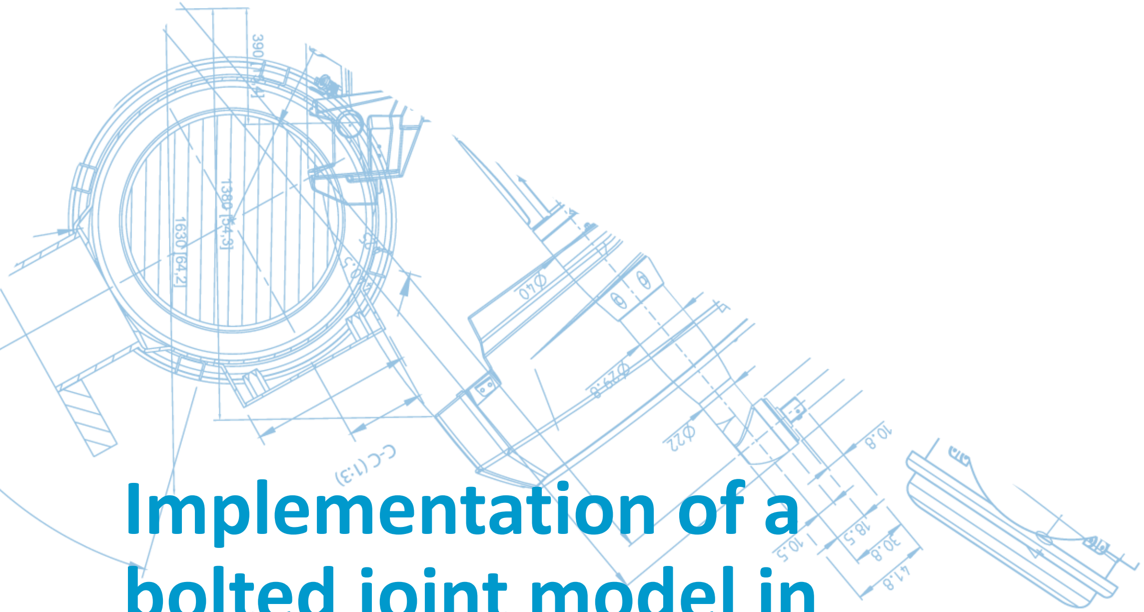
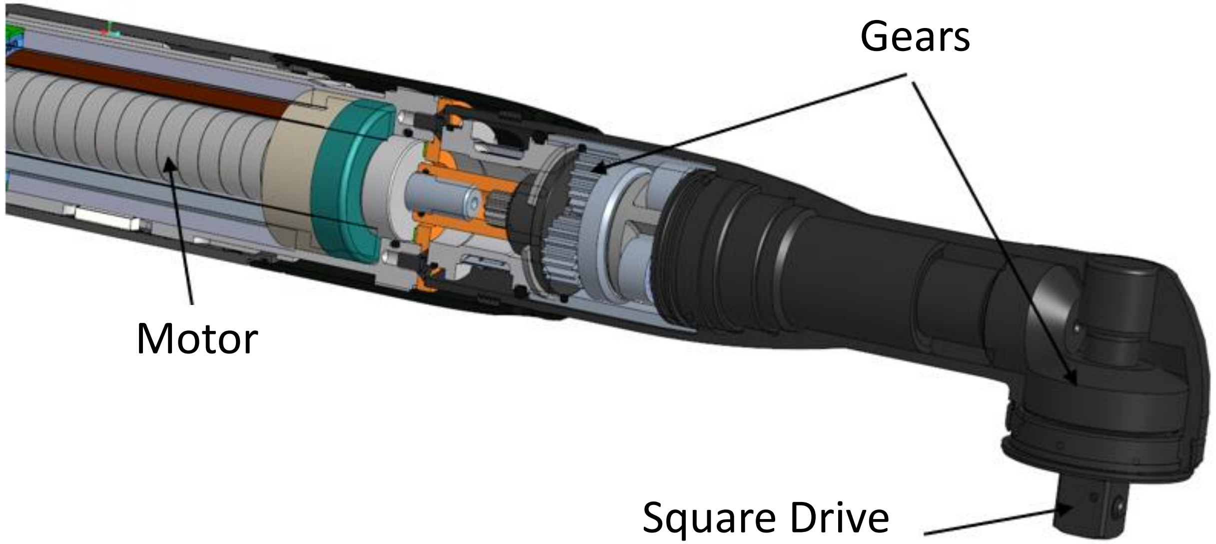
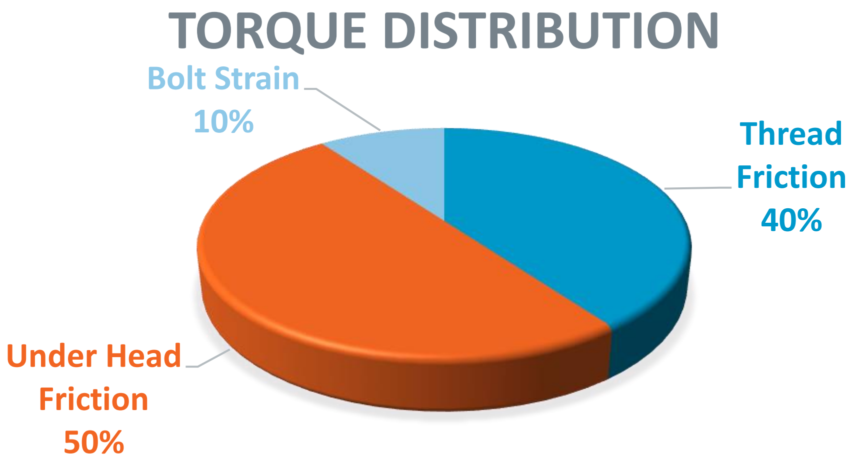


