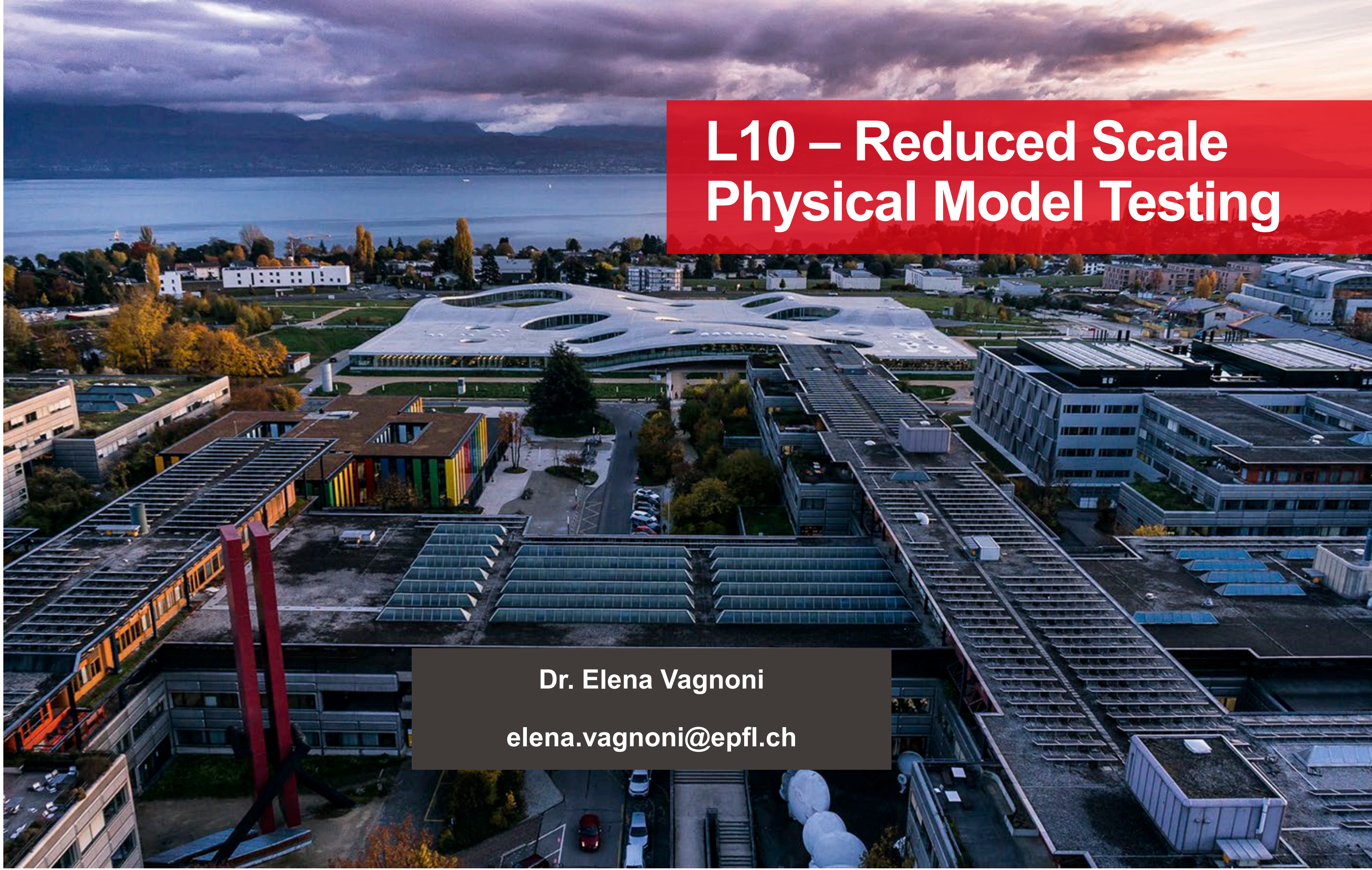

L10 – Reduced Scale Physical Model Testing

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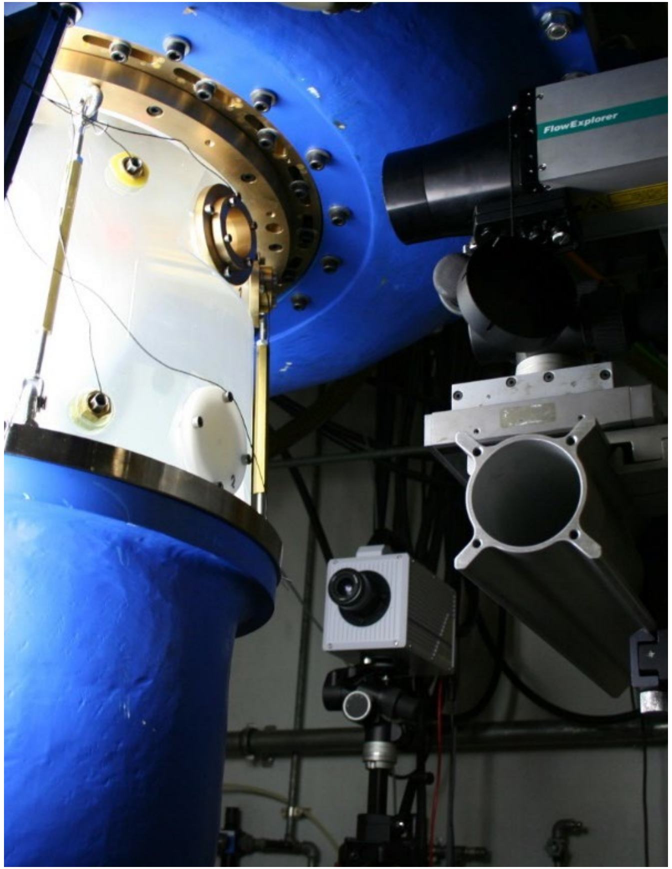
Topics of the lecture

- Purpose and reasons of Independent Model Testing
- Dimensional analysis and similarity
- Practical implementation
- Machine performance (measurements, analysis and presentation)
  - Productivity prediction
  - Liable operation



Why model testing?

Dimensional analysis and similarity

Performance characteristics

Before constructing or manufacturing hydraulics structures or machines, tests are performed on their reduce scale models to obtain desired information about their performance.

Similarity: is defined similarity between model (M) and prototype (P) when both have similar proprieties:

- ✓ Geometric
- ✓ Kinematic
- ✓ Dynamic

Geometric similarity

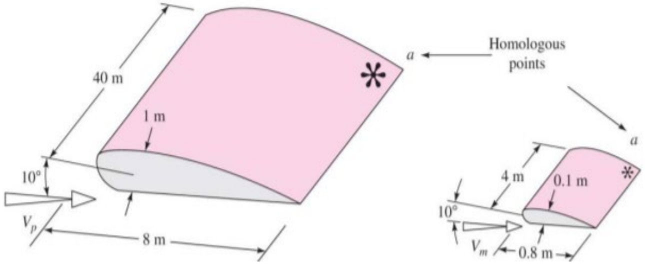
$$\lambda_r = \frac{L_M}{L_P} = \frac{D_M}{D_P}$$

Where:

λ_r:scale ratio

L: Length

D: Diameter



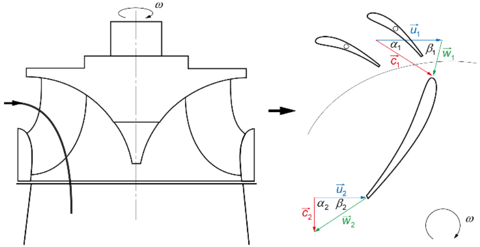
Kinematic similarity

$$C_r = \frac{C_M}{C_P}$$

Where:

C_r :Velocity ratio

C: Velocity



Homology of velocity triangles

Dynamic similarity

$$F_r = \frac{(F_i)_M}{(F_i)_P} = \frac{(F_v)_M}{(F_v)_P} = \frac{(F_g)_M}{(F_g)_P}$$

Where:

F_r: force ratio

F_i: Force inertia

F_v: Force viscous

F_g: Force gravitational

Dimensional analysis and similarity
Performance characteristics

To obtain performance characteristics of turbomachines conveniently and accurately, it is essential to use dimensional analysis → it reduces the variables to a number of manageable dimensional groups.

Dimensional analysis applied to turbomachines has two important uses:

- ✓ To predict prototype behavior and characteristics from the model tests results
- ✓ To evaluate the runner performances (determination of the most suitable type of machine, on the basis of maximum efficiency, for a specified range of head, speed, and flow rate)

Dimensional analysis and similarity

Dimensionless numbers

Dimensionless numbers are the number which are obtained by dividing the inertia force by the viscosity or gravity or pressure force or surface tension or elastic force

Inertia force to viscosity force	$Re = \frac{\pi n D^2}{\nu}$	$Re_P = Re_M$
Inertia force to gravity force	$Fr = \left(\frac{E}{gD}\right)^{0.5}$	$Fr_P = Fr_M$
Thoma number: suction head to available head	$\sigma = \frac{NPSE}{E}$	$\sigma_P = \sigma_M$
Inertia force to surface tension force	$We = \frac{\rho L v^2}{\sigma^*}$	$We_P = We_M$

Source: IEC 60193:2019

Similarity
IEC recommended dimensionless terms

Head and discharge are usually converted into dimensionless number: n_{ED}, Q_{ED} , P_{ED}, T_{ED} taking into account the laws of similarity

