Optimal Control of Threaded Fastener Tightening Processes

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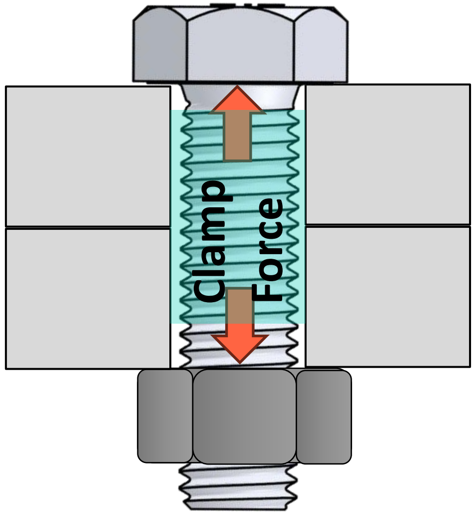
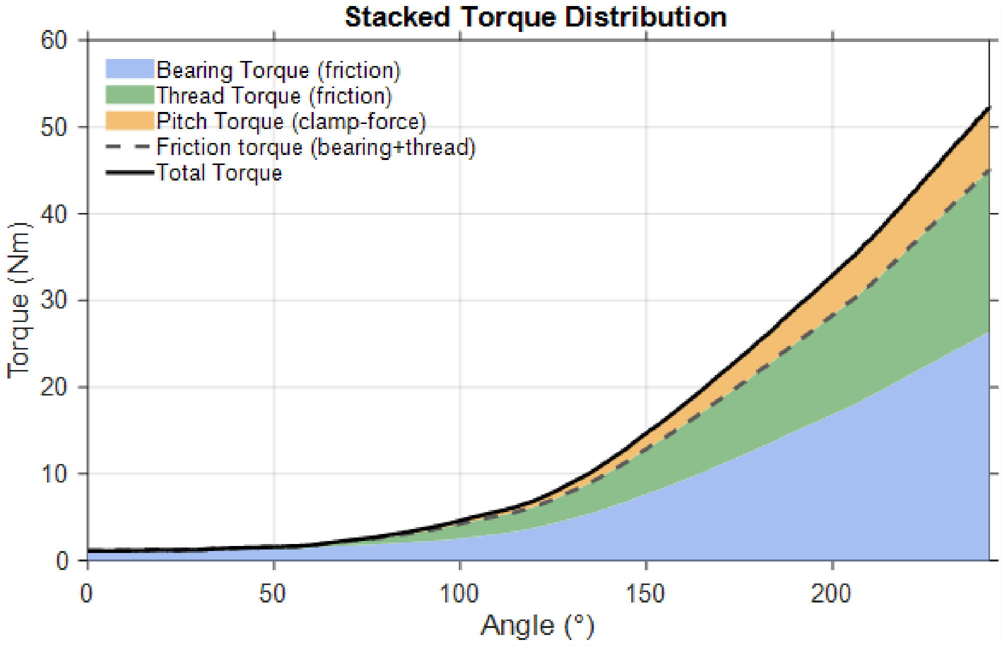
Optimal process control strategies for tightening processes

