 \times f_{\text{grid}}}{z_p} \text{ (Hz)}$$

$\frac{1}{n_q} = \frac{N}{\frac{Q^2}{H^3}}$
Hydro Turbines International Market

- Breakdown by Types of Turbines
  - 1’038 GW Installed Capacity in 2012
  - Modernization Market
  - 1’000 GW to be built before 2050
  - Greenfields Project

- Pie chart showing:
  - Francis 61%
  - Kaplan 17%
  - Pump-Turbine 12%
  - Pelton 8%
  - Bulb 2%

Turbine Specifications
Matching Turbine Specific Speed to Site Conditions

- Site Potential Specific Energy: \( g(Z_B - Z_B) \)
- Site Specific Energy: \( gH_1 - gH_\bar{1} = g(Z_B - Z_B) - \sum gH_r \ (J \cdot kg^{-1}) \)
- Data Science: Flow Duration Statistics
  - Average Discharge: \( Q_{\text{Instal.}} \ (m^3 \cdot s^{-1}) \)
Matching Turbine Specific Speed to Site Conditions

- **Targeted Unit Specific Speed**  
  \[ n_Q = N \frac{1}{\sqrt[3]{Z_{\text{units}}}} \frac{Q_{\text{instal.}}}{H^4} \]

  - **Rated Head**  
    \[ E = gH \]
  
  - **Specification of Unit Number**  
    \[ Z_{\text{units}} \]
  
  - **Specification of rotating frequency**  
    \[ N = \frac{2f_{\text{grid}} \times 60 \text{ s}}{Z_p} \]

- **Runaway Speed Limitation**

- **Limitation of Apparent Power per Poles**
  
  - **Air cooling** < 28 MVA < **Water cooling** < 35 MVA
1'269 MW Bieudron Power Plant
3 Pelton Turbines

- 500 MVA Generators
  - 428.5 min⁻¹
  - 14 poles, 35.7 MVA/pole*
  - Water Cooled

- 423 MW Pelton*
  Turbines, 5 injectors
  - 1'883 mWC Head*
  - 25 m³/s Discharge
  - D1 = 3.993 m
  - ~28 t Runner Mass
Impinging Jet on Pelton Buckets
FVPM Flow Numerical Simulations

Christian VESSAZ, EPFL Doctoral Thesis N° 6470, 2014

Pelton Turbines
Silt Erosion

- Needle Severe Erosion
- Erosion Ripples on Buckets
- ~2'500 Total Hours of Operation

Pelton Turbines
SPHEROS Finite Volume Particle Method Solver
Multi Scale Silt Laden Flow Erosion Simulation

Copper sample
Ø 3 mm slurry jet, 10 m/s

Pelton Turbines

LEGUIZAMON Sebastián, EPFL Doctoral Student, CTI Project GPU-SPHEROS
Giga Hydropower Plants are Francis Powered

<table>
<thead>
<tr>
<th>Hydropower Plant</th>
<th>Country</th>
<th>Capacity (MW)</th>
<th>Energy (TWh)</th>
<th>Capacity Factor</th>
<th>EPFL Model Testing</th>
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</table>

Francis Turbines

Tucurui Dam, Eletro Norte
Xiangjiaba Power Station  
(Jinsha River, Yunnan)

- 8 Francis Turbines
- 825 MW Max. Power
- 10.5 m Diameter
- $\approx 406,000$ kg

What level of $p$ fluctuations to be expected for a 800 MW turbine?
HYPERBOLE Turbine Case Study
Hill Chart and Operating Range

Deep Part Load  Part Load  Full Load

Francis Turbines
Unsteady Flow in Francis Draft Tube

Müller et al., Experiments in Fluids n° 54 : 1514, 2013.


Simon Pasche PhD Work, SNF GRANT N° 200021_149818

Francis Turbines
Machine Setting Level

**IEC 60193 Definitions**

- **Specific Energy**
  
  \[ E \triangleq gH_i - gH_T > 0 \quad (\text{J} \cdot \text{kg}^{-1}) \]

- **Net Positive Suction Specific Energy**

  \[ \text{NPSE} \triangleq gH_i - \frac{p_v}{\rho} - gZ_{\text{ref}} \quad (\text{J} \cdot \text{kg}^{-1}) \]

- **Setting Level**

  \[ h_s = Z_{\text{ref}} - Z_{\text{B}} \]


**Turbine Specifications**
HYPERBOLE
ERC/FP7-ENERGY-2013-1-Grant N° 608532

- HYdropower plants PERformance and flexiBle Operation"towards Lean integration of new renewable Energies
  - Dynamic Assessment of Francis Turbines & Pump-Turbines
  - 42 Months, EUR 6.3 Mio
  - EUR 4.3 Mio Supported by European Commission

- Consortium coordinated by EPFL
HYdropower plants PERformance and flexiBle Operation towards Lean integration of new renewable Energies

- **Hydraulic Eng.**
- **Mechanical Eng.**
- **Electrical Eng.**
- **System Approach**

**HYPERBOLE**

ERC/FP7-ENERGY-2013-1-Grant 608532
System Approach Methodology

WP5
Field Test Based Validation

WP6
Powerplant Network Integration

WP4
Hydroelectric System Modelling

WP2
Mechanical Structure Dynamics

WP3
Electrical Machine and Power Electronics

WP1
Hydraulic Excitation Sources Induced by Off-Design Operations

Experimental Investigations using Reduced-Scale Physical Model

SIMSEN: System Dynamics Numerical Simulation Software

Francis Turbines
Deep part load operating conditions $Q \ll QBEP$

- Inter blades vortices

**Francis Turbines**
Deep part load
Inter blades vortices
Visualization

- Hollow guide vanes with window
- Boroscope with swivelring prism
- High Speed Camera
- High intensity Xenon flash
- Compact power LED

Francis Turbines
Deep part load
Inter blades vortices

Flow Numerical Simulations

Void Fraction 10% Isosurface
Hydroelectric Plants Generate 17% of the World Electricity

Unleashing Limitless Energy
The Digital Hydro Power Plant

THANK YOU FOR YOUR ATTENTION

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