Speed factor

$$n_{ED} = \frac{nD}{E^{0.5}}$$

Power factor

$$P_{ED} = \frac{P_m}{\rho_1 D^2 E^{1.5}}$$

Discharge factor

$$Q_{ED} = \frac{Q_1}{D^2 E^{0.5}}$$

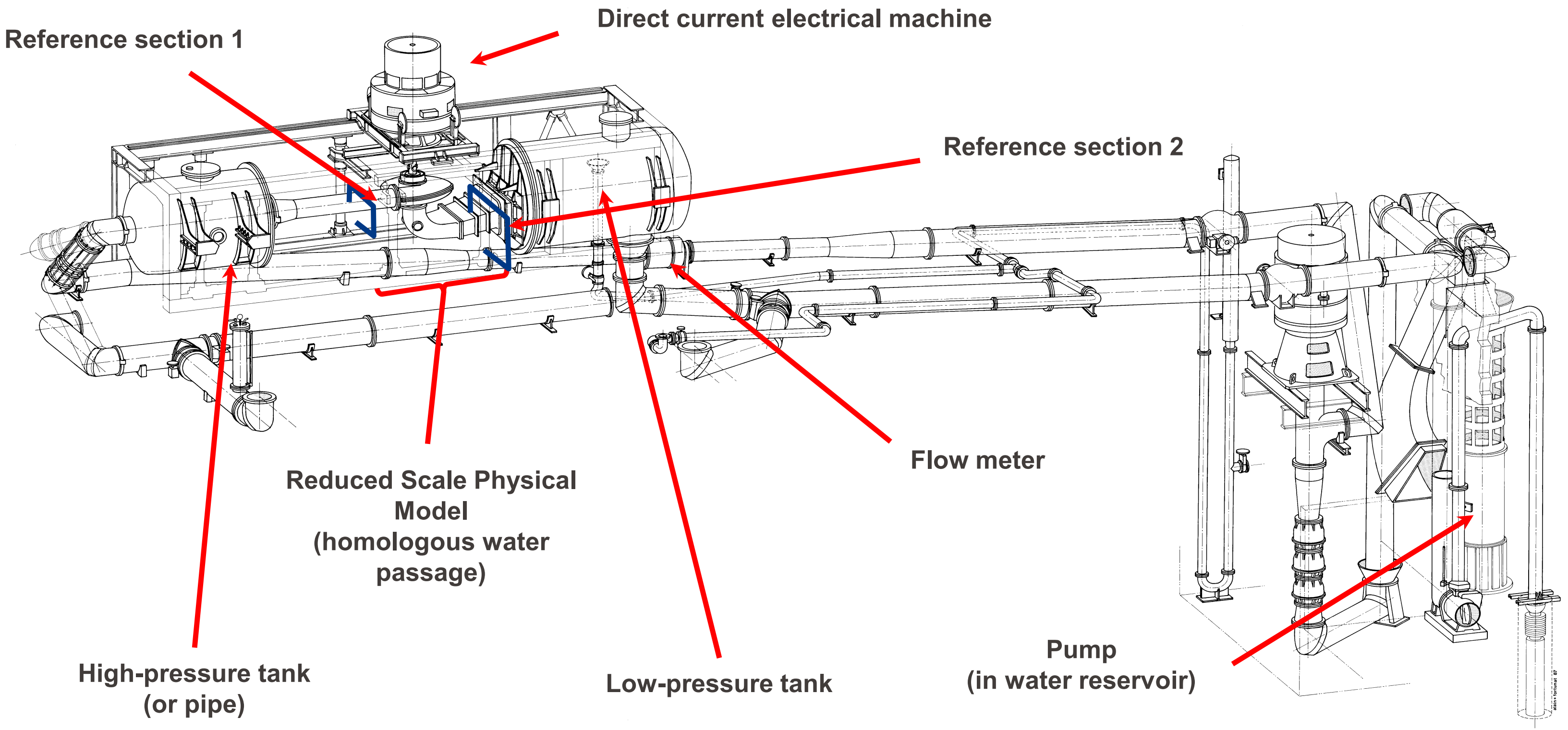
Torque factor

$$T_{ED} = \frac{T_m}{\rho_1 D^3 E}$$

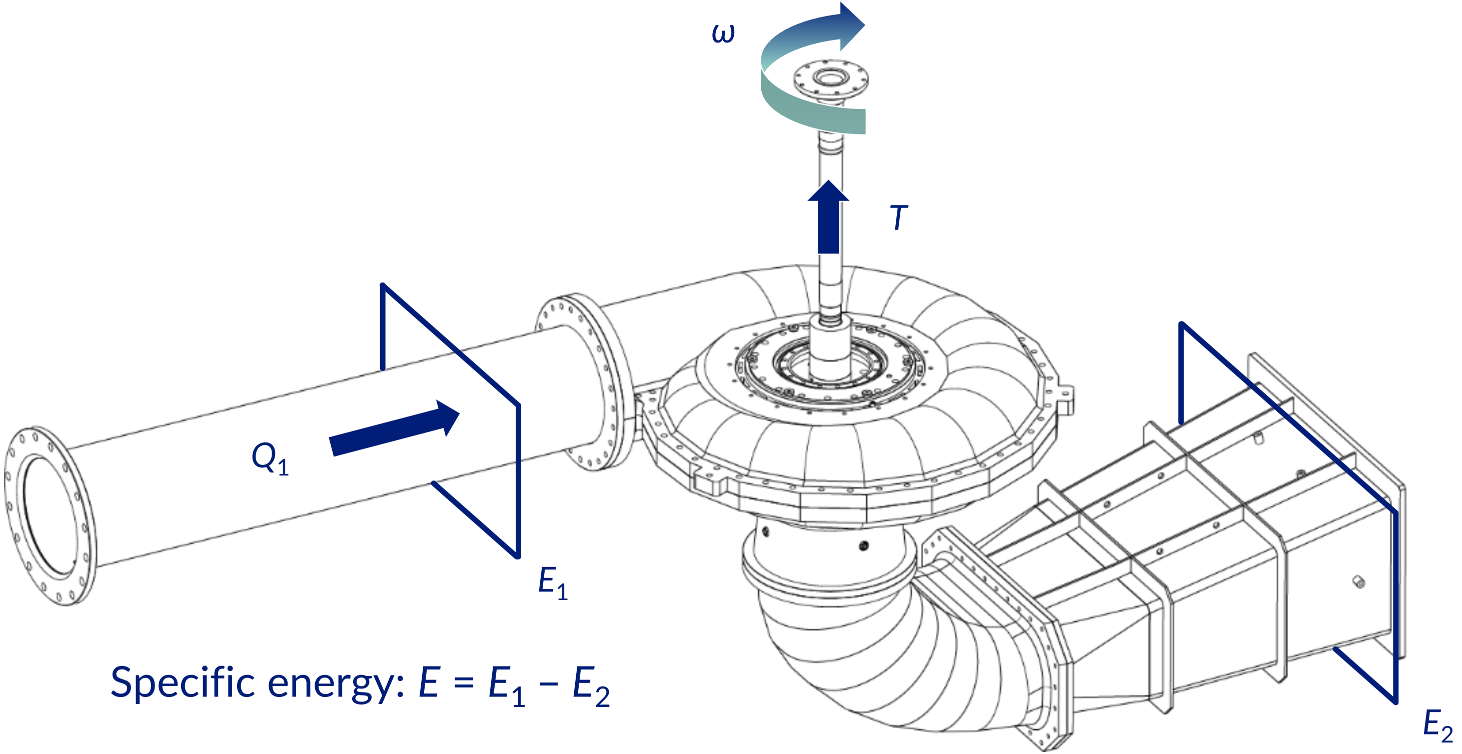
Source: IEC 60193:2019

Practical implementation

Instrumentation and test rig set-up



Performance measurements

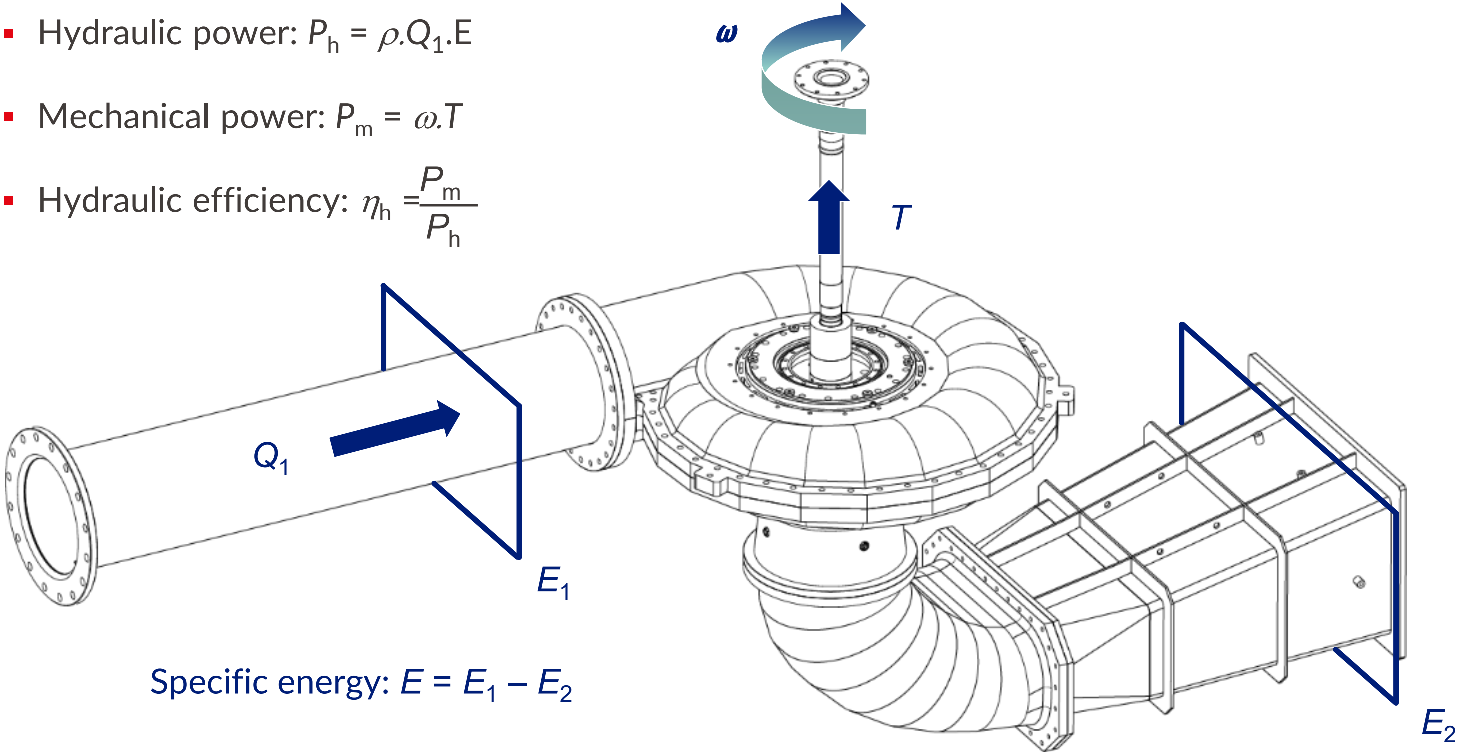


Specific energy: $E = E_1 - E_2$

Performance measurements

Determining hydraulic power

- Hydraulic power: $P_h = \rho.Q_1.E$
- Mechanical power: $P_m = \omega.T$
- Hydraulic efficiency: $\eta_h = \dfrac{P_m}{P_h}$

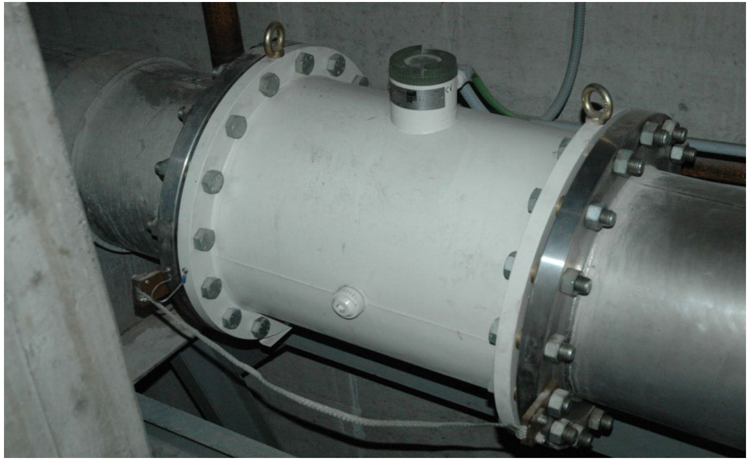


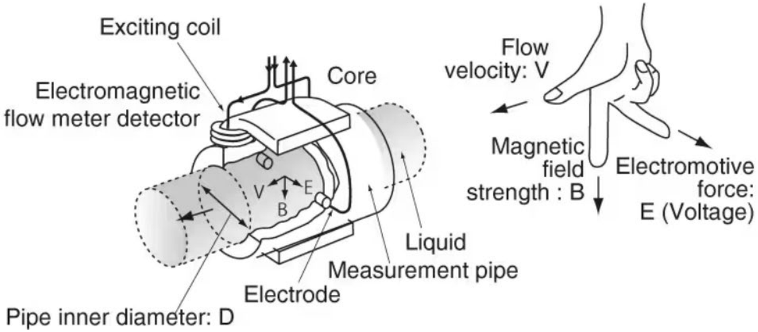
Specific energy: $E = E_1 - E_2$

Performance measurements
Determining hydraulic power: discharge

Example of discharge measuring device

- Electromagnetic flow meter
- Diameter 0.400 m
- Measuring range 0.05 – 1.40 $m^3 \cdot s^{-1}$
- Calibrated with a 150 m^3 volumetric tank
- Advantages
  - Accuracy of measure
  - Direct measure of flow in 2 directions
  - Non-intrusive: does not influence flow





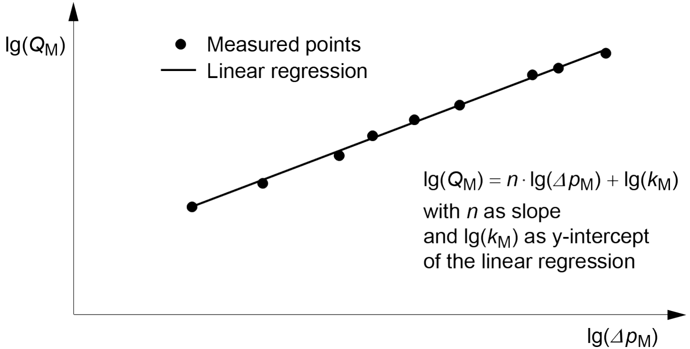
Faradays law: $E = V \cdot D \cdot B$

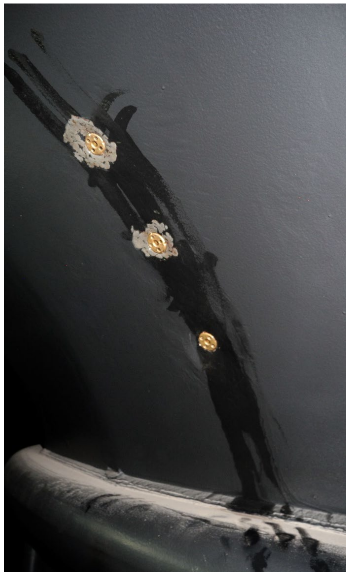
Practical implementation
Instrumentation for Winter-Kennedy test

Index testing (Winter-Kennedy)