Tightening Tools and Controllers

Threaded Fastener Joints



Tightening Torque Distribution



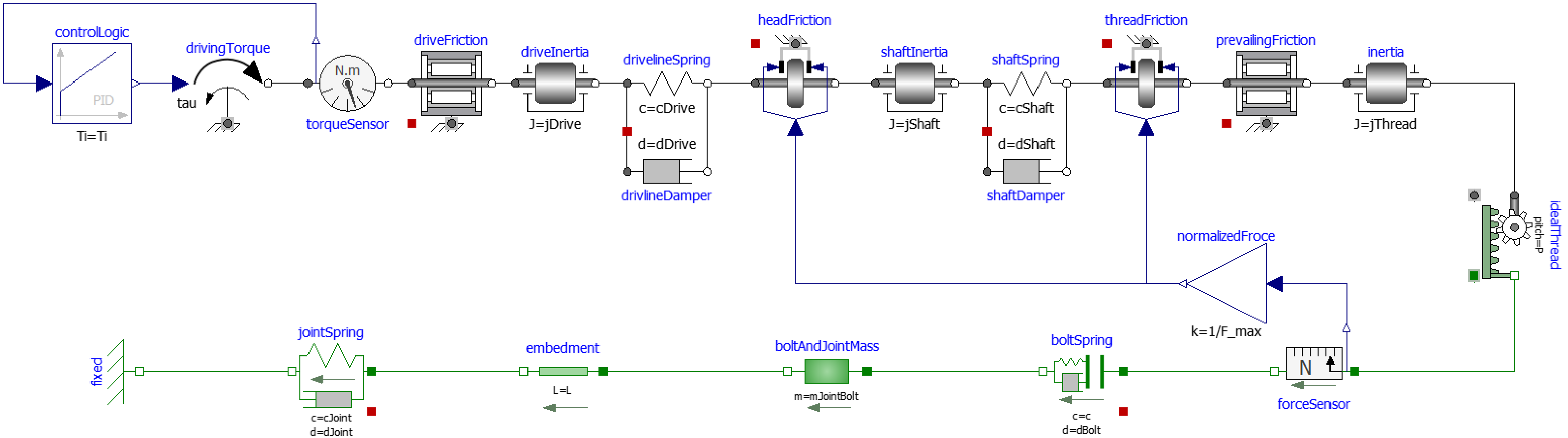
Clamp Force

Main purpose of a threaded fastener joint

Friction dissipates≈ 90% of tightening energy

Understanding it is key to precision and control

Dynamic Tightening Model

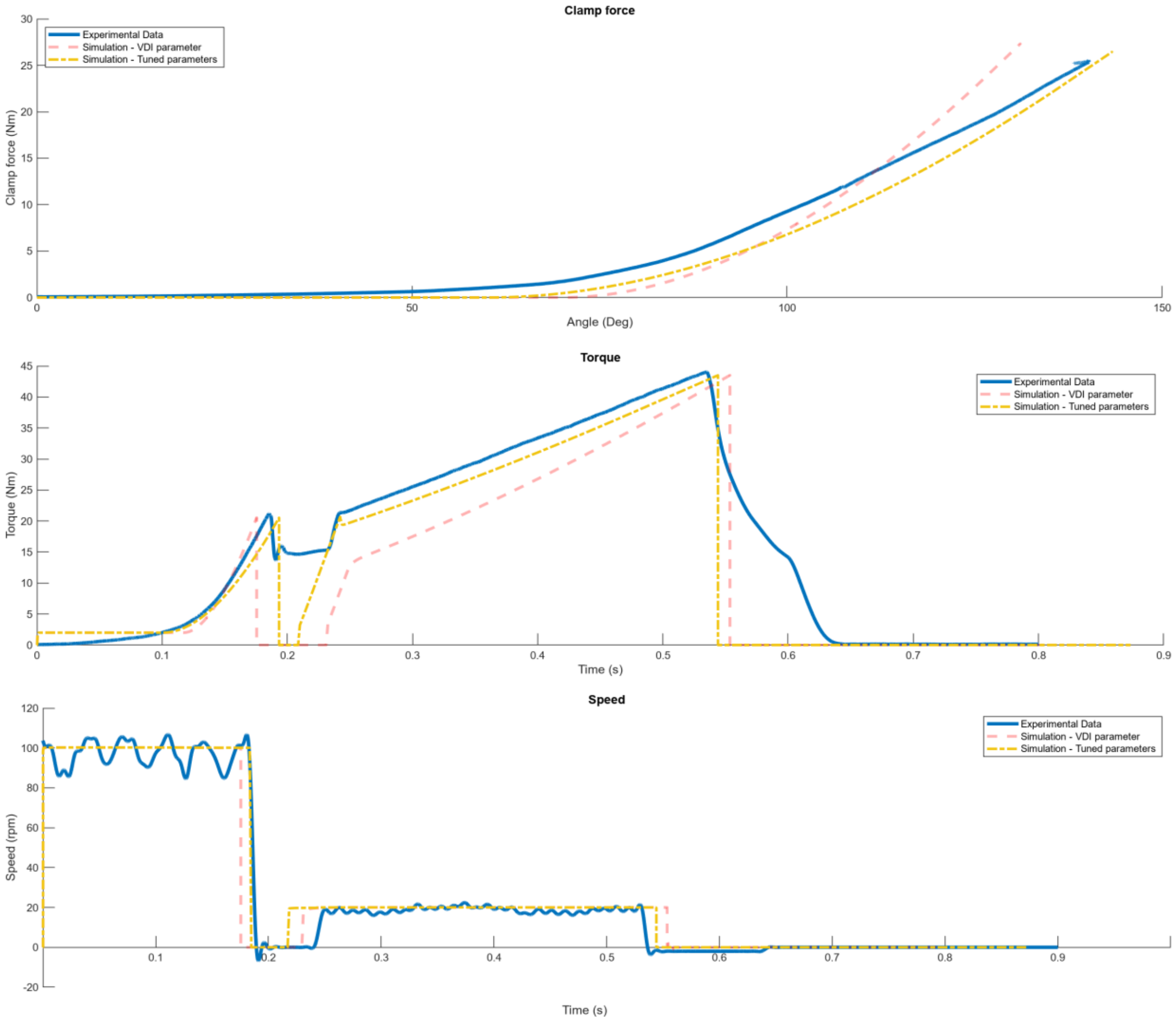


Control-oriented multibody model of the tightening process

- Tool, driveline and threaded fastener joint
- Rotation-to-clamp-force transformation
- Bolt/joint compliance and embedment
- Thread and under-head friction
- Implemented in OpenModelica

Outcome:
Reusable framework for tightening dynamics, friction studies and control-oriented analysis.