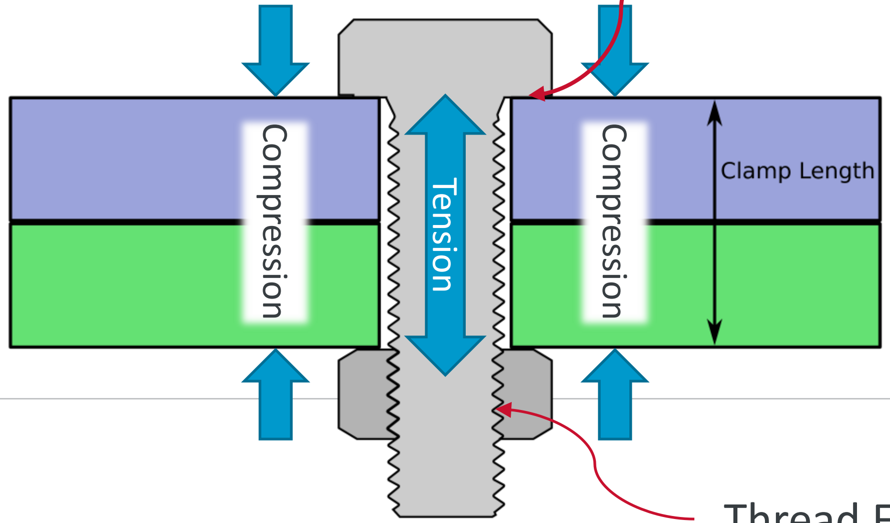
Implementation of a bolted joint model in Modelica