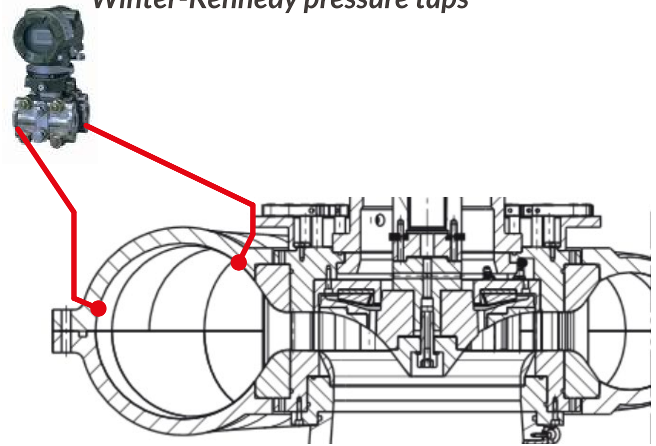
- Typically measured with differential pressure transducers
- Can be used to calculate energy losses, flow in the spiral case, Pelton needle-jet flow, flow characteristics in channels, etc.
- Transposable to prototype using a linear regression using the least square method and the following equation: $Q = a\Delta p^{b}$

  With the value of *b* the same for model and prototype and *a* defined by: $a_P = a_M \left(\frac{D_P}{D_M}\right)^{(3-2b)} \left(\frac{n_P}{n_M}\right)^{(1-2b)}$





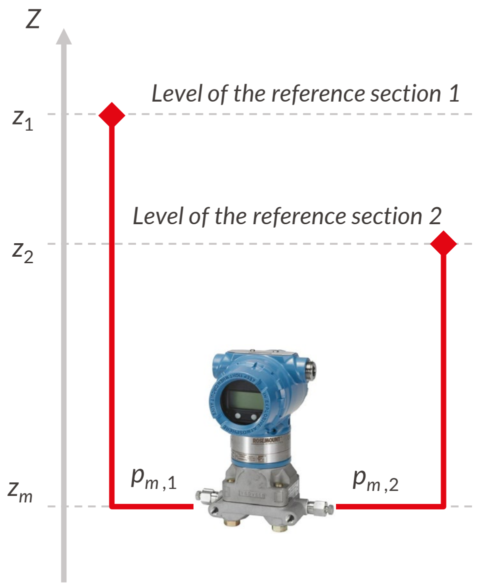
Winter-Kennedy pressure taps



Performance measurements
Determining hydraulic power: specific energy

Example of pressure transducer set-up

- Differential pressure transducer
- Measuring ranges:
  - ✓ 0 – 5 bar
  - ✓ 0 – 10 bar
- Advantages
  - Only one transducer is needed
  - Reference level of measuring instrument not necessary



$$\Delta p = p_{m,1} - p_{m,2} = \left(\rho \cdot g \cdot (Z_1 - Z_m) + p_1\right) - \left(\rho \cdot g \left(Z_2 - Z_m\right) + p_2\right)$$

$$\boxed{\Delta p = \left(\rho \cdot g \cdot Z_1 + p_1\right) - \left(\rho \cdot g \cdot Z_2 + p_2\right)}$$

Performance measurements

Determining hydraulic power: specific energy

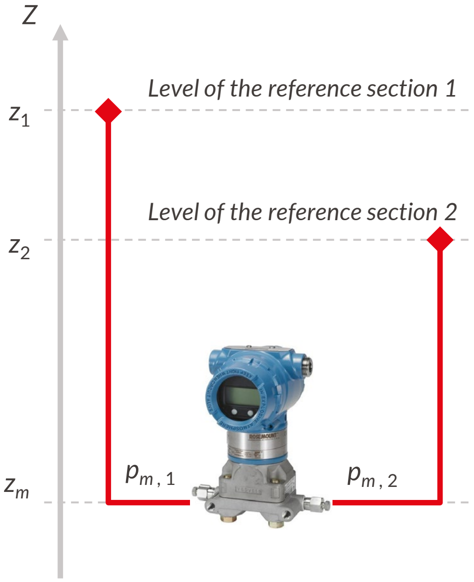
From Model Head to Specific Energy

$$E = \left(g \cdot Z_1 + \frac{p_1}{\rho} + \frac{C_1^2}{2} \right) + \left(g \cdot Z_2 + \frac{p_2}{\rho} + \frac{C_2^2}{2} \right)$$

$$E = \left[\left(g \cdot Z_1 + \frac{p_1}{\rho} \right) - \left(g \cdot Z_2 + \frac{p_2}{\rho} \right) \right] + \left[\left(\frac{C_1^2}{2} + \frac{C_2^2}{2} \right) \right]$$

$$E = \frac{\Delta p}{\rho} + \frac{Q^2}{2} \left[\frac{1}{S_1^2} - \frac{1}{S_2^2} \right]$$

with S_1 and S_2 being the upstream and downstream measuring sections



Performance measurements
Determining mechanical power: torque

Examples of torque measuring devices

- Torque meter mounted on shaft (torque measured directly)
- One resistive torque meter to measure the torque transmitted from the shaft to the electrical machine
- Measuring up to 2000 Nm
- Force transducer with torque lever and weights

$$T = F \cdot L$$

Source: IEC 60193:2019

Performance measurements

Determining mechanical power: torque

Friction torque

- Shaft bearing mounted on an hydrostatic swinging frame (blue)
- No friction between swinging frame (green) and fixed bench (gray)
- Friction torque transmitted from the shaft to the swinging frame directly measured by a load cell
- Range of the friction torque: 10 -15 N·m depending on rotational speed and the axial thrust
- Example using a force transducer

$$T_{fr} = F \cdot L_{Lm}$$

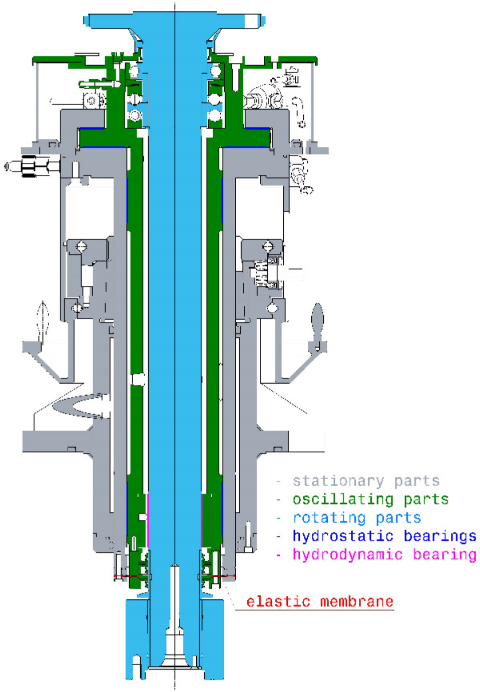
- Total torque in turbine mode

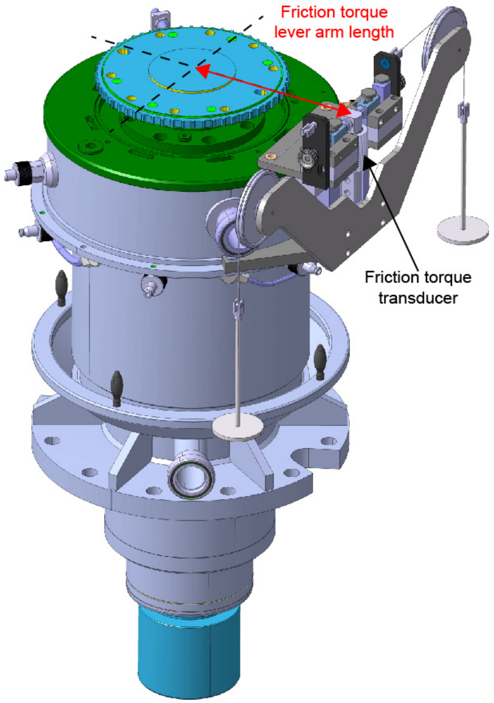
$$T_m = T + T_{fr}$$

- Total torque in pump mode

$$T_m = T - T_{fr}$$

T_{fr} : Friction torque in guide bearings, thrust bearings and shaft seals of the hydraulic machine





Turbine mechanical power

Mechanical power used in efficiency calculation determined from mechanical torque

$$P_m = 2\pi n T_m$$

Performance measurements
Determining mechanical power: rotational speed

Rotational speed measurement:

Instrument type: Magnetic cell
Model: Type IMRM 12N1501
Manufactured by: BAUMER Electric

$$\omega_M = \frac{2\pi n_M}{60}$$

Source: IEC 60193:2019

Practical implementation
Calibration

All instruments shall be calibrated prior to testing:

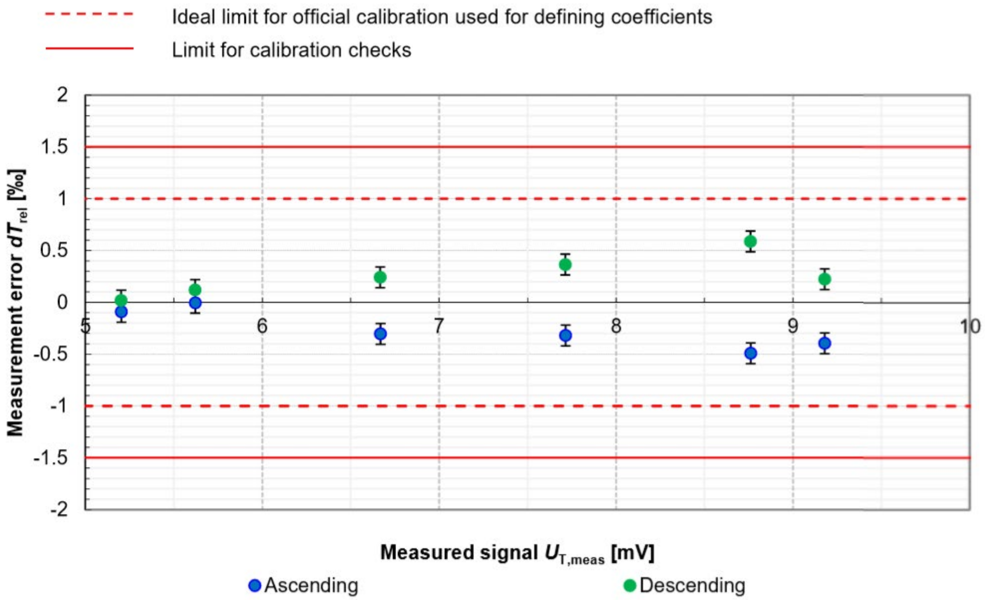
- Primary methods such as weighing, dimensional measurements, etc. are preferred.
- Secondary methods, such as calibrated pressure measuring devices, etc. can also be used, but require secondary certificates and frequent off-site verification/calibration
- The calibrations shall represent the functional domain of the measured quantity during the testing series whenever possible (at least within the normal operating range of the machine)
- The errors in the calibration shall rest within certain limits in order to guarantee measurement quality
  - Errors on instruments for performance measurement should be on the order of 0.1%
  - Errors on other instruments can be significantly higher due to type of instrument, measuring methods, etc. For example, errors of 5% in the calibration of strain gauges on guide vane shafts is not unreasonable
  - Errors outside of normal operating range can also be higher

