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Barotrauma detection sensors: the experiments in Sweden

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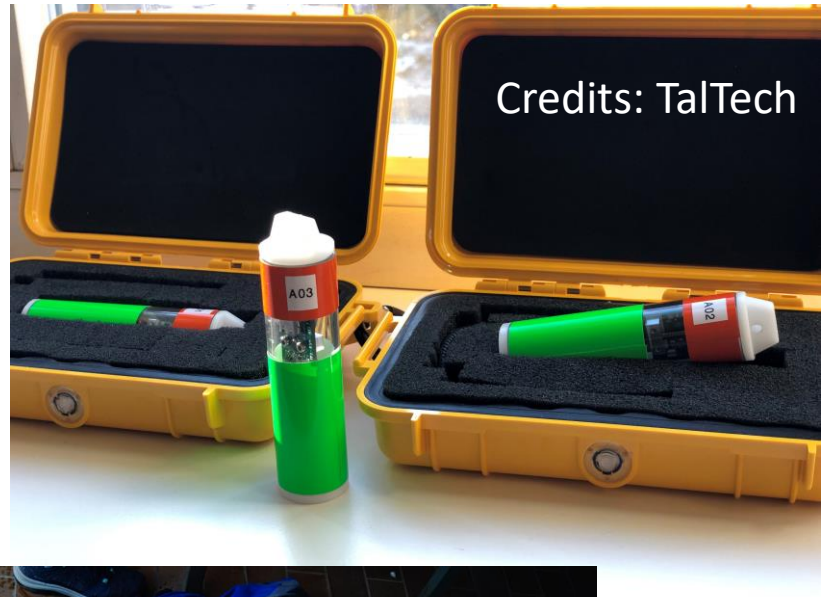
In collaboration with Energiforsk

Barotrauma detection sensors

- Sensors to measure pressure and number of strikes (in relation to size)
- Events that happen when fish migrating downstream and pass through the turbines
- Consequences on fish
  - Physical Injuries: barotraumas, stress, disorientation
  - Behavioral Changes: disrupted migration, reproductive success
- Useful for :
  - Fish injury and mortality due to pressure changes
  - Validating blade striking models



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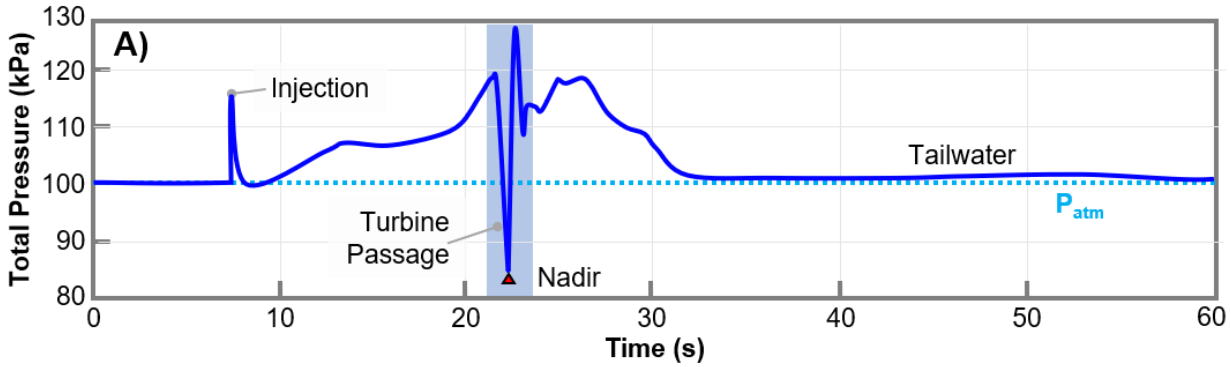
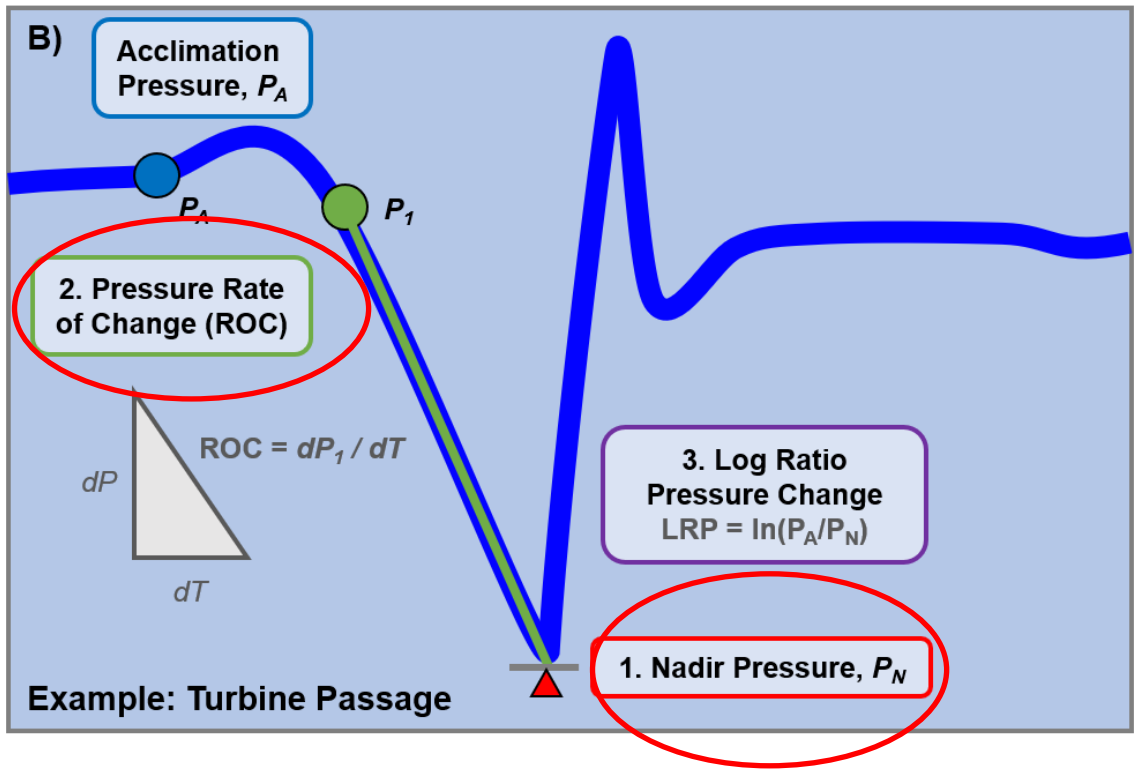
Sensor Passage Experiments