Limitation:
Transient friction behavior became the main challenge.

Challenge: Calibration and Robust Simulation



VDI-based parameters:
Reasonable start, but not direct experimental fit

Tuned parameters:
Better agreement with torque and clamp-force data

Smooth excitation:
Constant speed and rate-limited transitions improve robustness

Closed-loop control:
Adds transients near zero speed and stick-slip regions

Takeaway:
A useful tightening model must balance experimental agreement, parameter calibration and numerical robustness.

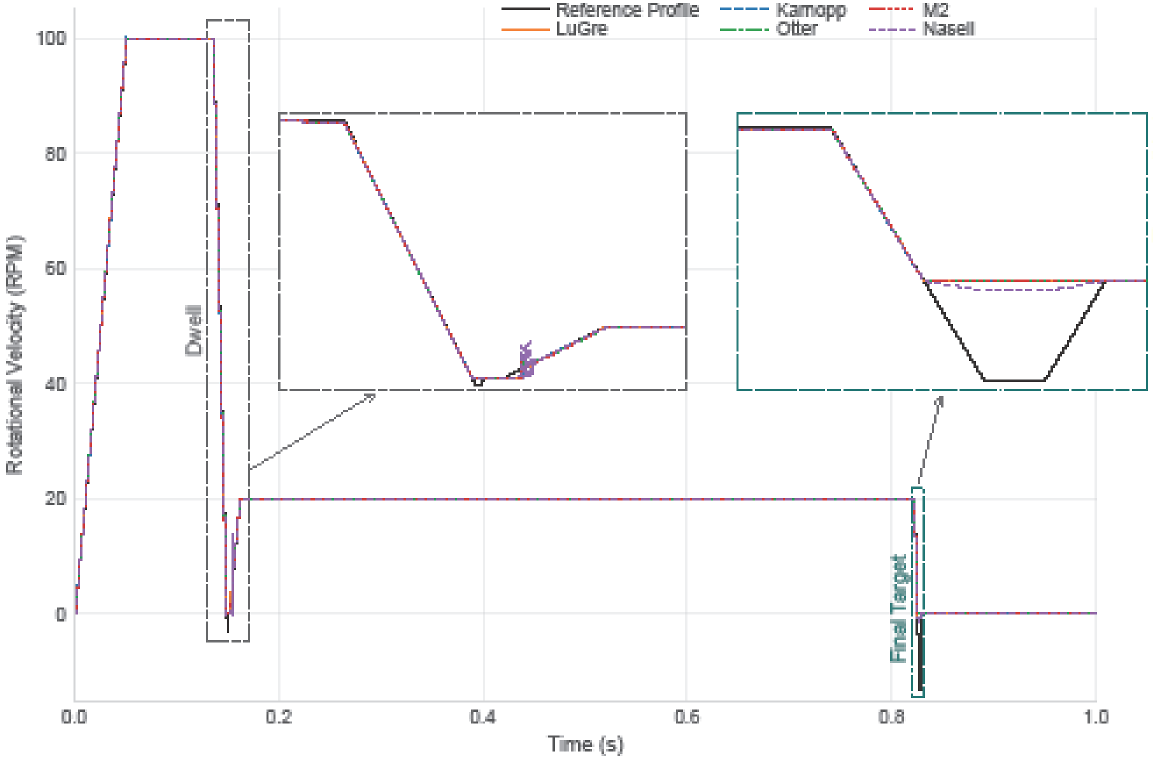
Systematic Comparison of Friction Models