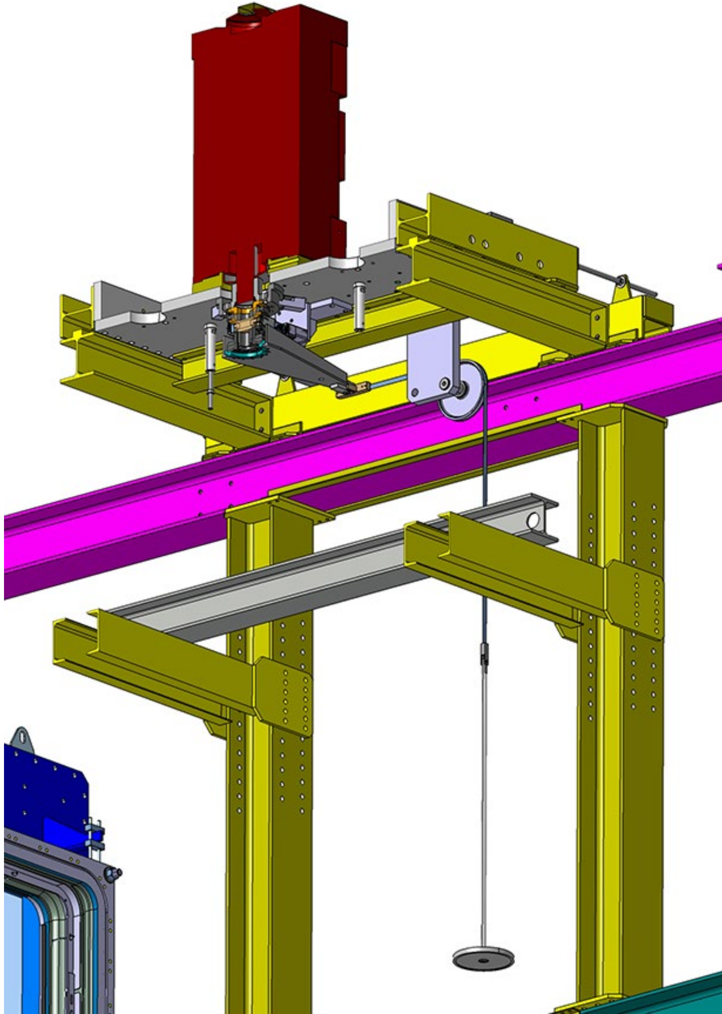
EPFL

Practical implementation
Calibrations

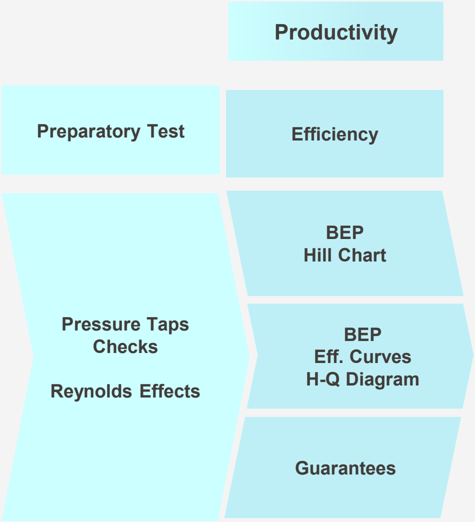
Example of primary method to calibrate torque measuring device

→ Length of lever and masses can all be verified during tests



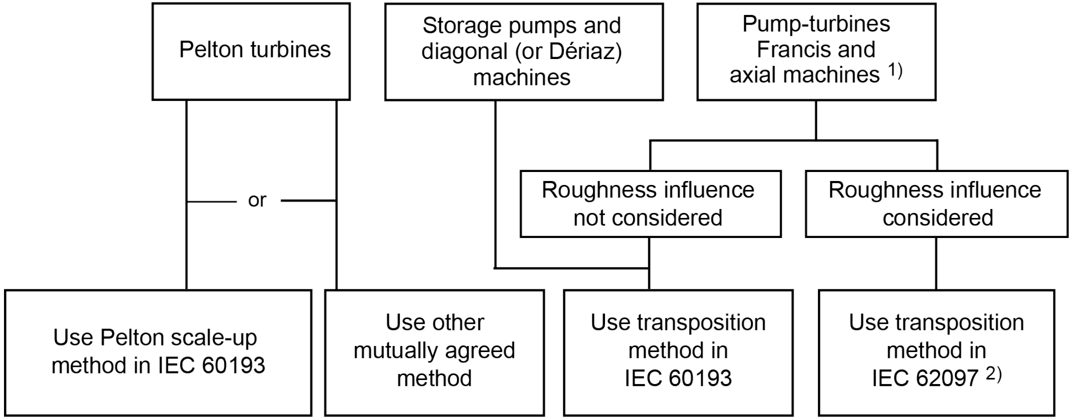


Performance measurements
Phase of model testing



How to measure performance :
Transposition methods for scale-up

Source: IEC 60193:2019



IEC 60193 efficiency correction for Pelton turbines

- Takes into account Reynolds, Froude and Weber similitude
- Often no scale-up formula are applied as on-site performance measurements are more reliable and easy to obtain

IEC 62097 efficiency correction for reaction machines

- Addresses some of the limitations of the IEC 60193 scale-up
- Takes into account roughness of machine components
- Takes into account the shift in energy, discharge and power factors for scale-up
- Cannot be used for all types of reaction machines (e.g. storage pumps)
- Application limited for some machines (e.g. axial machines)

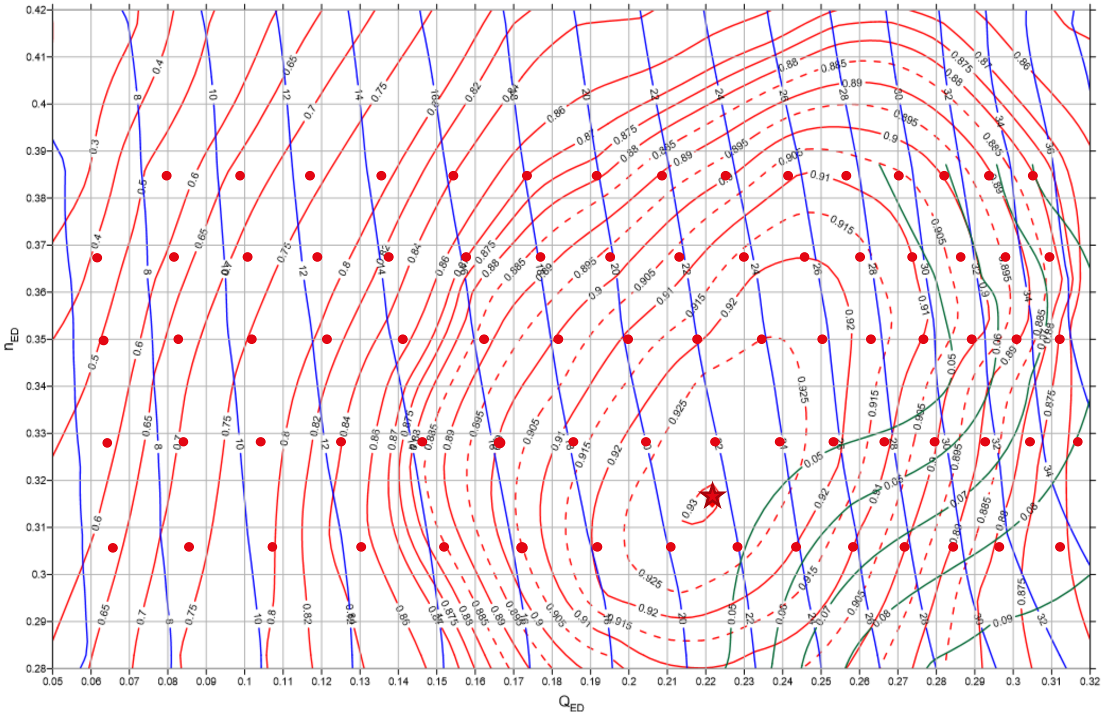
Data processing, analysis and presentation

Productivity prediction

Model performance

- Reported on a graph showing values relative to energy and flow coefficients
- Iso-lines shall indicate guide vane opening, corrected model efficiency, and can include other coefficients like torque and power
- Optimum efficiency point and operating zone are often included

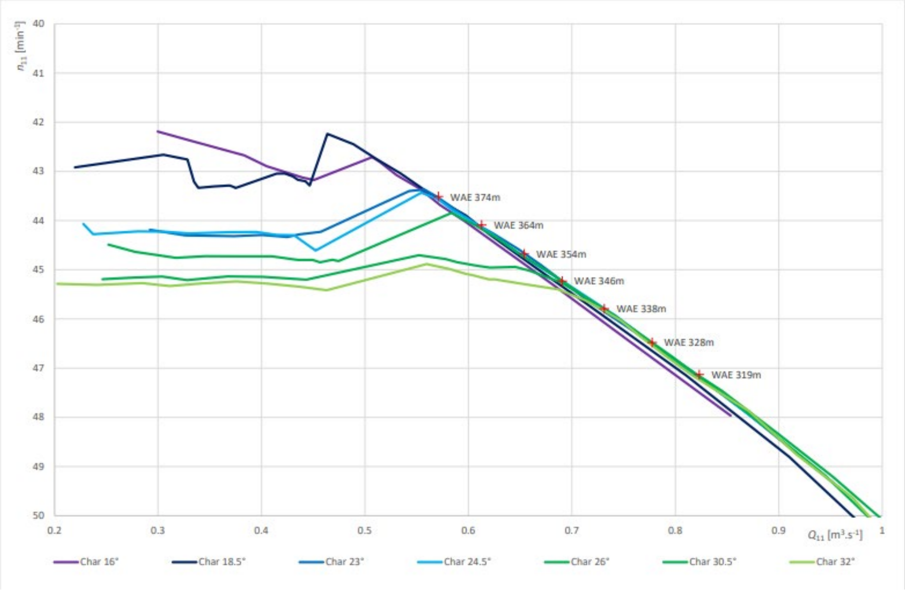
Hillchart of reduced scale model single regulated (mode turbine)

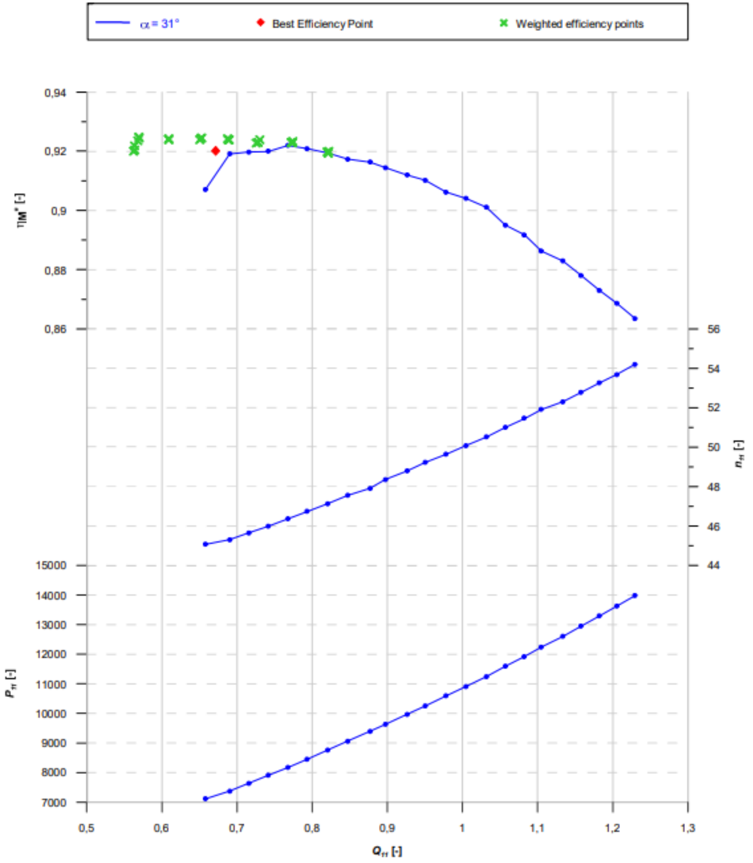


Data processing, analysis and presentation
Productivity prediction

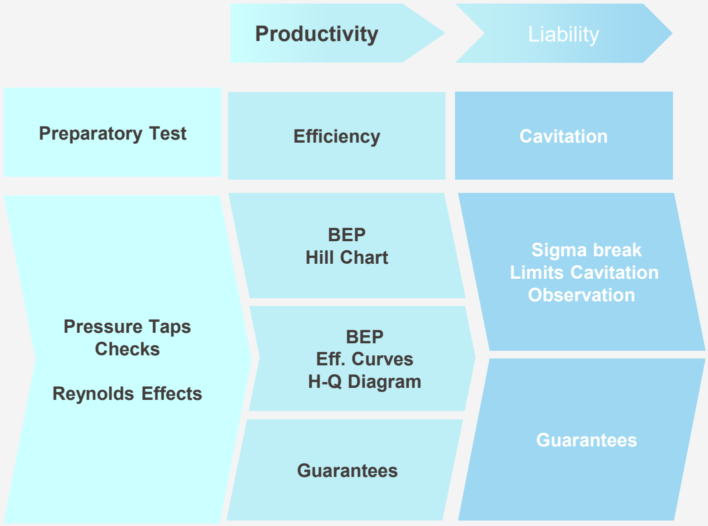
Efficiency Characteristic curves
(Pump-turbine with guide vane) in pumping mode

