Mechanical Life Prediction of Hydropower Machinery

The Role of Rotor Dynamics and Load Characterization

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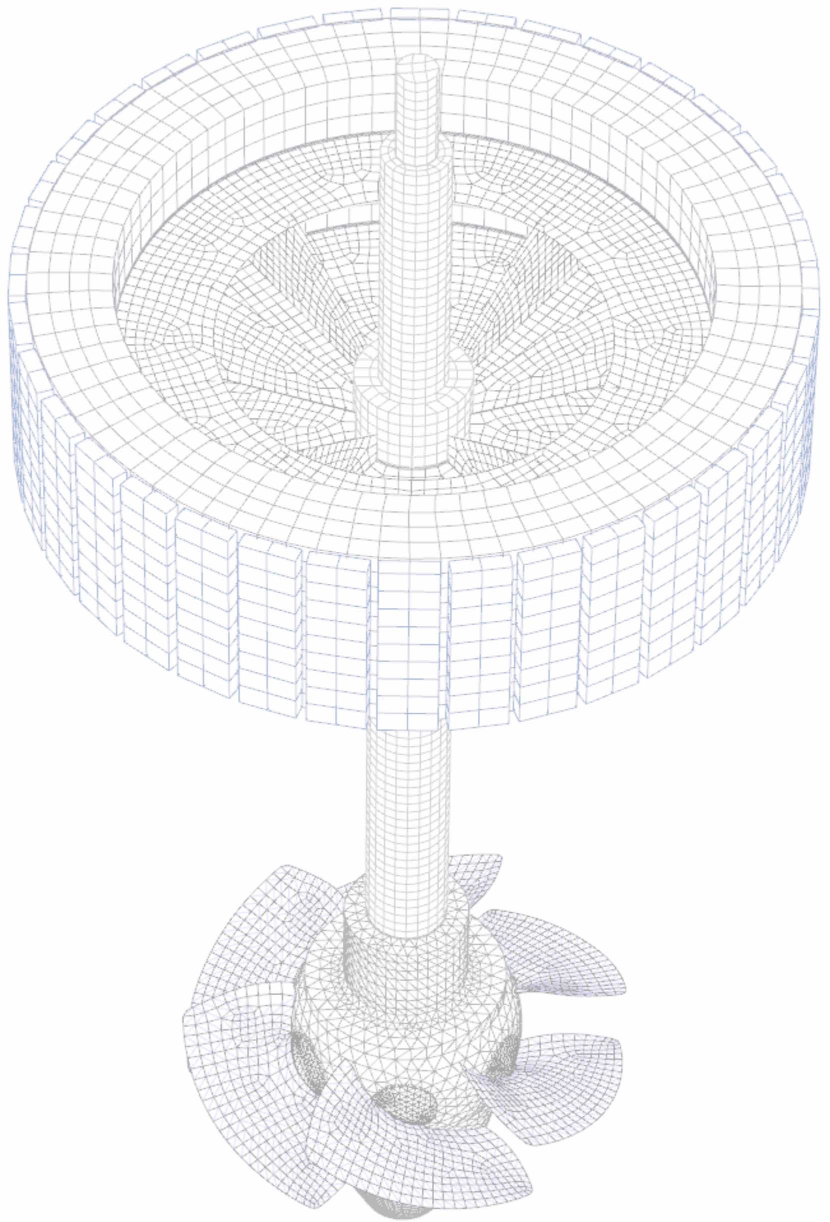