Nils Dressler, Ph.D. Student – Atlas Copco / Linköping University

Background



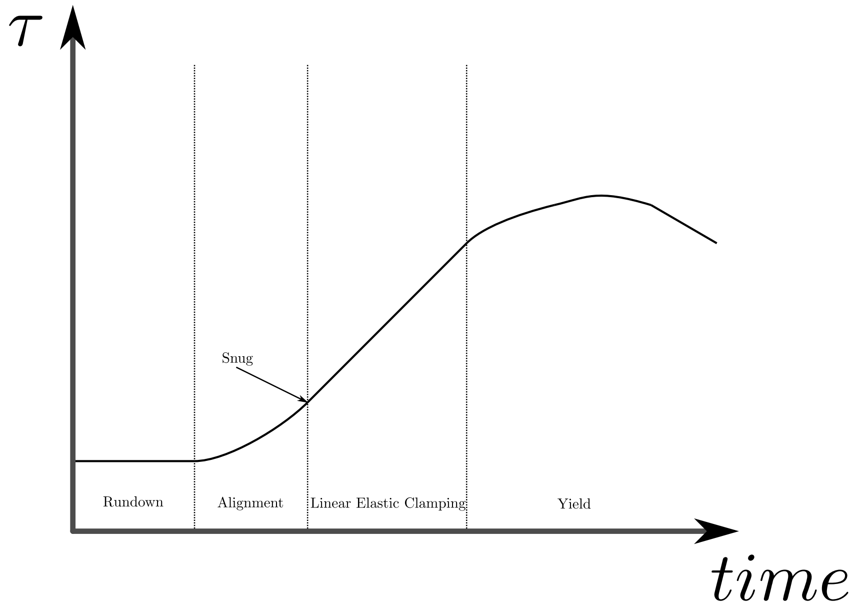




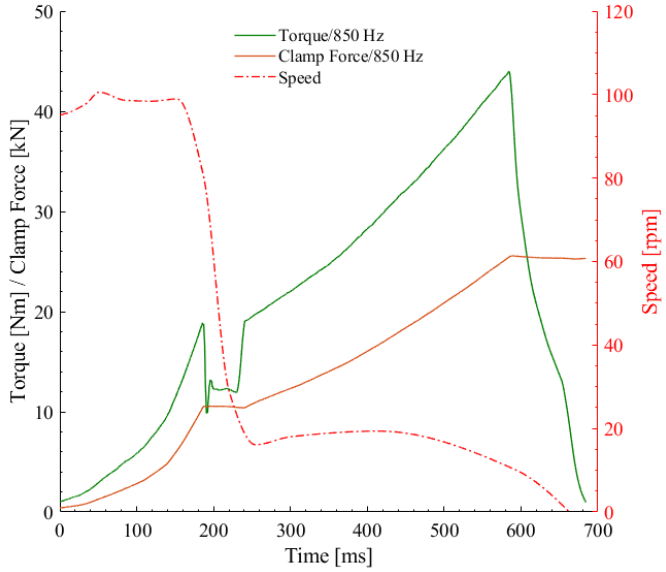
Biggest challenge:
Uncertainty in friction