- Efficiency curve
- H-Q diagram
- Guarantees



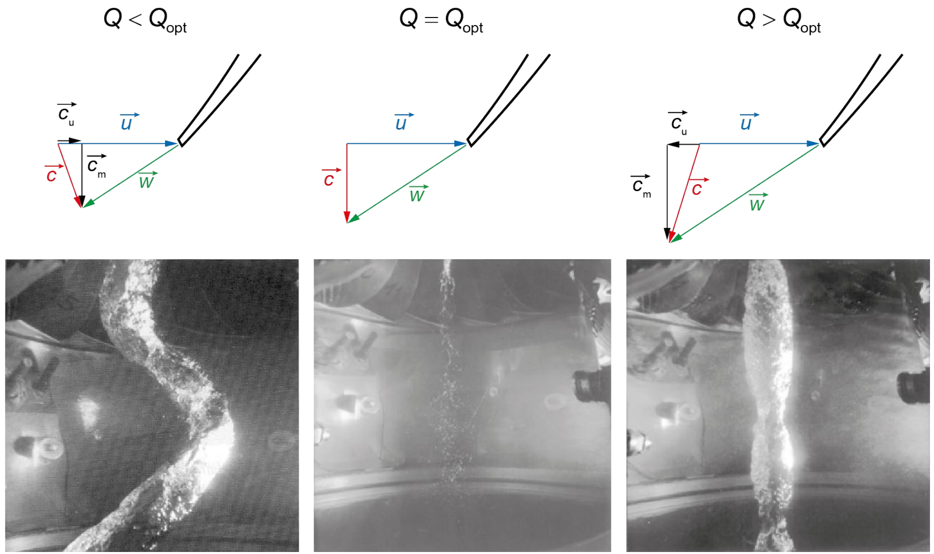


Performance measurements
Phase of model testing

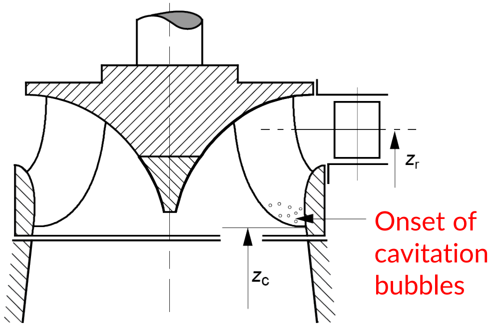


Performance measurements
Cavitation conditions – Thoma similitude

Thoma number: $$\sigma = \frac{H_{amb,M} - H_{va,M} - H_{sM} + \left(\frac{Q_{1M}}{S_2}\right)^2 \cdot \frac{1}{2g_M}}{H_M} = \frac{NPSH}{H}$$



Cavitating vortex rope in the draft tube of a Francis turbine operating at part load and full load



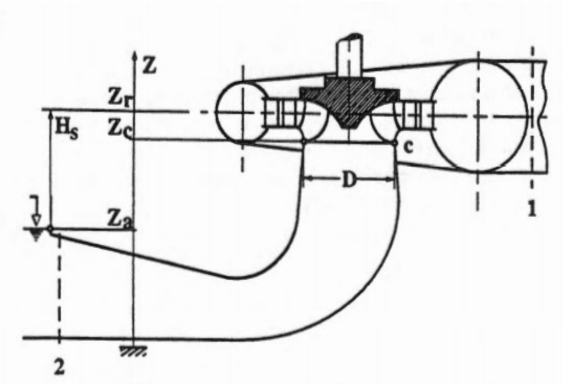
Source: IEC 60193:2019

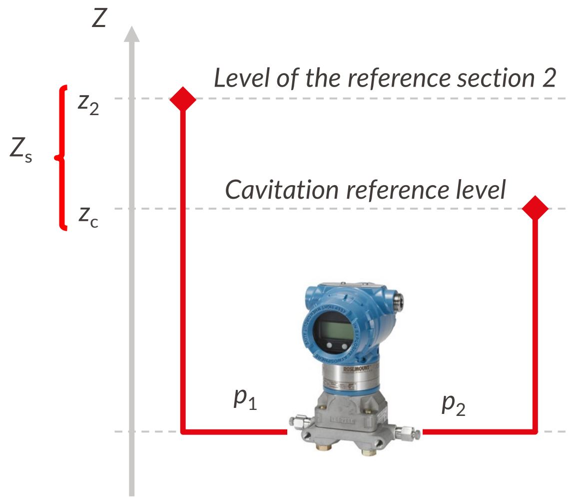
Practical implementation

Determining suction head H_{SM}

Measurement of net positive suction specific energy

- Using a differential pressure transducer, similar to energy measurement
- The cavitation reference level z_c is typically taken as the machine reference level z_r
- Measures the differential pressure Δp_σ between a free surface at atmospheric pressure located at the elevation of the center line of the distributor and the pressure of the measuring section 2 at the outlet of the draft tube
- The dimensionless Thoma number is recommended during model testing for ease of transposition
- Measuring ranges:
  - ✓ -1 bar to 1 bar

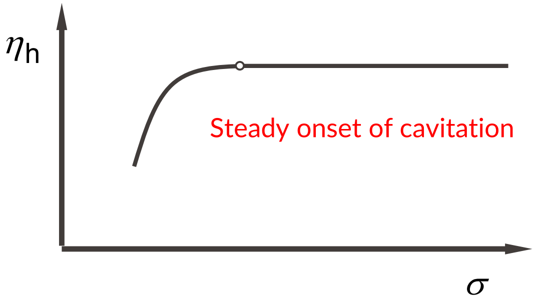




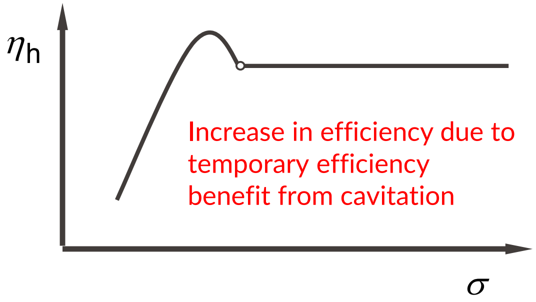
Data processing, analysis and presentation
Characteristic forms of cavitation

Break curve forms typical of certain operating conditions

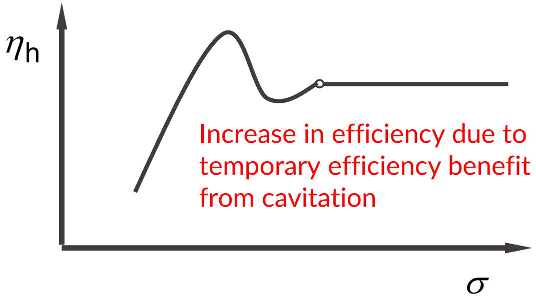
Near BEP



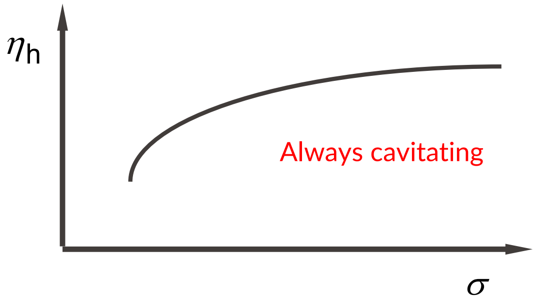
Inlet cavitation



Inlet cavitation at full-load



Low-head axial machine

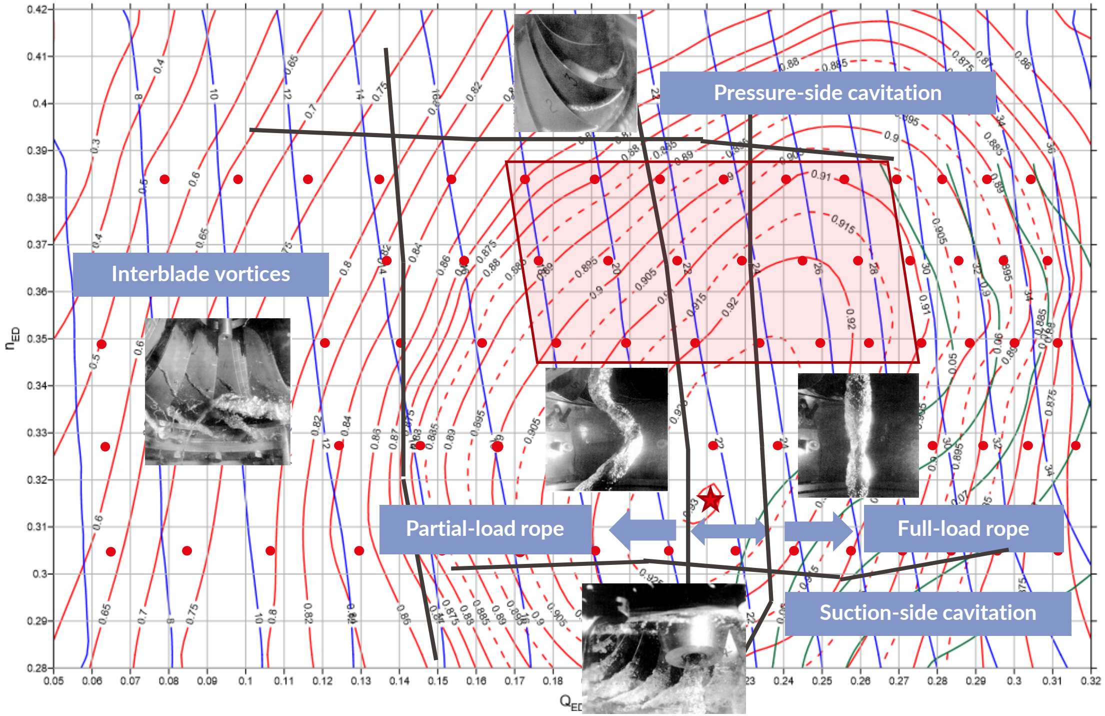


Data processing, analysis and presentation
Machine performance

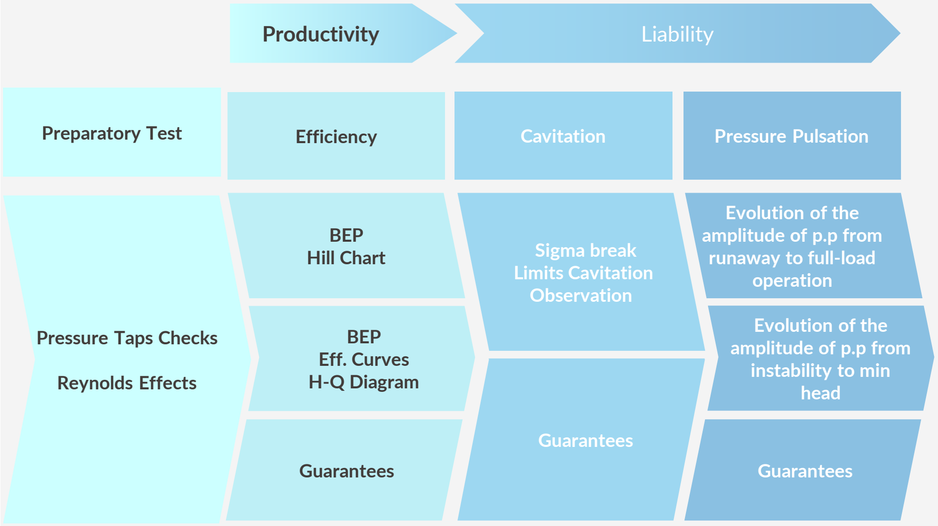
Model performance

- Reported on a graph showing values relative to energy and flow coefficients
- Iso-lines shall indicate guide vane opening, blade opening (for double-regulated machines), corrected model efficiency, and can include other coefficients like torque and power
- Other iso-lines can include cavitation limits, pressure fluctuations and critical sigma values
- Optimum efficiency point and operating zone are often included