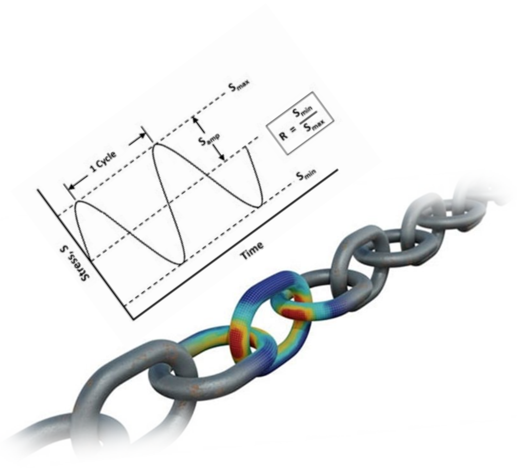
Agenda

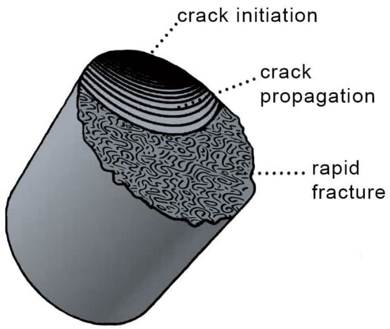
- Fatigue Failures in Hydropower Machinery
- How Machine Dynamics Govern Fatigue
- Dynamic Modeling – Advances and Challenges
- From Modeling to Prediction: Why Load Characterization is Essential

Fatigue governs mechanical life

- Dominant failure mode in rotating machinery [1]
- Under cyclical loading, small defects propagate to large-scale, rapid fracture
- Fatigue depends on entire load
- Fatigue damage is a function of distributed **load** and **number of cycles**

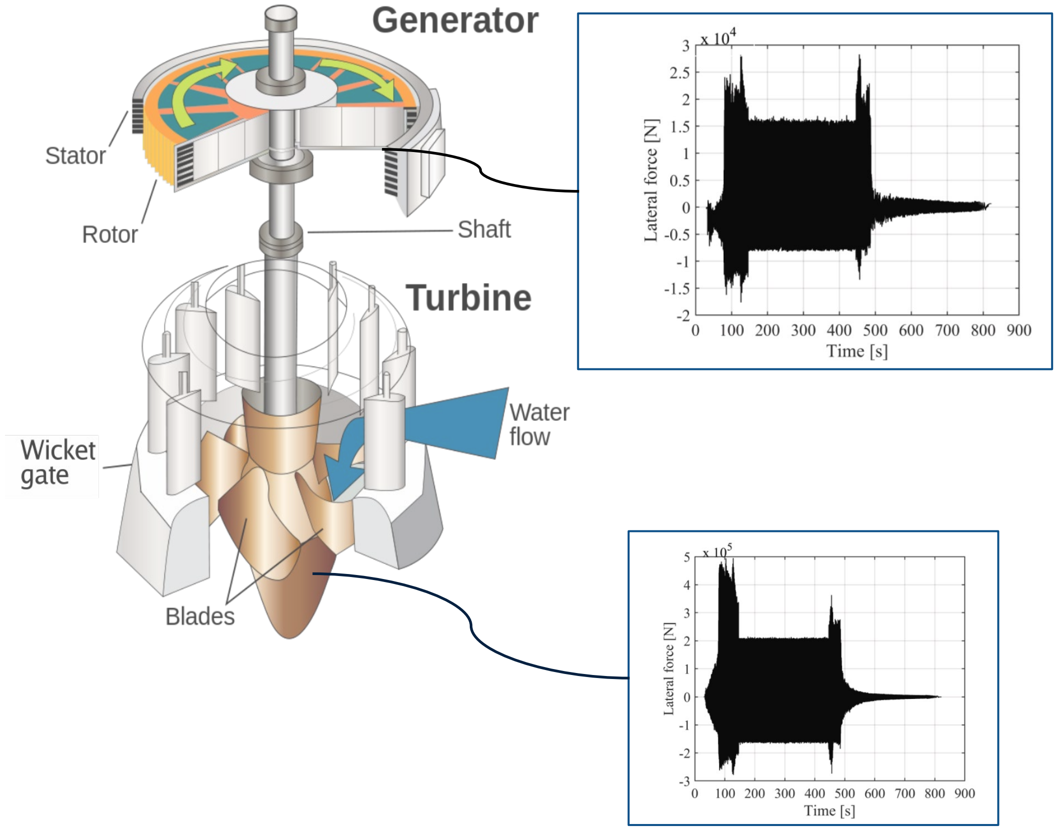
What loads drive fatigue in hydropower?