Tightening Phases and Drive Methods

4 Tightening Phases

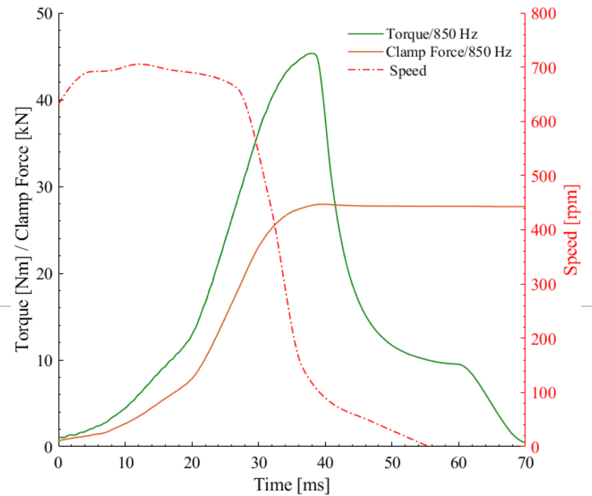


Standard 2 Step Constant Speed Tightening Torque Shutoff

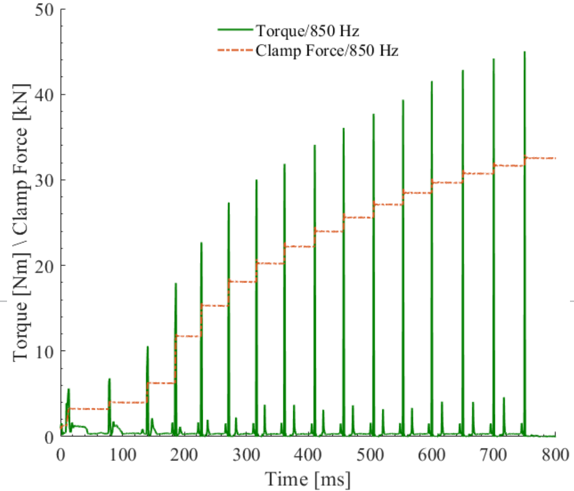


Exists with Angle Shutoff

Inertia Controlled Tightening



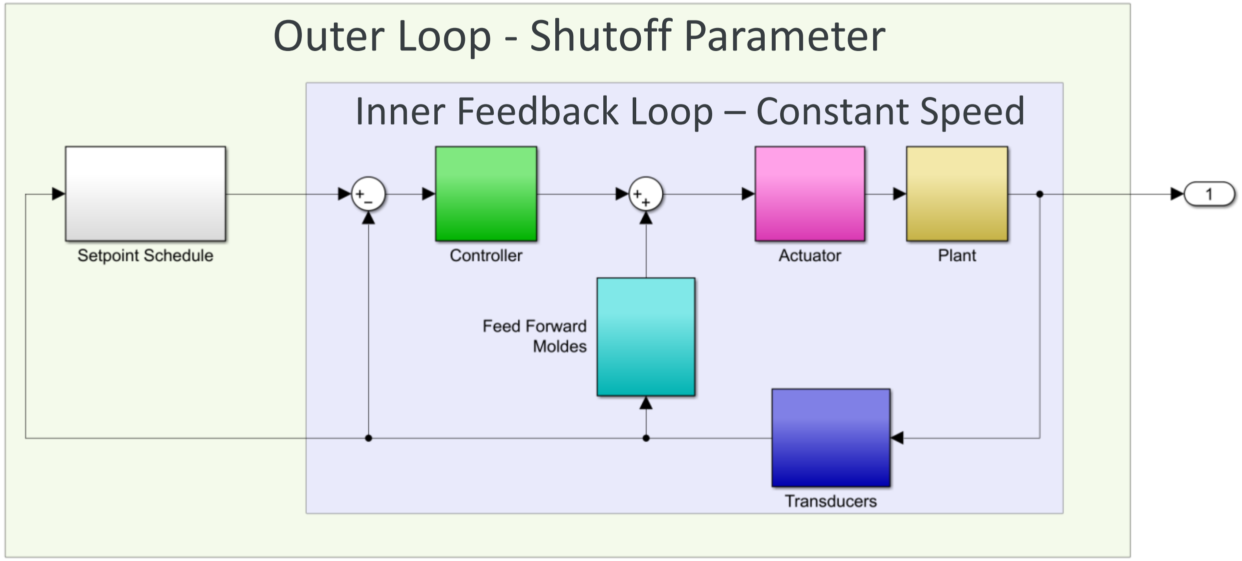
Pulse Tool Tightening



State of the Art in Tightening Control – Future Vision

State of the art

Cascaded Control



Used Models