What are we measuring?





Focus on 2 pressure indicators

- Nadir pressure
- Pressure rate of change

Value of these indicators should never exceed thresholds from literature

Number of hits (limitation due to size)

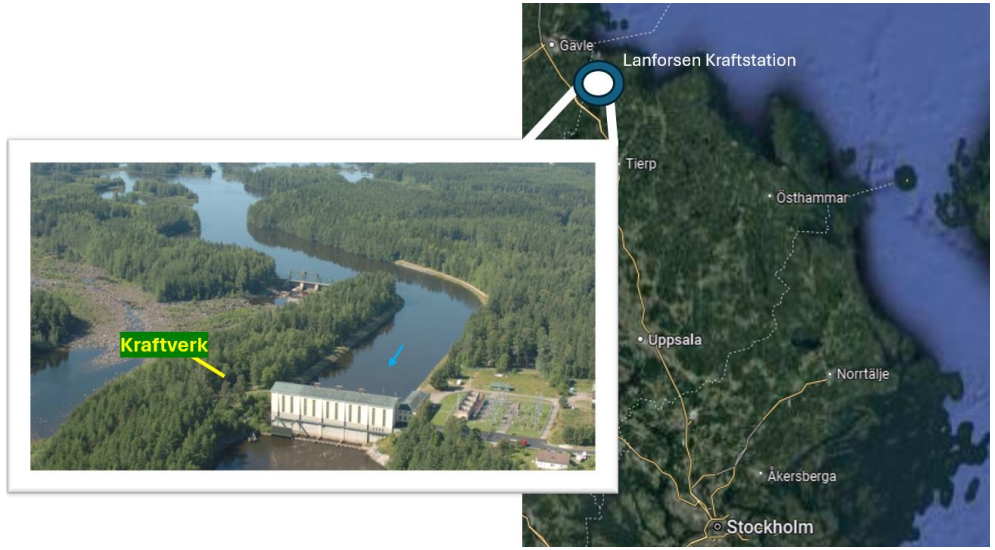
Case studies

- Ätrafors:
  - 3 Francis turbines
  - little space between blades
  - Focus on the eel
    - Nadir pressure threshold: 2.7 kPa
    - ROC threshold: 550 kPa/s

  Thanks to Johan Tielman, Olle Calles and his group (Hanna)!

- Lanforsen:
  - low head Kaplan turbines
  - more space between blades
  - Focus on the Atlantic salmon
    - Nadir pressure threshold: 20 kPa
    - ROC threshold: 550 kPa/s

  Thanks to Marco Blixt for driving the boat!