Origin of fatigue-driving loads

- **Load history** is determined by operating **conditions with increasing variety** [2]
- As operating patterns shifts, loads change correspondingly
- Forces enter through the **prime movers** and propagate through the mechanical chain
- **Vibration-driving fatigue** is the system's dynamic response to these forces



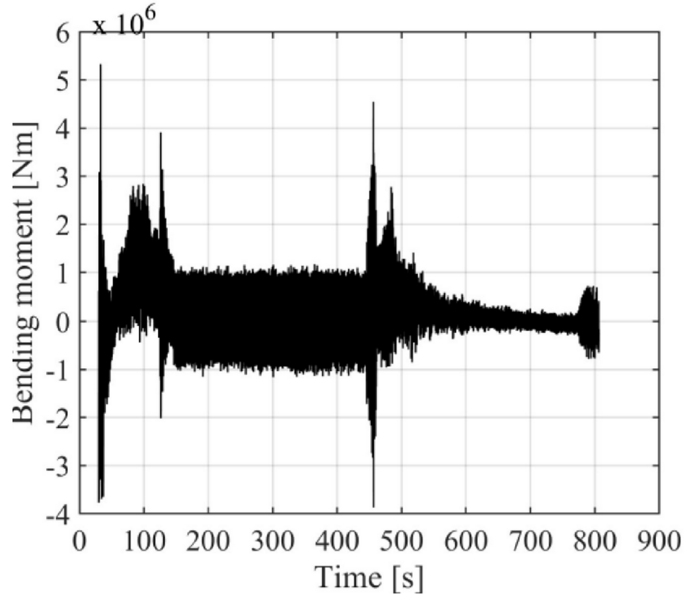
From load cycle to fatigue damage

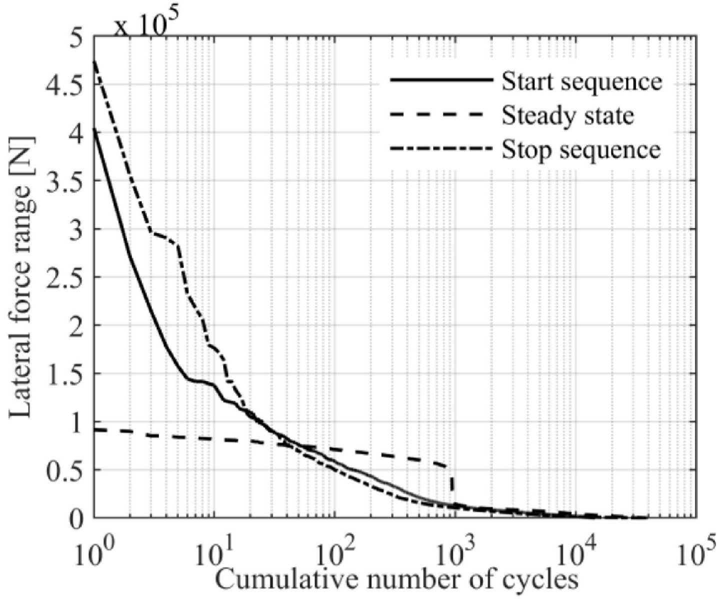
- Fatigue damage depends on both **load severity** and **cycle count,** which can be into condensed into **load spectra**

- Load spectra are applied to a component to evaluate **component-specific stress spectra**

- Reliable probabilistic assessment requires **rigorous characterization of the load history**