Five friction models:
Karnopp · Otter · LuGre · M2 · Nåsell

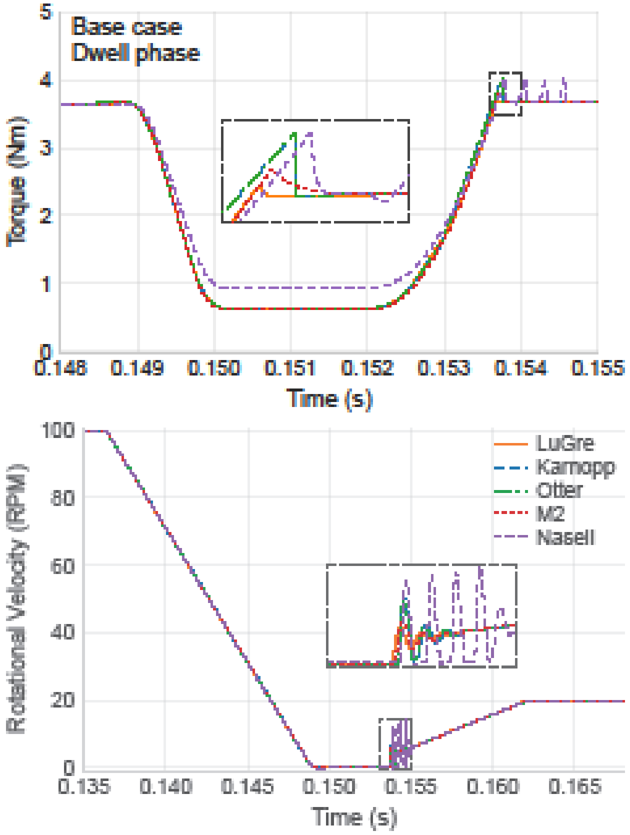
Focus:
Dwell · break-away · zero-velocity crossings · final target stop

Benchmark setup:
Same joint model, shared tightening scenarios, different friction formulations.