Hill chart of reduced scale model



Performance measurements
Phase of model testing

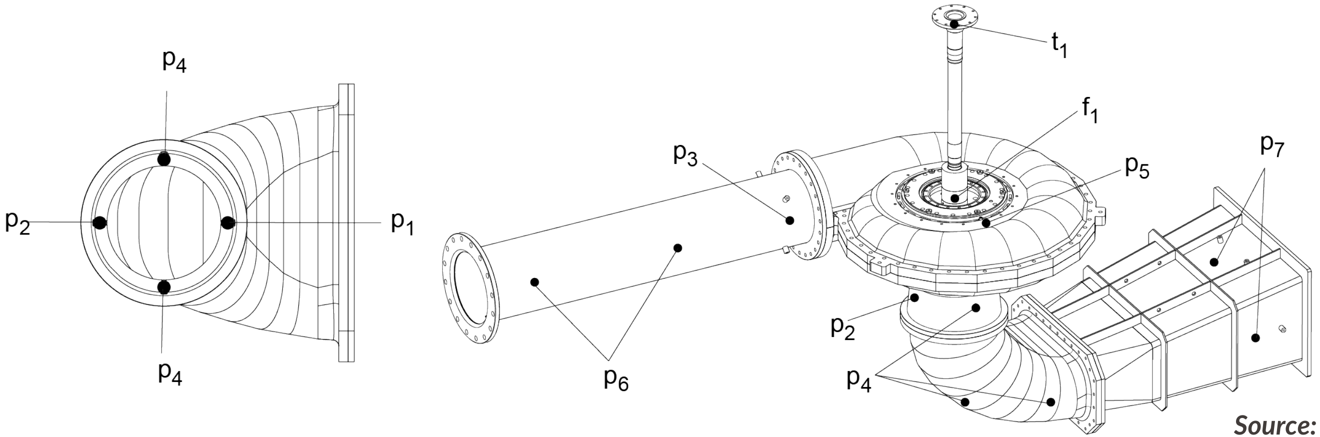


Practical implementation

Instrumentation for pressure fluctuations

Pressure fluctuations

- Measured with dynamic pressure transducers mounted flush with model walls
- Frequency of acquisition should by high enough to obtain accurate measurements of frequencies of interest (see IEC 60193 for guidelines)
- Preventing or filtering any potential test-rig frequencies allows for prototype scaling



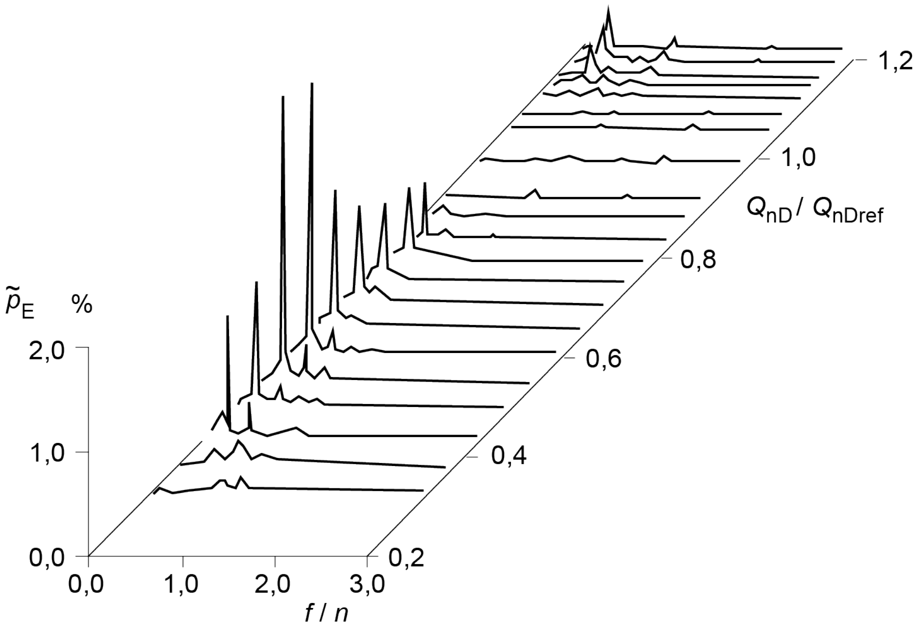
Source: IEC 60193:2019

Data processing, analysis and presentation

Characteristic forms of pressure fluctuation

Waterfall diagram of peak fluctuations in the draft-tube of a Francis turbine

- Evolution of the peak frequencies relative to reference discharge (usually the discharge at the point of optimum efficiency)
- Peak pressure fluctuations will occur in the partial-load region
- Pressure fluctuations will also increase in the full-load region and can be quite important
- Evolution of the amplitude of pressure fluctuation from runaway to full-load operation
- Spectra in time and freq. domain
- Guarantees (placement of transducers and method of determining max need to be specified)
- Evolution of the amplitude of pressure fluctuation from instability to min head



Source: IEC 60193:2019

Data processing, analysis and presentation

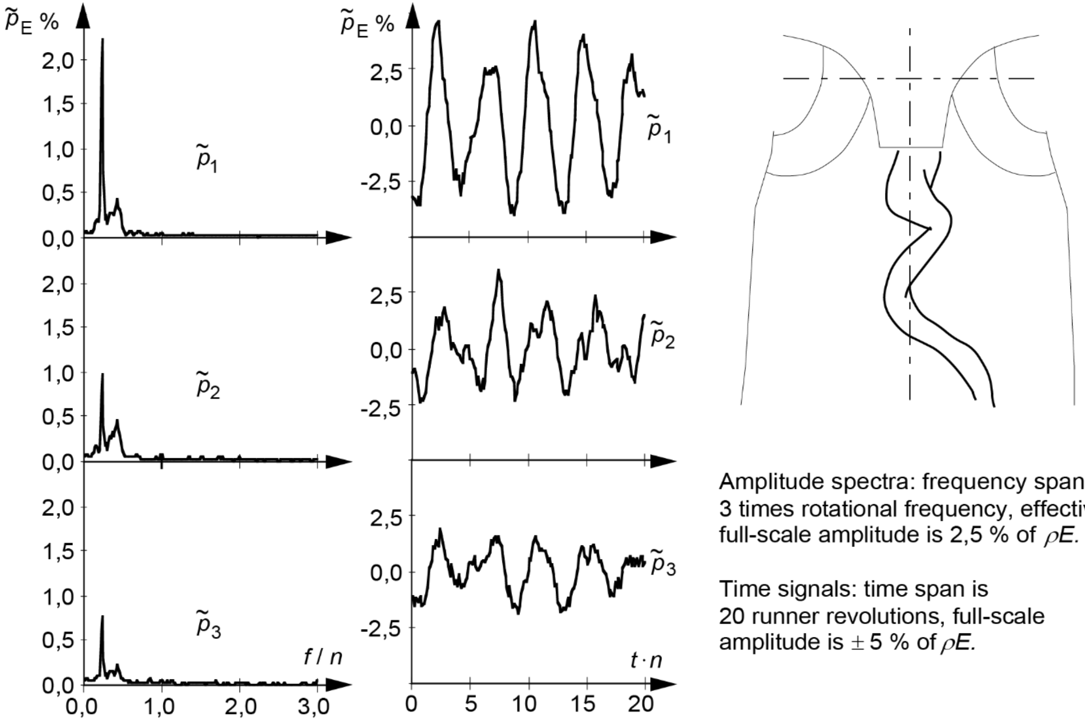
Characteristic forms of pressure fluctuation

Francis runner at part-load operation

Draft-tube cone downstream

Draft-tube cone upstream

Inlet to spiral case



Amplitude spectra: frequency span is 3 times rotational frequency, effective full-scale amplitude is 2,5 % of ρE.

Time signals: time span is 20 runner revolutions, full-scale amplitude is $\pm$ 5 % of ρE.

Source: IEC 60193:2019

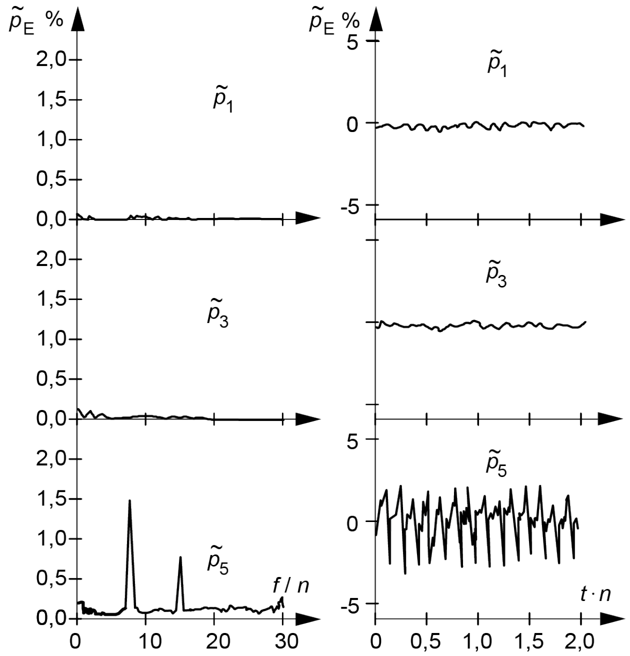
Data processing, analysis and presentation
Characteristic forms of pressure fluctuation

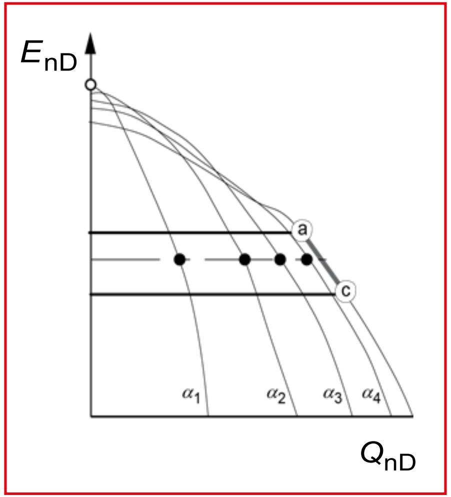
Pump in normal operating range (along envelope a-c)