- **Poorly bounded uncertainty** results in unnecessary conservative designs



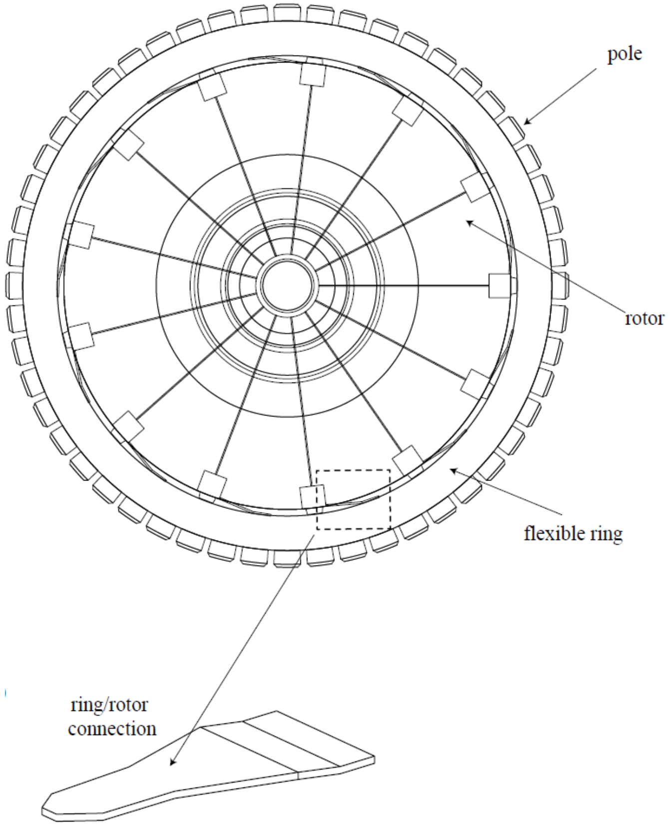


Sayano-Shushenskaya disaster (2009)

- **Vibration induced fatigue-failure** of turbine mountings
- Simultaneous flaws in **machine design, maintenance** and **process control**
- Full production regained after **six years**

Caption: Post-accident machine hall at Sayano-Shushenskaya powerplant
Image source: Ministry of Emergency Situations of Russia, via AFP / Wikimedia Commons

Damaged flexure plates in generator



Can we predict this?

Yes - but not without understanding **force transmission of the greater system – the generator**

- Fatigue damage was likely caused by **vibrations of the generator,** causing cyclical loading at component level
- This originates in the generator's dynamic response - a system property

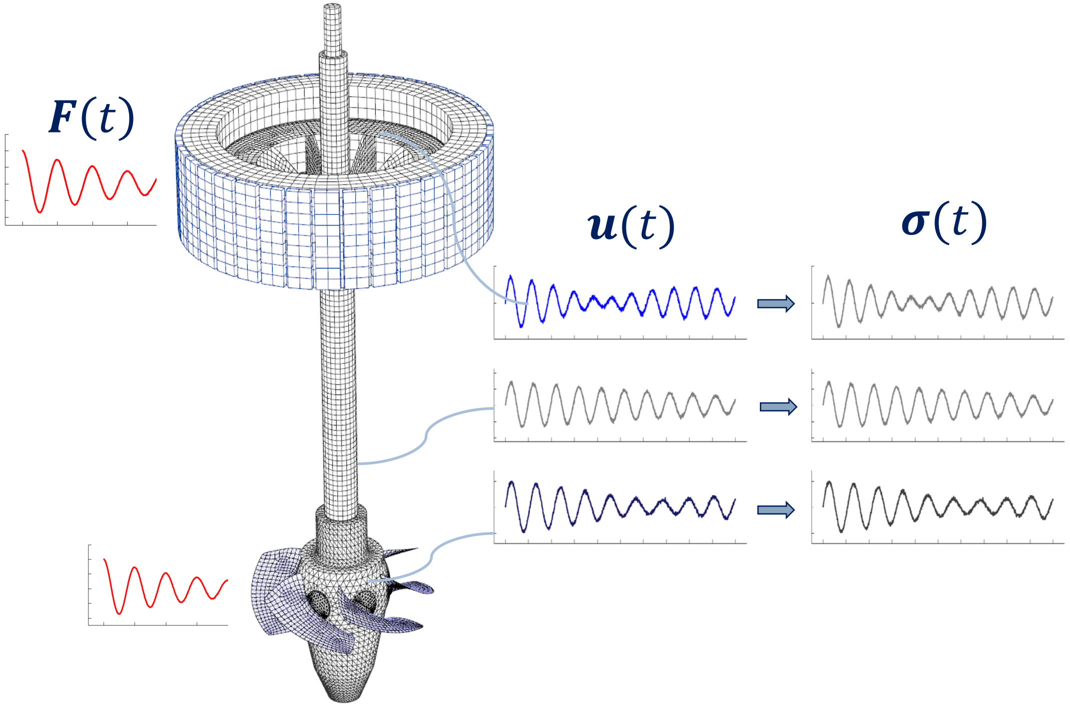
Dynamic modeling is one way to estimate this