Field work in Ätrafors

- 3 turbines:
  - 2 similar inside the power plant (one was closed due to maintenance)
  - 1 outside the power plant

- 2 scenarios:
  - Scenario I: turbine n.1 inside at 25 m^3/s (max load)
  - Scenario II: turbine outside at 16 m^3/s (max load)

  - Deployment with pole shear downstream the rack

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Results: Ätrafors

- Scenario I
  - Deployment challenging, added weights to the sensors (washers)
  - Some sensors resurfaced upstream

	Deployed	Lost	Destroyed	Clean Data	Unusable Data	Hit, Clean Data	Hit, No Data
Sensors	41	5	0	27	5	7	0
Dummies	25	1	0	0	0	0	2
Total	66	6	0	27	5	7	2
Percentage		9.1%	0.0%	75.0%	13.9%	19.4%	5.6%

- Scenario II (outside)
  - Deployment challenging, added weights to the sensors (washers)
  - Some sensors resurfaced upstream

	Deployed	Lost	Destroyed	Clean Data	Unusable Data	Hit, Clean Data	Hit, No Data
Sensors	35	1	0	30	0	16	0
Dummies	10	0	0	0	0	0	0
Total	45	1	0	30	0	16	0
Percentage		2.2%	0.0%	83.3%	0.0%	44.4%	0.0%

Results: Ätrafors

Scenario I and Scenario I

General statistics

- data are consistent around the mean/median

Variable	Mean	Median	Max	Min	Range	Q3	Q1	IQR	STD
Nadir (kPa)	43.1	43.8	57.6	19	38.6	49.1	40.4	8.6	9.4
PRC (kPa/s)	258.7	256.5	282.7	237.8	44.9	266.6	251.6	15.1	11

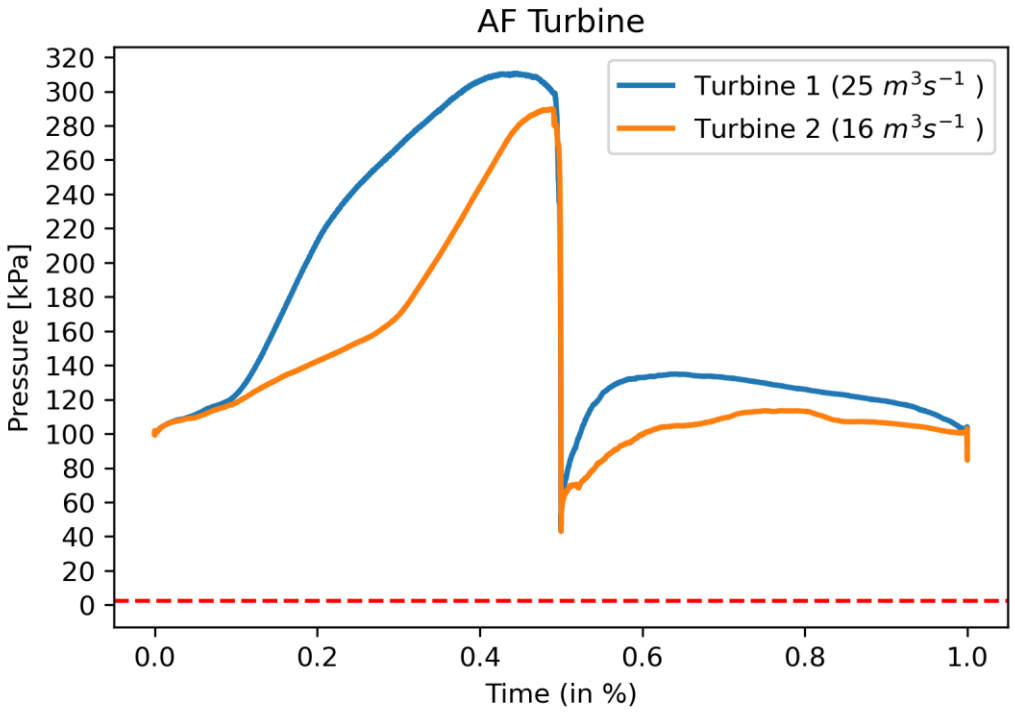
Variable	Mean	Median	Max	Min	Range	Q3	Q1	IQR	STD
Nadir (kPa)	43	44.7	52.8	29.1	23.7	49.6	37.6	12.1	7.6
PRC (kPa/s)	248.5	247.2	275.4	229.1	46.3	253.2	242.2	10.9	11.6