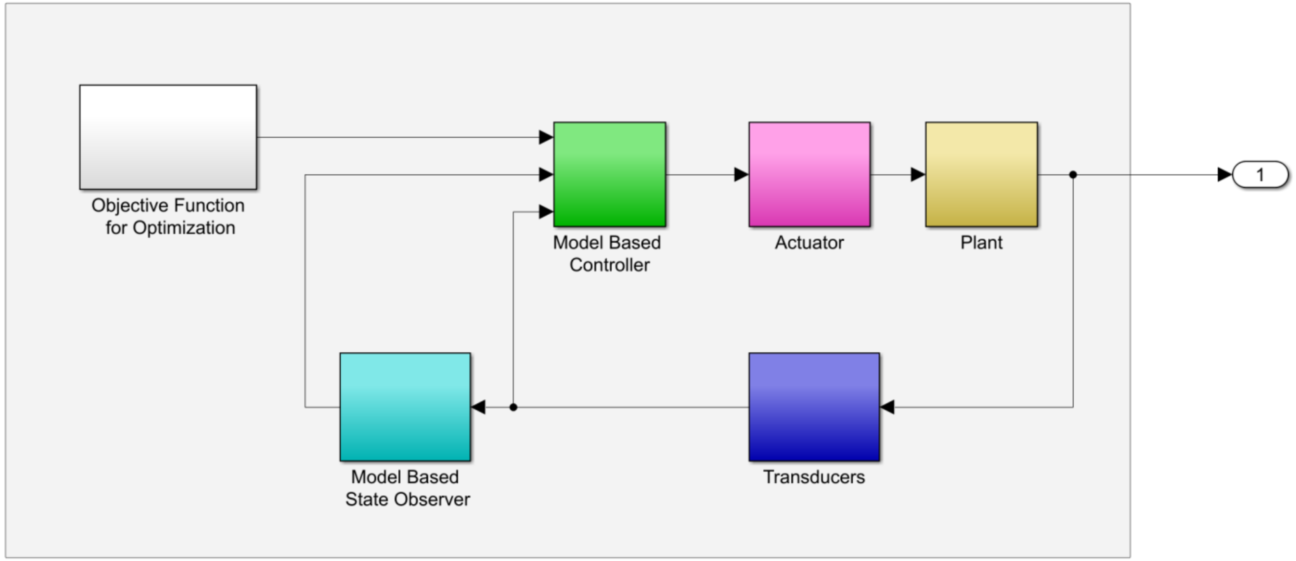
$$\tau_M = k_T i$$

Torque-Current relationship

τ_M = Motor Torque
k_T = Torque Constant
i = Morot Current

Future vision

Model Based Control



Target: Model-based control with dynamic tightening

Main obstacle: Uncertainties in friction

-> Need for
System Understating
Good Models

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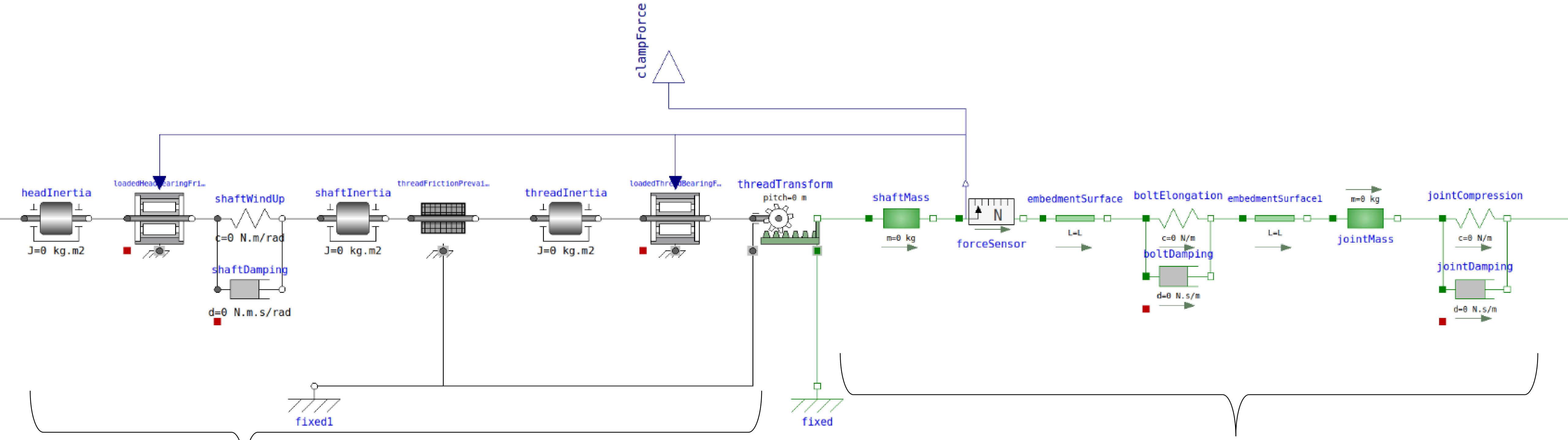
High Level Implementation