Excitation and velocity response

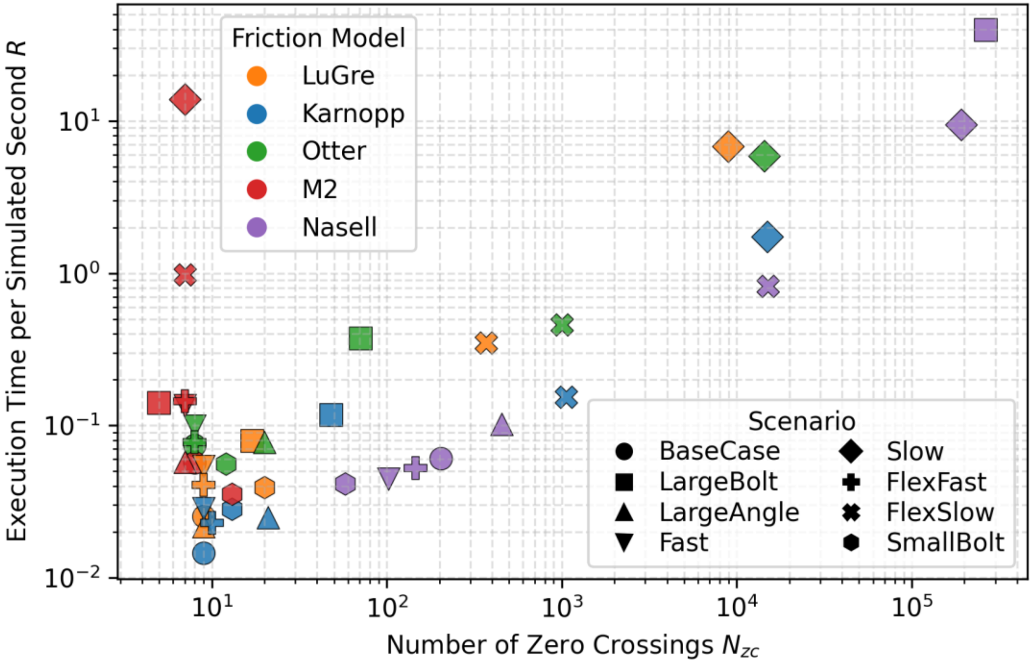


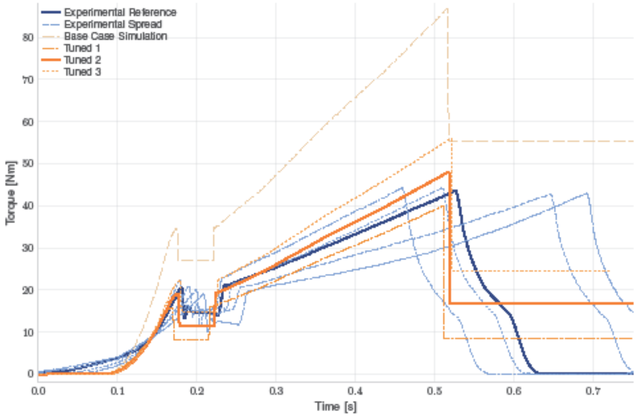
Dwell torque and velocity response

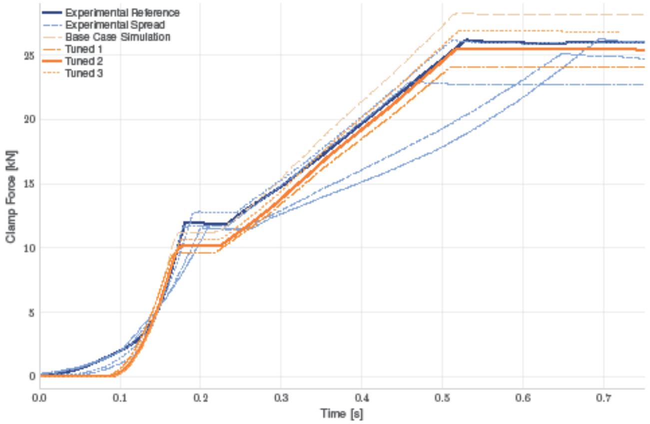


Observation:
Differences are clearest near zero relative velocity.

Robustness and Parameter Sensitivity







Numerical robustness

- Solver effort varies by orders of magnitudeZero crossings indicate difficult transient behavior
- Regularization and excitation affect simulation cost

Parameter sensitivity

- Several plausible parameter sets can fit the trend
- Simulation spread is comparable to experimental spread

Main Findings

Smooth tightening:
Models often give similar global responses

Transients:
Dwell and break-away reveal differences

Numerics:
Regularization and excitation strongly affect robustness

Model choice:
Depends on the intended application

Next Steps

Clamp-force estimation

Model-based diagnostics

Robustness and sensitivity studies

Clamp-force-based / MPC / learning-based control

Takeaway
The model framework is now mature enough to move from friction-model evaluation toward estimation, diagnostics and control.