Draft-tube cone downstream

Inlet to spiral case

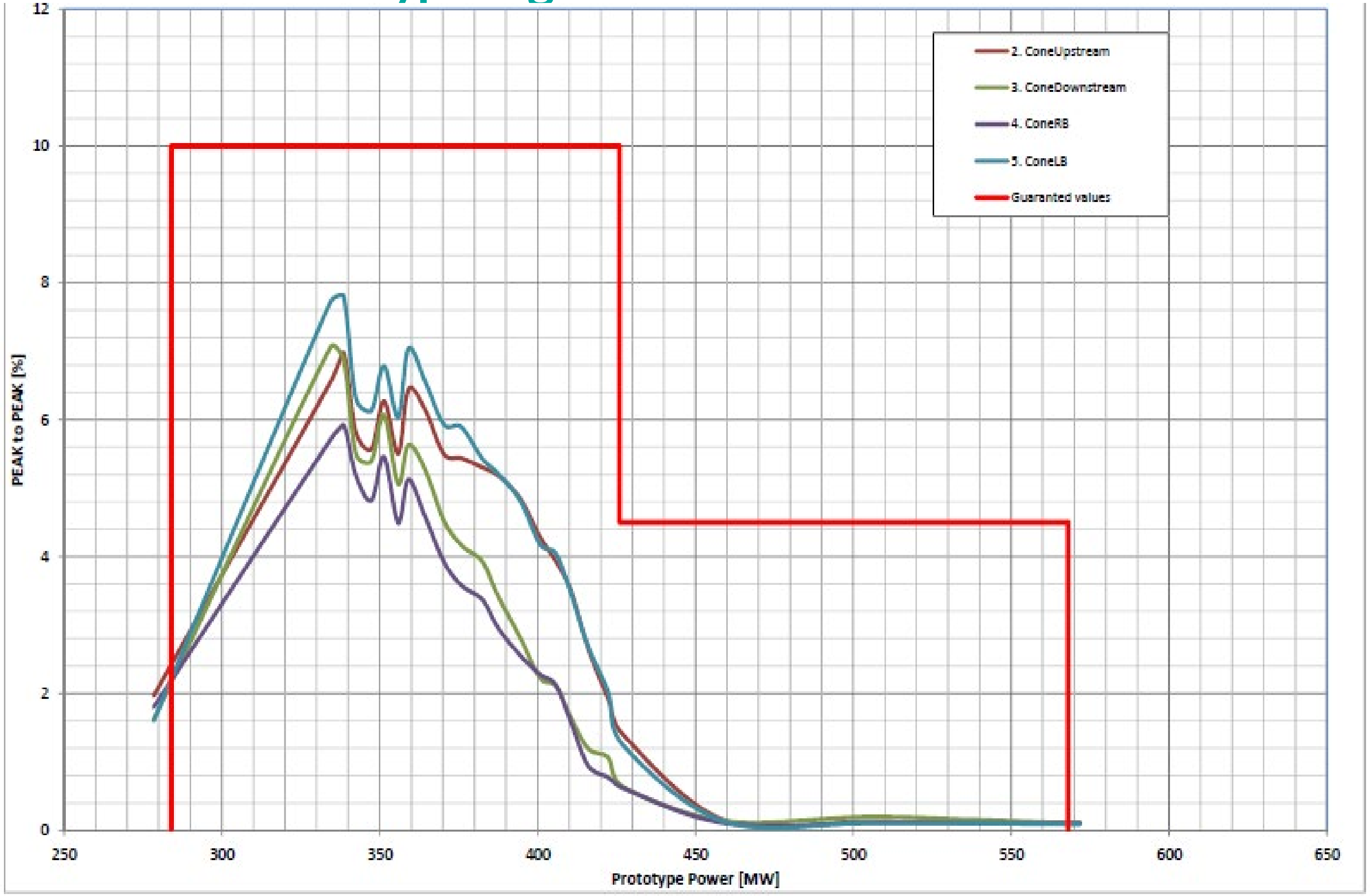
Vaneless space





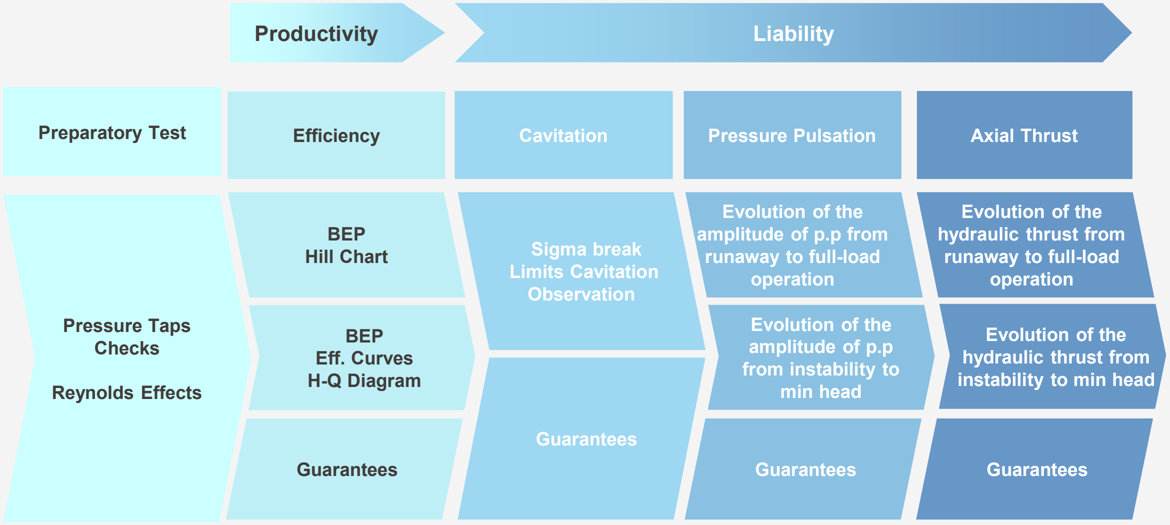
Source: IEC 60193:2019

Performance measurements
Pressure fluctuation - Typical guaranteed values



Performance measurements

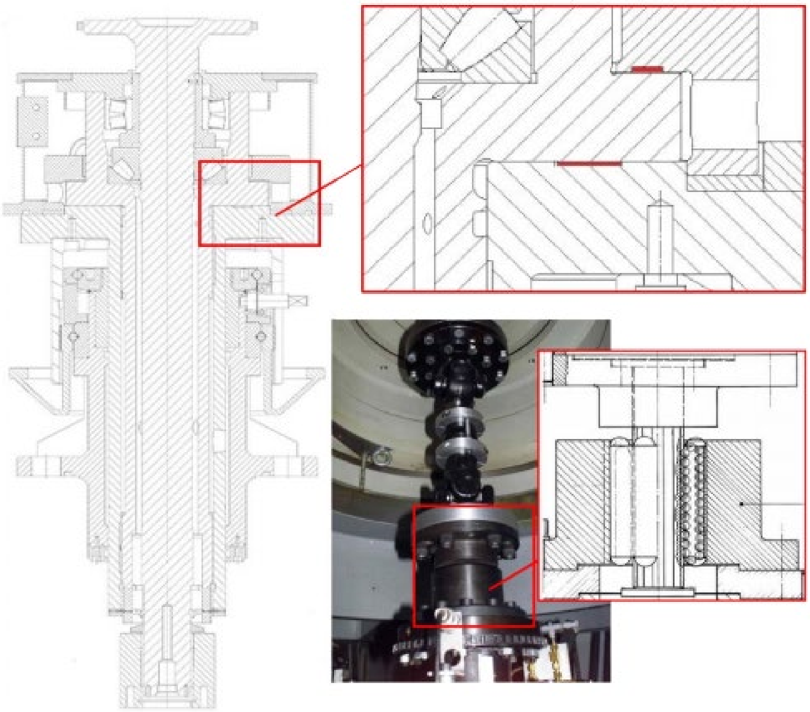
Phase of model testing



Practical implementation
Determination of hydraulic axial thrust

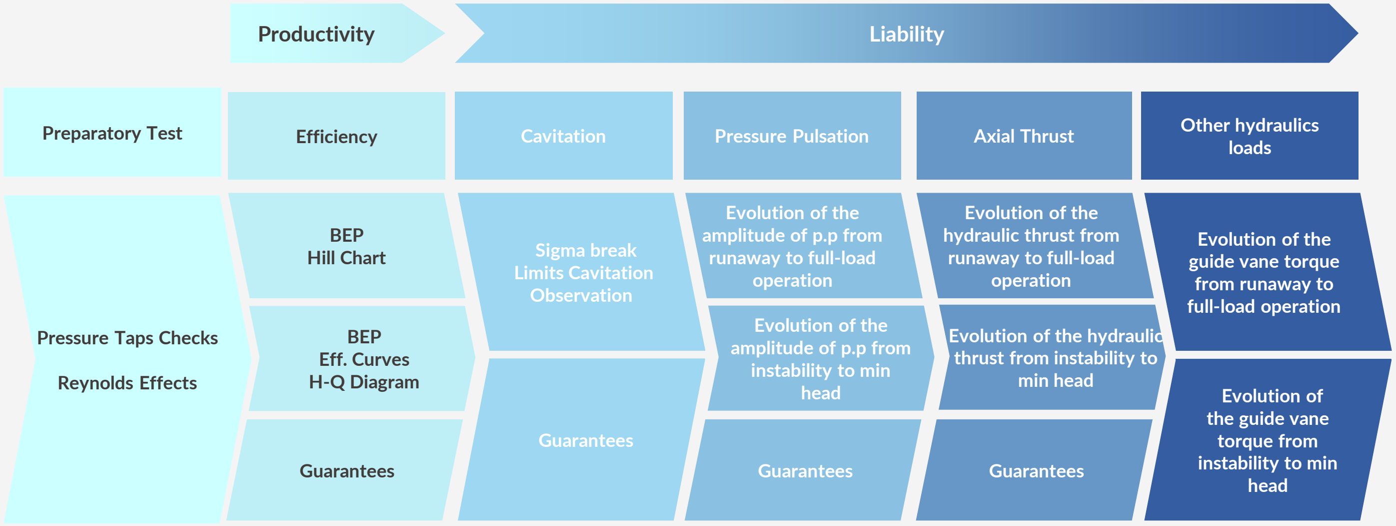
Axial thrust (Radial thrust is not transposable!)

- The axial thrust is obtained according to the oil pressure in the two chambers of the axial hydrostatic thrust block
- Ball sliding universal joint between the shaft and the electrical machine allows small axial movements of the hydrostatic thrust block of the turbine and then, the evolution of the oil pressure with good repeatability and accuracy of the measurement
- Max. rotational speed : 1'500 min^{-1}



Performance measurements

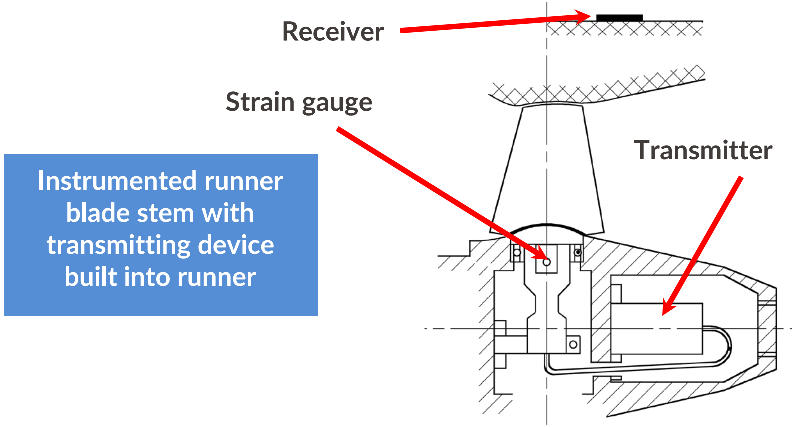
Phase of model testing

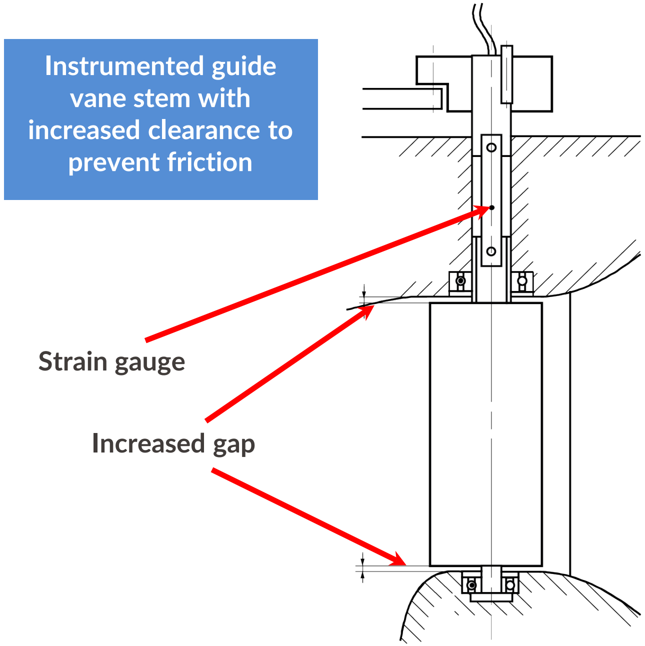


Practical implementation
Instrumentation for strain gauges

Hydraulic loads on control components

- Strain gauges mounted to guide vane shafts
- Strain gauges mounted to axial runner blades
- Pelton needle force and deflector torque