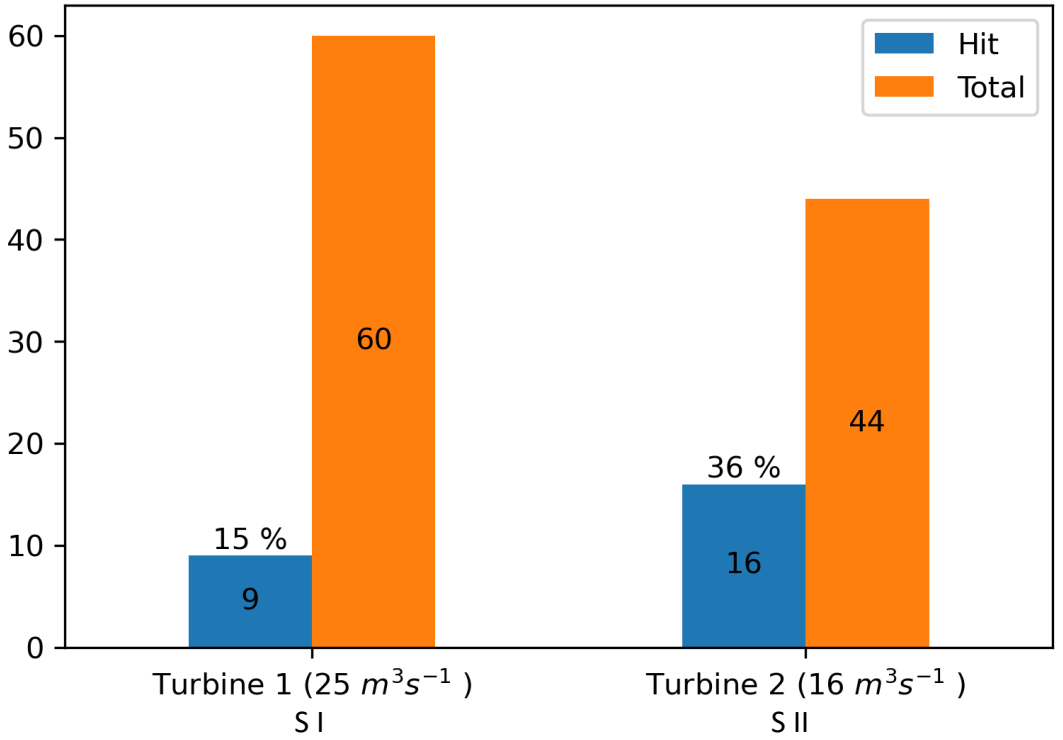
Results: Ätrafors

Average pressure in the 2 scenarios:

The dotted line is a reference value for eels from literature

Values should always be ABOVE this threshold





Number of hits:

Significant number of hits as expected for Francis turbines

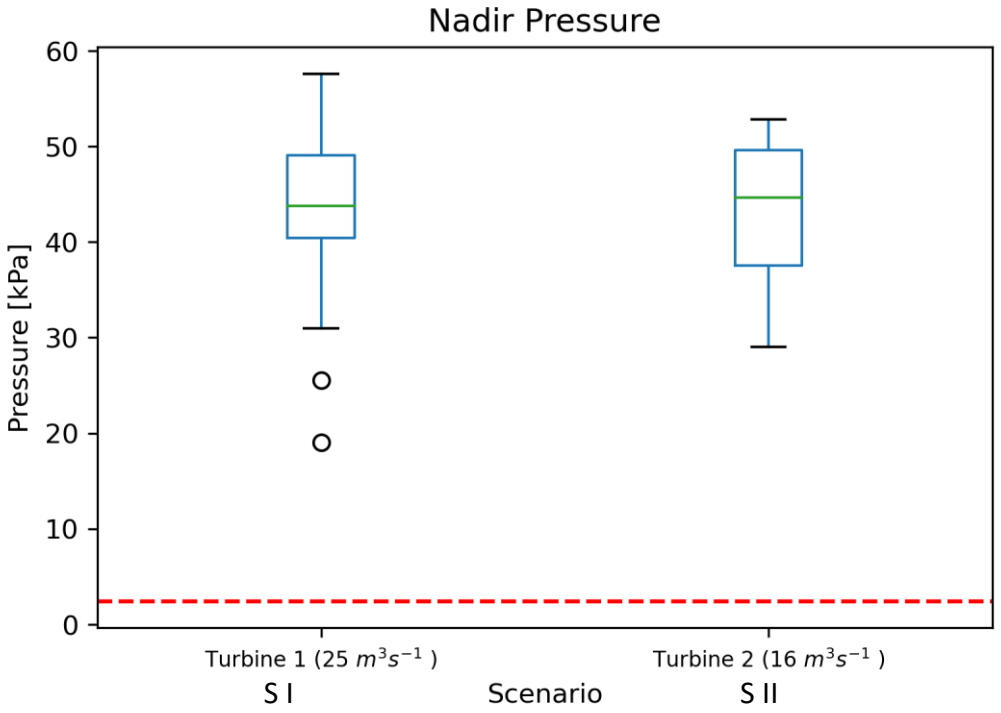
Deployment downstream the rack

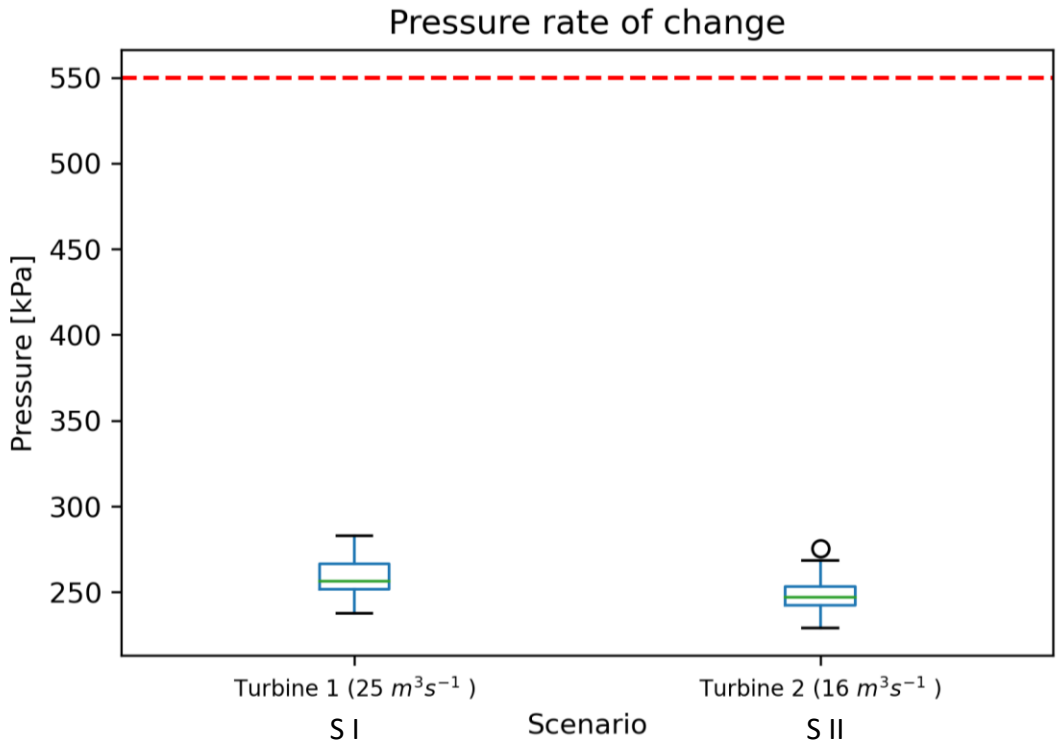
Results: Ätrafors

Nadir pressure: all values

The dotted line is a reference value from literature for eels (2.7 kPa)

Values should always be ABOVE this threshold





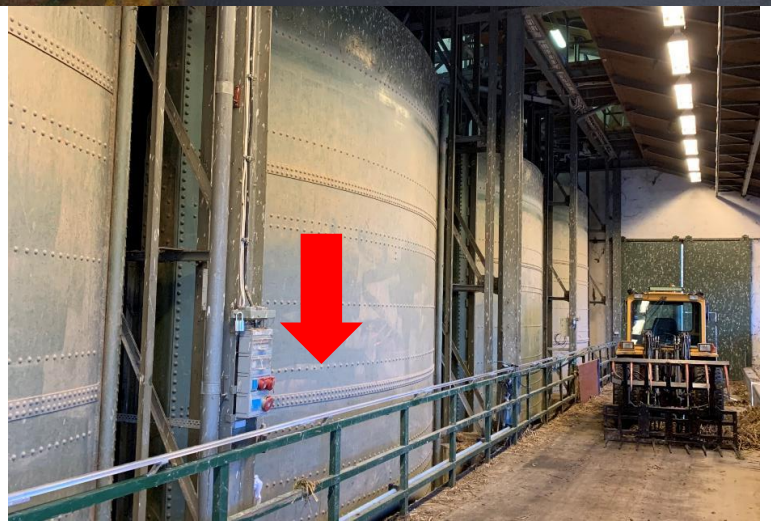
Pressure rate of change:

The dotted line is a reference value from literature for eels (550 kPa)

Values should always be BELOW this threshold

Field work in Lanforsen

- 4 turbines:
  - 4 Kaplan turbines, max load 620 m^3/s
- 3 scenarios:
  - Scenario I: Turbine n.2 80 m^3/s
  - Scenario II: Turbine n.3 80 m^3/s
  - Scenario III: Turbine n.3 100 m^3/s
  - Scenario III with fewer deployments
    - Change of flow due to maintenance operations upstream/downstream, not at the facility
  - Deployment of the sensors by hand
  - Downstream the rack



Results: Lanforsen

- Scenario I
  - Deployment with added weights (washers)
  - Unusable data because sensors surfaced upstream

Scenarios	Category	Deployed	Lost	Destroyed	Strike	Data	Unusable Data
S I	Sensors	32	1	0	0	25	6
	Dummies	11	0	0	0	0	0
	Total	43	1	0	0	25	6
	Percentage		2.3%	0.0%	0.0%	80.6%	19.4%

- Scenario II
  - Deployment with added weights (washers)
  - Some sensors resurfaced upstream

Scenarios	Category	Deployed	Lost	Destroyed	Strike	Data	Unusable Data
S II	Sensors	40	1	0	0	31	7
	Dummies	2	0	0	0	0	0
	Total	42	1	0	0	31	7
	Percentage		2.4%	0.0%	0.0%	79.5%	17.9%

- Scenario III
  - Deployment with added weights (washers)
  - Many sensors lost due to experimental conditions
  - Fewer data series

Scenarios	Category	Deployed	Lost	Destroyed	Strike	Data	Unusable Data
S III	Sensors	22	7	0	0	14	1
	Dummies	5	0	0	0	0	0
	Total	27	7	0	0	14	1
	Percentage		25.9%	0.0%	0.0%	93.3%	6.7%

Results: Lanforsen

- Scenario I general statistics
  - STD and IQR suggest higher variability compared to Ätrafors

Variable	Mean	Median	Max	Min	Range	Q3	Q1	IQR	STD
Nadir (kPa)	63.4	66.2	78.6	18.9	59.6	74.8	58.3	16.5	14.7
PRC (kPa/s)	82.7	80.9	125.5	45	80.5	86.8	74.3	12.5	15.5

- Scenario II general statistics
  - STD and IQR suggest higher variability compared to Ätrafors
  - Two turbines with similar discharge show slightly different values
  - p-value SI vs SII KW Anova = 0.06

Variable	Mean	Median	Max	Min	Range	Q3	Q1	IQR	STD
Nadir (kPa)	72.8	75.2	99.4	34.7	64.7	80.1	67.8	12.3	11.7
PRC (kPa/s)	78.4	79.4	112.1	0.7	111.4	86.6	73.2	13.4	18.8

- Scenario III general statistics
  - Higher variability (IQR) compared to SI and SII
  - P-value vs SII < 0.05
  - Smaller statistical sample

Variable	Mean	Median	Max	Min	Range	Q3	Q1	IQR	STD
Nadir (kPa)	40.1	33.7	63	23.6	39.4	53.3	29.6	23.7	13.9
PRC (kPa/s)	104.3	108.8	124.5	78.1	46.4	113	92.7	20.3	14.5

Results: Lanforsen

Average pressure in the 3 scenarios:

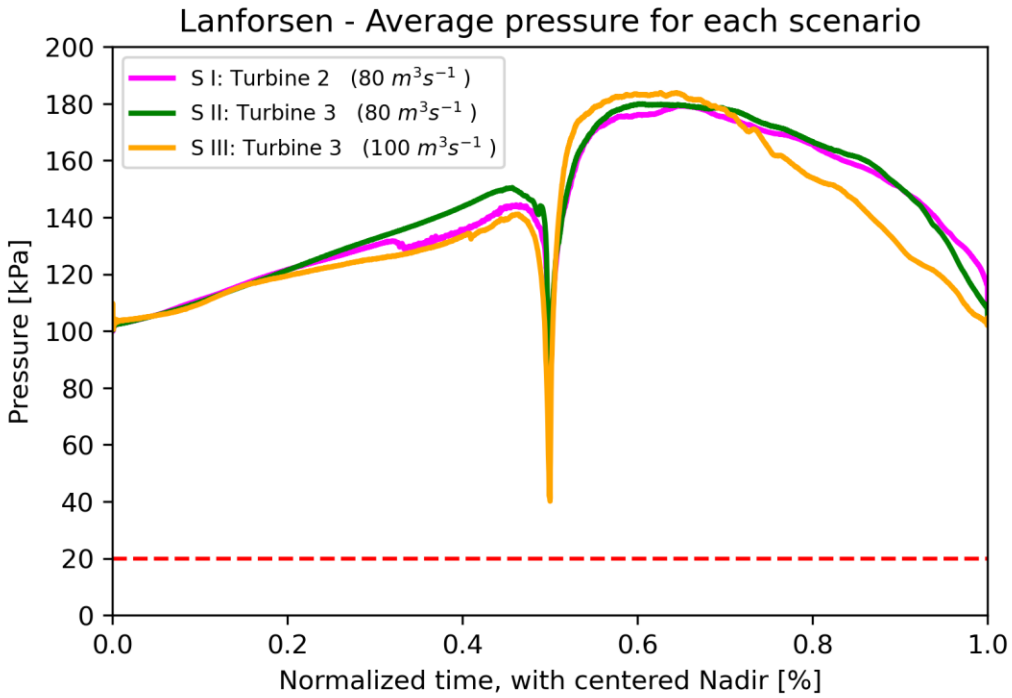
The dotted line is a reference value for salmon from literature

No threshold for the Atlantic salmon is available in literature, thus we choose twice the value for the Chinook salmon (20 kPa)

Values should always be ABOVE this threshold

Number of hits:

For the Kaplan turbines in Lanforsen, no hits were recorded

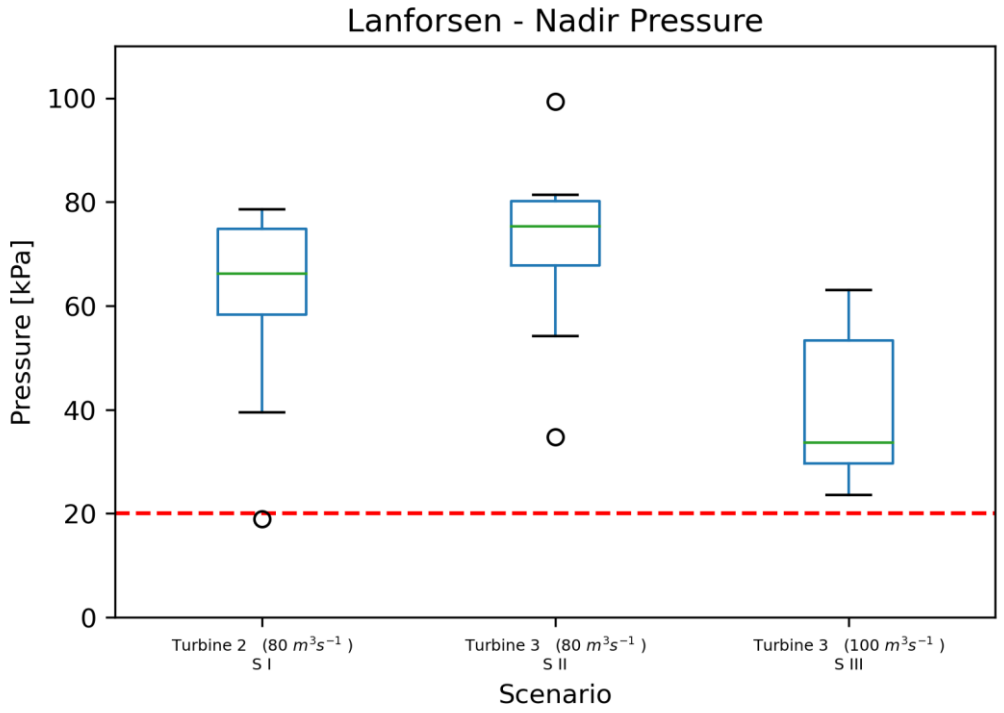


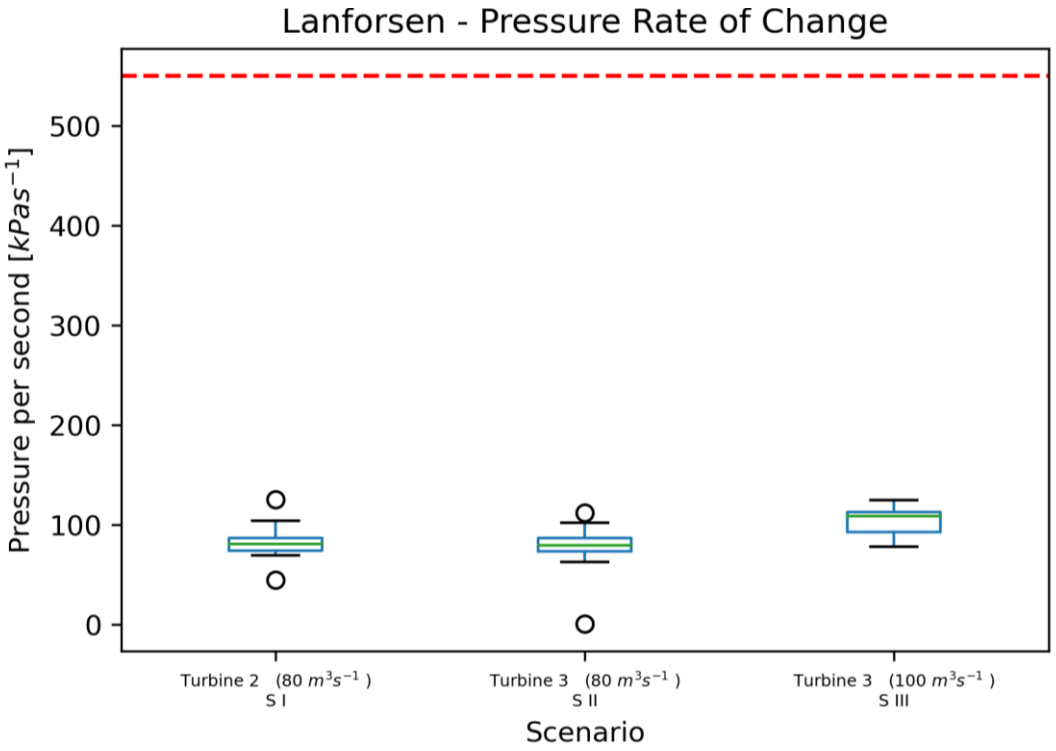
Results: Lanforsen

Nadir pressure: all values

The dotted line is a reference value from literature for salmon (20 kPa)

Values should always be ABOVE this threshold





Pressure rate of change:

The dotted line is a reference value from literature for a generic fish species (550 kPa)

Values should always be BELOW this threshold

Discussion

Ätrafors Case Study:

- S I and S II: Pressure variables not exceeding the limits, strikes detected
- Both scenarios maintained pressure above critical threshold, minimizing risks to eels
- Strikes detected and very likely underestimated due to the size of the sensors in comparison with adult eels
- Strikes detected also in previous studies (Calles et al., 2013)
  - 3 out of 5 eels hit

Calles, O., Karlsson, S., Vezza, P., Comoglio, C. and Tielman, J. (2013), Success of a low-sloping rack for improving downstream passage of silver eels at a hydroelectric plant. Freshw Biol, 58: 2168-2179. https://doi.org/10.1111/fwb.12199

Discussion

Lanforsen Case Study:

- S I: Pressure variables exceeding the limits only for one outlier, strikes not detected
- S II: Pressure variables not exceeding the limits, strikes not detected
- S III: Pressure variables not exceeding the limits, strikes not detected
- No Strike events detected
  - same result in literature (Vikström et al., 2020) for smolt of size similar to sensors (smolt 13-20 cm, sensors 10 cm)
  - Kaplan turbines in Norway: low number of strikes detected
- Scenario III caution: higher discharge rate (100 m^3/s) shows a decrease in Nadir pressure, suggesting potential risks with further increases.
  - Is this a trend?

Vikström, Linda, Kjell Leonardsson, Johan Leander, Samuel Shry, Olle Calles, and Gustav Hellström. 2020. "Validation of Francis–Kaplan Turbine Blade Strike Models for Adult and Juvenile Atlantic Salmon (Salmo Salar, L.) and Anadromous Brown Trout (Salmo Trutta, L.) Passing High Head Turbines" Sustainability 12, no. 16: 6384. https://doi.org/10.3390/su12166384

Summary & recommendations

- Key Findings:
  - **Pressure conditions:** thresholds maintained in both power plants.
  - **Strike events:** Relatively high incidence at Ätrafors, posing injury/mortality risks despite safe pressure levels.
    - Expected in Francis turbine
- Recommendations:
  - **Rack modifications:** reduce entrainment in the turbines (already in place in Ätrafors)
  - **Strike events:** validate with rubber fish (adult size)
  - **Trend with flow:** necessary to monitor operations (same turbine, increasing flow)

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Thank you for your attention!

Any question?