The dynamic model

- A dynamic model describes how **forces distribute throughout a mechanical system**
- The equation of motion describes the response, $\boldsymbol{u}(t)$, from the input forces $\boldsymbol{F}(t)$

$$\mathbf{M}\frac{d^2\boldsymbol{u}(t)}{dt^2} + \mathbf{D}\frac{d\boldsymbol{u}(t)}{dt} + \mathbf{K}\,\boldsymbol{u}(t) = \boldsymbol{F}(t)$$

- The system's response, $\boldsymbol{u}(t)$ can be used to compute the stress state, $\boldsymbol{\sigma}(t)$
- Important to decide **where the system ends** and what **phenomena it should capture**



What can we use a dynamic model for?

- **Provide direct assessment**
  - Predict vibration characteristics
  - Evaluate stability margins
- **Support other models**
  - Extract load cases for studies of isolated components
  - Generate time-histories of stress and strain
  - Supply physics-consistent data for AI-models

Modeling rotating systems

- **Rotor is the main carrier of dynamic forces** and must be represented accurately

- Rotation introduces new phenomena that affect **stability and response -** not accounted for in traditional structural dynamics

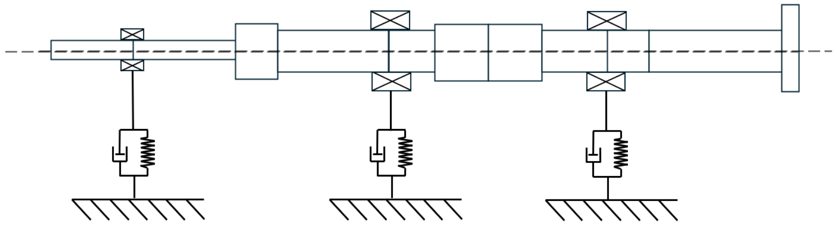
- Prominent effects for rotors that are:
  - fast-spinning
  - slender
  - high-mass rotors

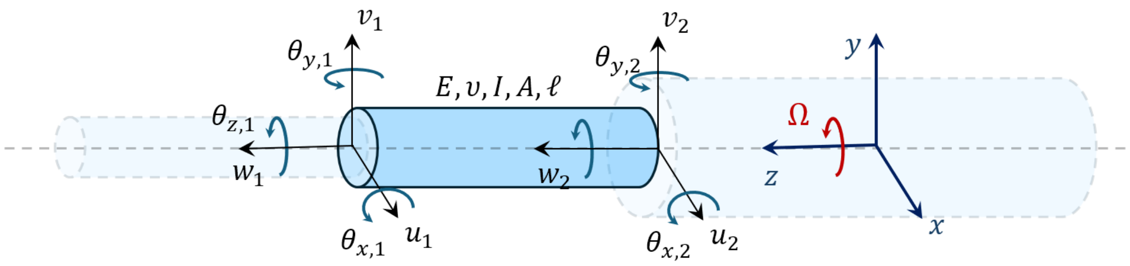
How do we model rotating systems?

Finite Element Modeling of Rotors

- Finite element method (FEM) remains the dominant approach for complex systems
  - Condenses rotor in discrete **elements,** which are connected at **nodes**
- Traditional methods utilize **beam elements:**
  - Describe global dynamics with low computational effort ✔
  - Limited resolution of geometry and distribution of internal forces ❌