3 inertia spring-damper system
Rotational
Subject to friction

Coupled through
fastener thread

2 mass spring-damper system
Translational
Affected by embedment

- Main approach: Modeling tightening phases by state depended spring behavior

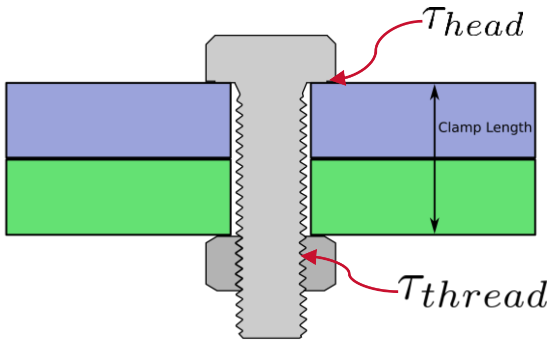
Implementation of Friction Models

- Friction Components:
  Under Head, Thread and Bearing Friction

$$\tau_{fa} + \tau_{fb} + \tau = 0$$

$$\tau = \frac{1}{2} d_i \mu_m \tanh(h_c \omega) \cdot \begin{cases} f_n, & \text{if } f_n > 0 \\ 0, & \text{otherwise} \end{cases}$$

$\tau_i =$ torque
$fa =$ flange a
$fb =$ flange b
$d_i =$ friction diameter
$h_c =$ simualtion parameter
$\omega =$ angular velocity
$f_n =$ normal force



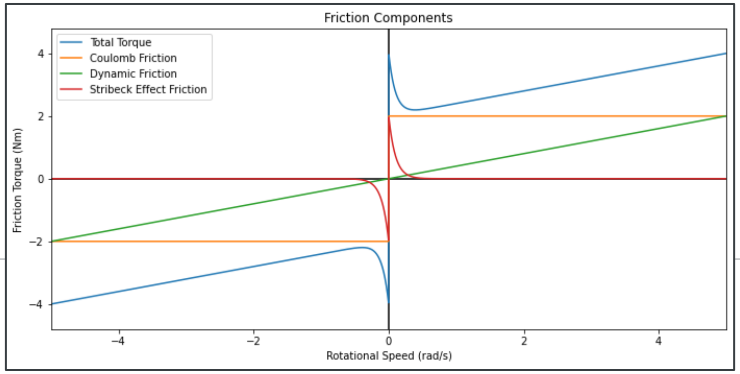

```
model UnderHeadFriction "Under Head Friction based on Coulomb friction"
extends ...Interfaces.PartialElementaryTwoFlangesAndSupport2;

  SI.Angle phi "...";
  SI.Torque tau "Friction torque";
  SI.AngularVelocity w "...";
  SI.AngularAcceleration a "...";
  Modelica.Blocks.Interfaces.RealInput force_n(unit = "N")
  "Absolute normal force inpu; friction is active if > 0)";

  parameter Real D_Km(final min = 0,unit="m") = 1 "d_i";
  parameter Real mue_pos[:,2] = [0 ,0.12] "Coeffiecient of Friction";
  parameter Real mue_stri = 0.36
      "Coefficient of friction for Stribeck Effect at its maximum";
  parameter Real fexp(final unit="s/m",final min=0,start=2) = 2
     "Exponential decay";

equation
  phi = flange_a.phi - phi_support;
  flange_b.phi = flange_a.phi;
  w = der(phi);
  a = der(w);

  flange_a.tau + flange_b.tau - tau = 0;
  tau = tanh(3600*w)* 0.5 * D_Km * (if force_n > 0 then force_n else 0)
        *(interpolate(mue_pos[:,1], mue_pos[:,2], w, 1)
         + mue_stri*exp(-fexp*abs(w));
```



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Implementation of Embedment

$$\frac{dl}{dt} = \begin{cases} \frac{1}{\tau_T}(l - l_{max}\frac{f_{fb}}{f_{max}}), & \text{if } f_{fa} > 0 + \epsilon \\ 0, & \text{otherwise} \end{cases}$$