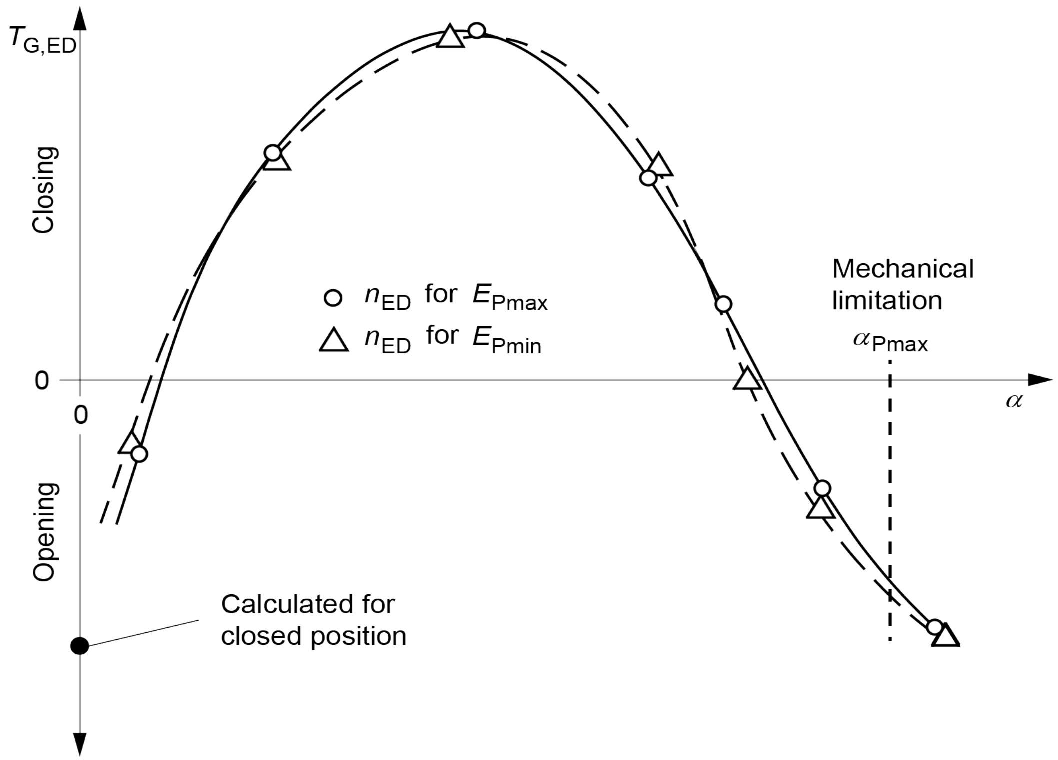


Source: IEC 60193:2019

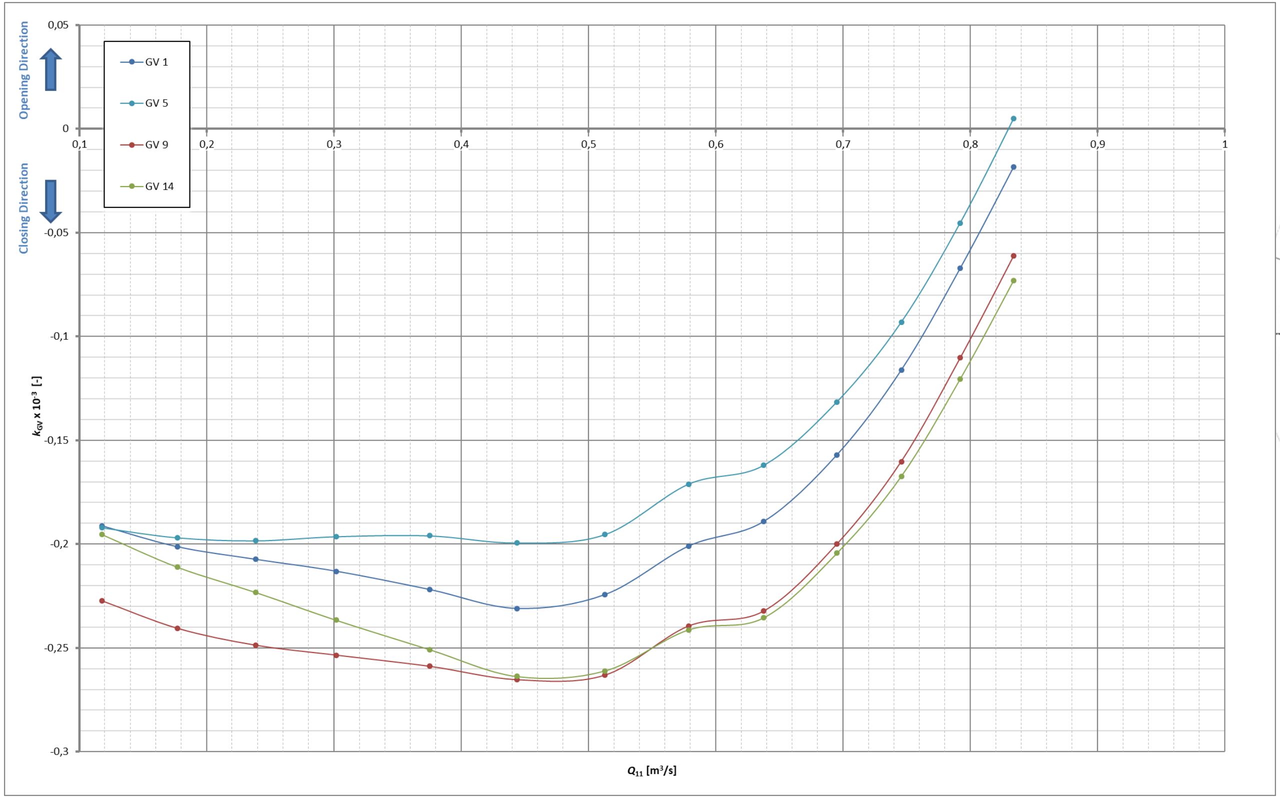
Data processing, analysis and presentation
Hydraulic loads on control components

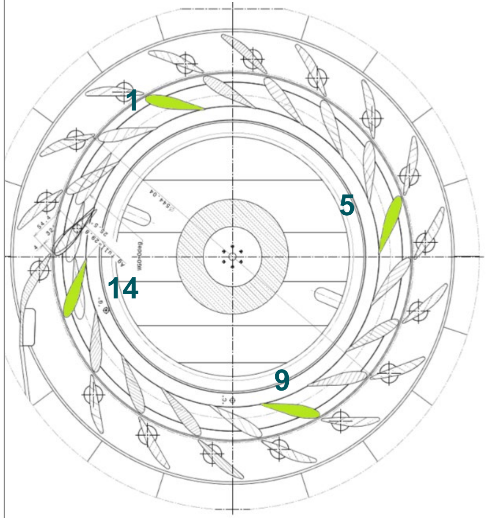
Torque on guide vanes

- The evolution of guide vane torque can be presented versus guide vane opening or discharge
- Asynchronous guide vane openings are commonly tested



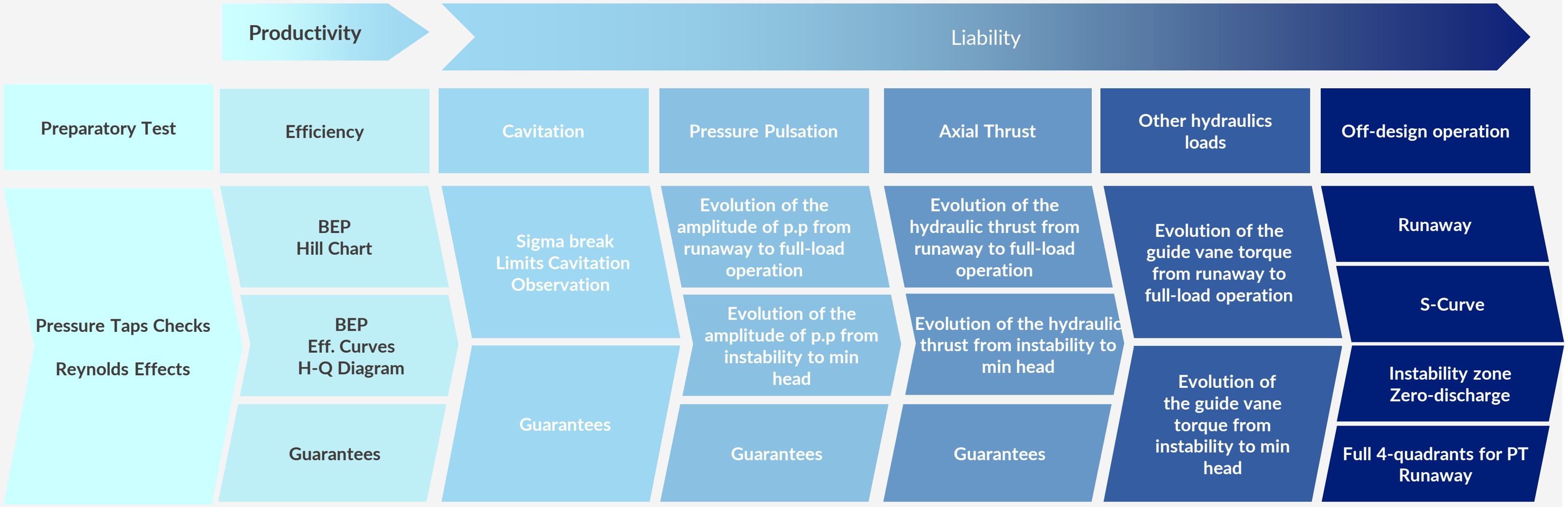
Performance measurements
Guide vane Torque





Performance measurements

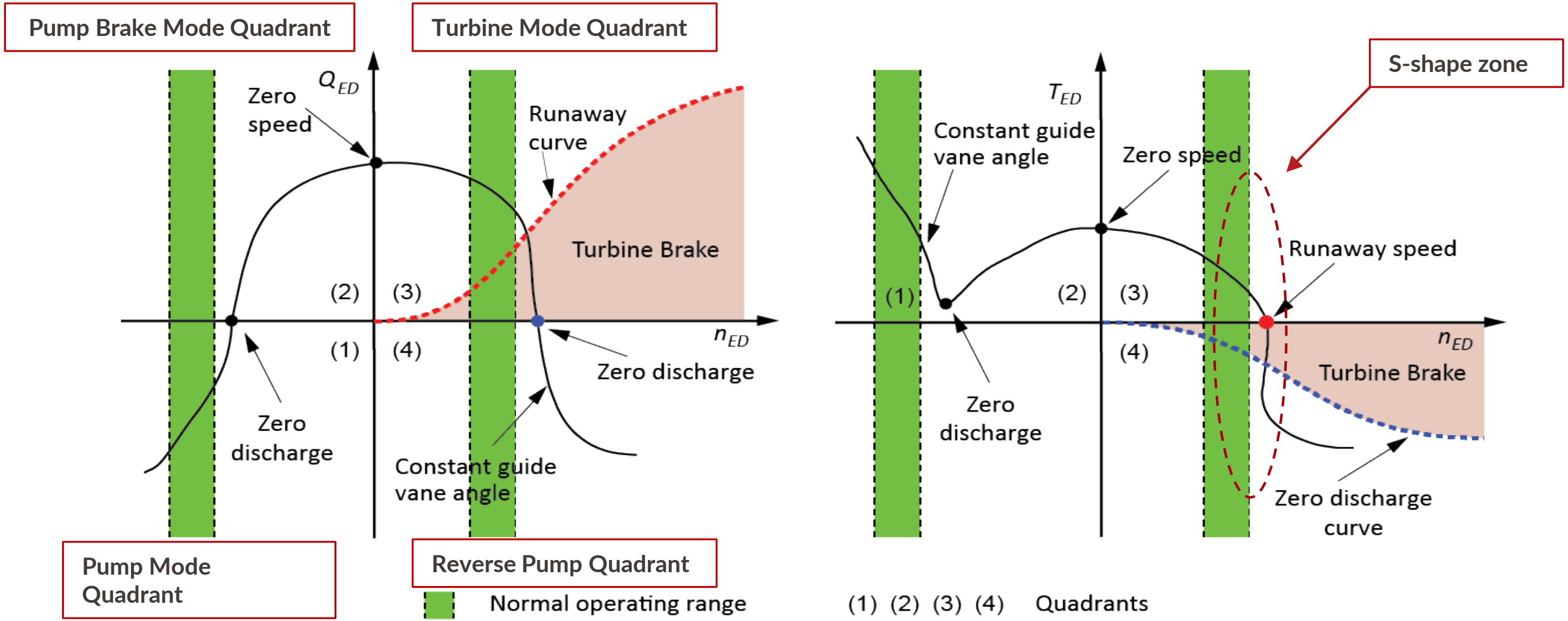
Phase of model testing



Data processing, analysis and presentation

Tests outside of normal operating range

Testing in the 4-quadrants

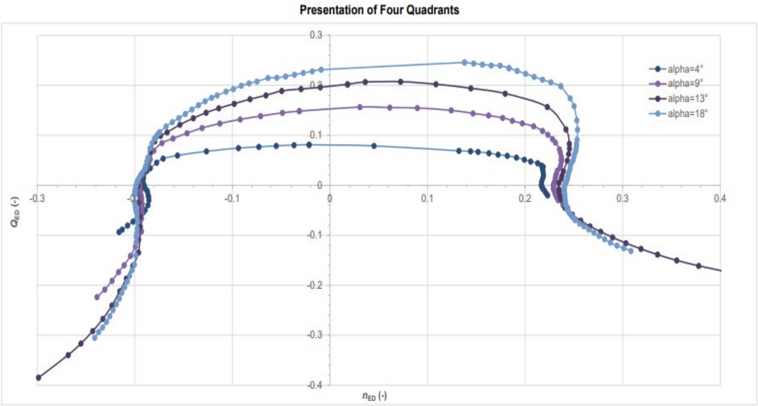


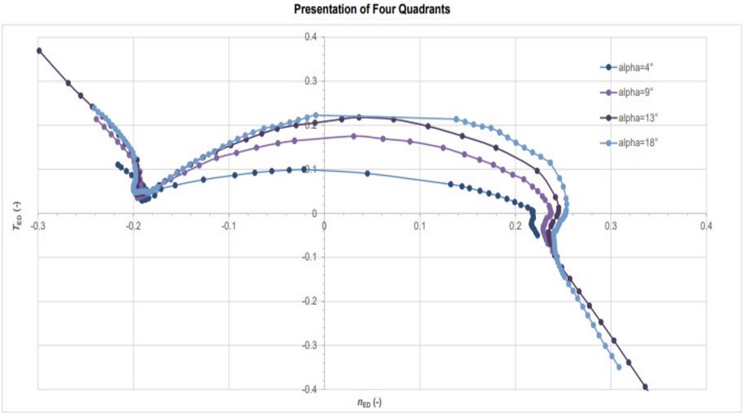
Data processing, analysis and presentation

Tests outside of normal operating range

Pump (or PT in mode pump)

- Instability zone
- Zero-discharge
- Full 4-quadrants for PT





Data processing, analysis and presentation

Off-design operation

Turbine Single-regulated (Runaway and S-curve)