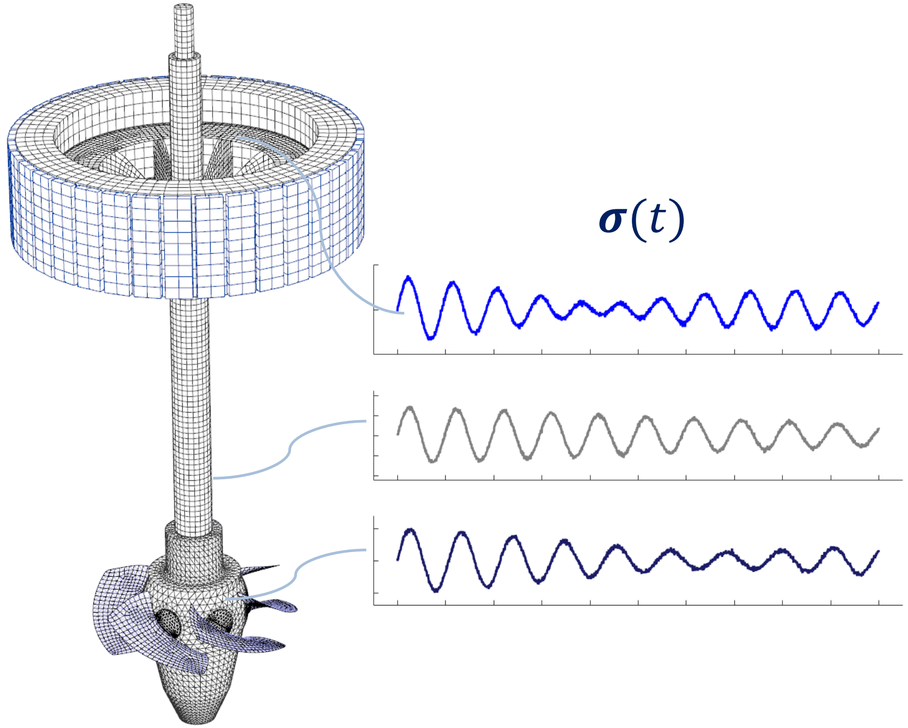
Traditional beam models cannot directly resolve fatigue-relevant stresses





High-resolution finite element modeling

- High-resolution modeling open possibilities
  - General, three-dimensional geometries
  - General, tri-axial stress and strain states
  - Advanced multi-physics coupling
- **Extremely late** to adopt 3D-finite element techniques
  - First publications ~ Early 2000:s
  - First commercial software ~ Early 2010:s

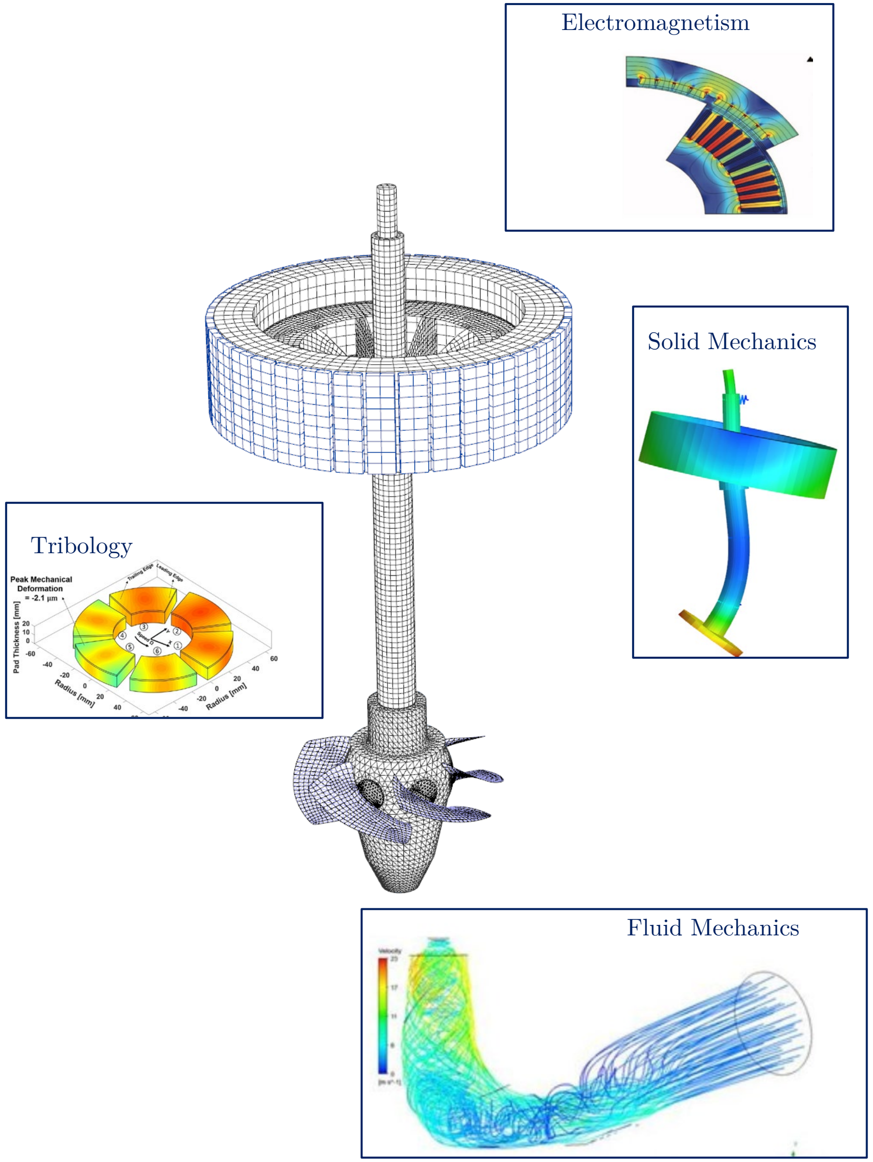


Theoretical framework is mature - but challenges remain specific for hydropower

Challenges – Integrating multi-physics

Multi-physical interactions must be incorporated – but selectively

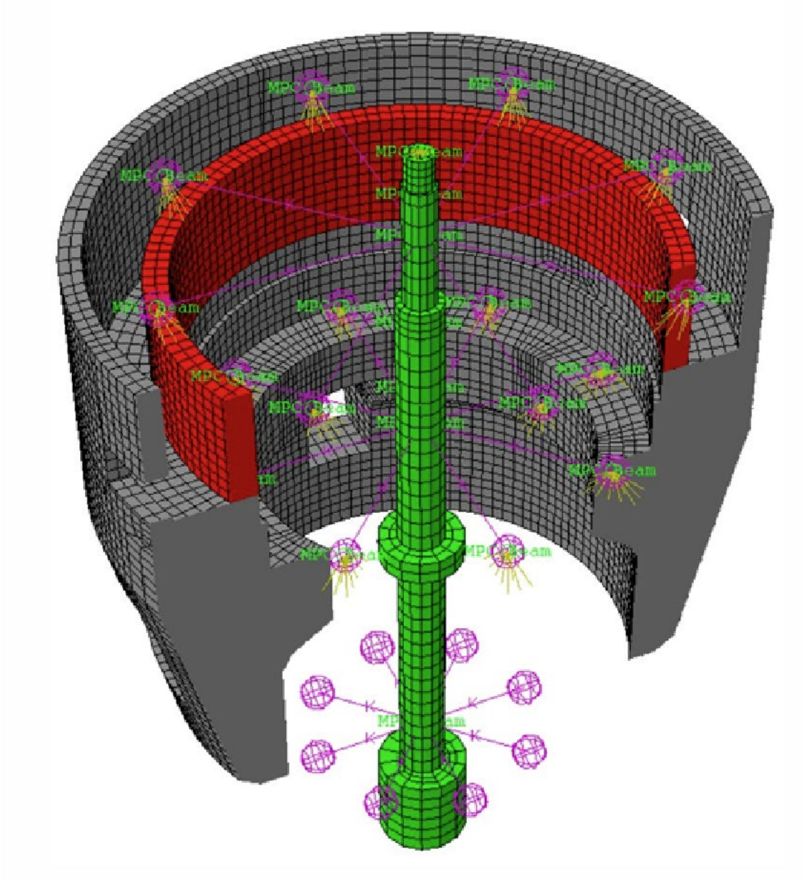
- Incorporating electromagnetism, fluid-mechanics and tribology important
- What are the large-scale forces that affect the mechanical system?
- Full multi-physics coupling is rarely appropriate
- **Careful** selection of **condensed models** needed – rotor dynamics is a product of **all these phenomena**



Challenges: Drawing system boundaries

Where do we draw a system's boundaries?

- Dynamic behaviour depends on the whole, rotating mechanical chain – and may extend further
- Each system-layer adds costly complexity and risks impractical models
- Large parameter spaces must be analyzed to evaluate a system -> Smart modeling essential for feasibility



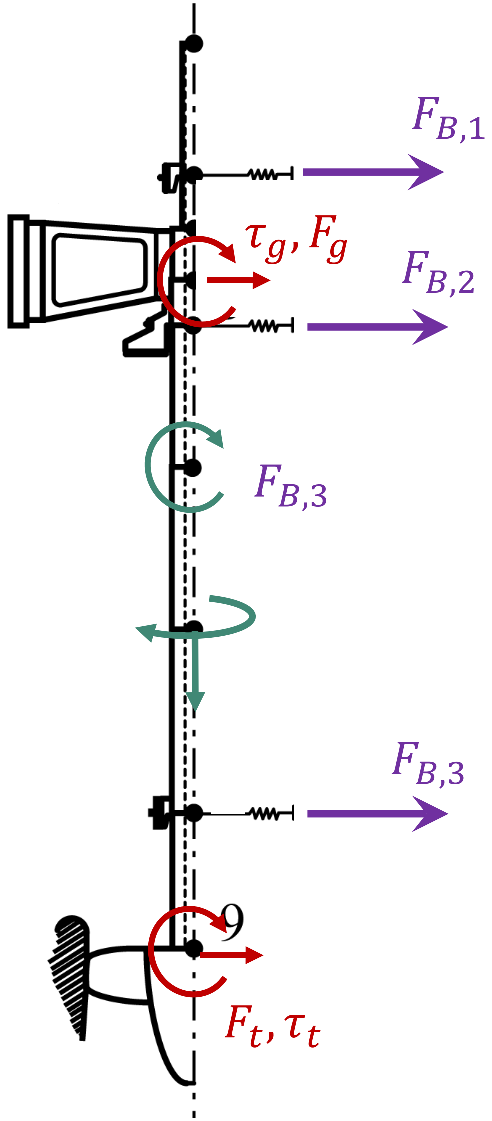
Modeling is advancing - but prediction capability is limited

- Research has been dedicated to develop and validate numerical models in hydropower rotor dynamics
- **BUT - Even advanced models remain constrained without validated input data**
- ❌ **Critical gap: Limited characterization of input loads**
  - What loads enter through the prime movers under a **specific mode** of operation?
  - Amount of cycles, amplitude variation, frequencies, ...
  - What is general and what is machine specific?

Measuring reality is the most robust way to map this area

Proposed teechnique for load measurements

- Turbine and generator loads unknown
- Requires measurement on shaft with simple, cost-effective relatively non-invasive procedures [3]
  - Axial loads, torsional moment and bending moments by strain-gauges on shaft
  - Bearing loads treated by numerical models by measuring displacement
- Local measurements are a useful complement, but must be synchronized to large-scale force characterization
- If properly validated, this allows us to rapidly gather data for different designs and different modes of operation



Practical impact

- **More robust statistical assessment**
  - Quantify uncertainity for probabilistic modeling
  - Basis to improve overly-conservative designs
- **Validated load cases**
  - Basis for standardized, validated load cases for specific operation
  - Improved understanding of machine specific and general load trends
- **Better engineering decisions**
  - Identification of decisive load mechanisms
  - Focus on critical components
  - Improved basis for inspection and actions for life extension

Conclusions

- **Fatigue** governs **mechanical life** in hydropower machinery
- **Fatigue-driving vibration** is a system response to **dynamic forces**
- **Rotor dynamic models** are our framework to predict these forces
- **Hydropower dynamics** demands simultaneous integration of **multi-physical phenomena** and **system-wide interaction** in **light-weight models**
- **Load characterization** bridges **rotor dynamic modeling** and **reliable lifetime prediction**

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References

- [1] Campbell, F.C., 2012. Fatigue and Fracture: Understanding The Basics, 1st ed. ASM International.
- [2] Nobilo M, Salehi S, Nilsson H. Lifetime analysis of hydro turbines with focus on fatigue damage in a renewable energy system – a review. Renew Sust Energ Rev. 2026. doi:10.1016/j.rser.2025.121511.
- [3] Gustavsson R, Isaksson E, Measurement of loads acting on a hydropower unit during stationary and transient operations, Applications in Engineering Science

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