l = surface height

l_{max} = surface deformation maximum

f_{fa} = normal force flange a

f_{fb} = normal force flange b

f_{max} = maximal normal force

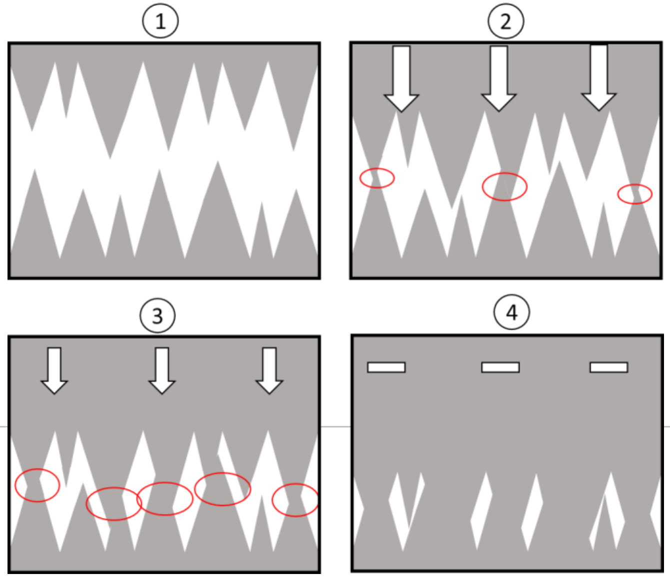
```
within ThreadedFastener;

model Emb_positive "Rigid connection of two translational 1D flanges"
  import SI = Modelica.Units.SI;

  SI.Position s "Absolute position of center ...";
  SI.Length l(start = 0) "Length of component ..."
  ...Translational.Interfaces.Flange_a flange_a "...";
  ...Translational.Interfaces.Flange_b flange_b "...";
  parameter SI.Distance l_max = 0.01
  "Height of the surface roughness at the interface";
  parameter SI.Time tauT = 0.5
  "Time constant for the change of the surface roughness";
  parameter SI.Force fmax = 10 "Maximum Force for the given spring";
  parameter Real epsilon = 0.1 "Threshold force to avoid chattering";
equation
  flange_a.s = s - L / 2;
  flange_b.s = s + L / 2;
  0 = flange_a.f + flange_b.f;
  der(L) = if flange_a.f > 0 + epsilon
           then -1 / tauT * (l - l_max * (flange_b.f / fmax))
           else 0;
end Emb_positive;
```

<u>Embedment Process</u>

2 Surface profiles with local contact pressure



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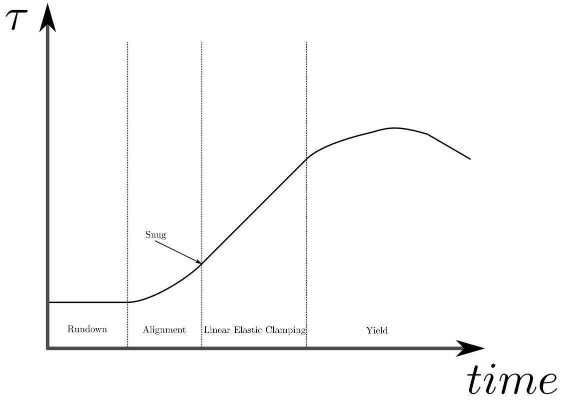
Implementation of Tightening Phases

$$f = \begin{cases} 0 & \text{if} \quad \delta \leq \delta_{rd} \\ c_{al}(\delta - \delta_{rd})^p & \text{if} \quad \delta_{rd} < \delta \leq \delta_{al} \\ c_{le}(\delta - \delta_{al}) & \text{if} \quad \delta_{al} < \delta \leq \delta_{yd} \\ g(\delta) & \text{if} \quad \delta_{yd} < \delta \end{cases}$$

Angle displacement relationship : $\varphi_i P = \delta_i$

f = Force between flanges
P = Thread pitch
p = Polynom degree for non-linearity
rd = Rundown
al = Alignment
yd = Yield
le = Linear elastic
$g(x)$ = Non linear function

Tightening Phases

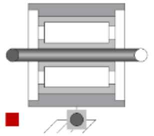


One Component Model

```
model 4 PhaseSpring "Joint Spring with 4 Pahses"
...
equation
  f =
  if s_rel < s_rd
    then c*(s_rel - s_rel0);
  else if s_rel > s_rd and s_rel < s_al
    then ...
  end if;
```

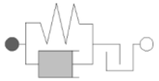
Combined Model

bearingFriction



Bearing Friction Model

elastoBacklash



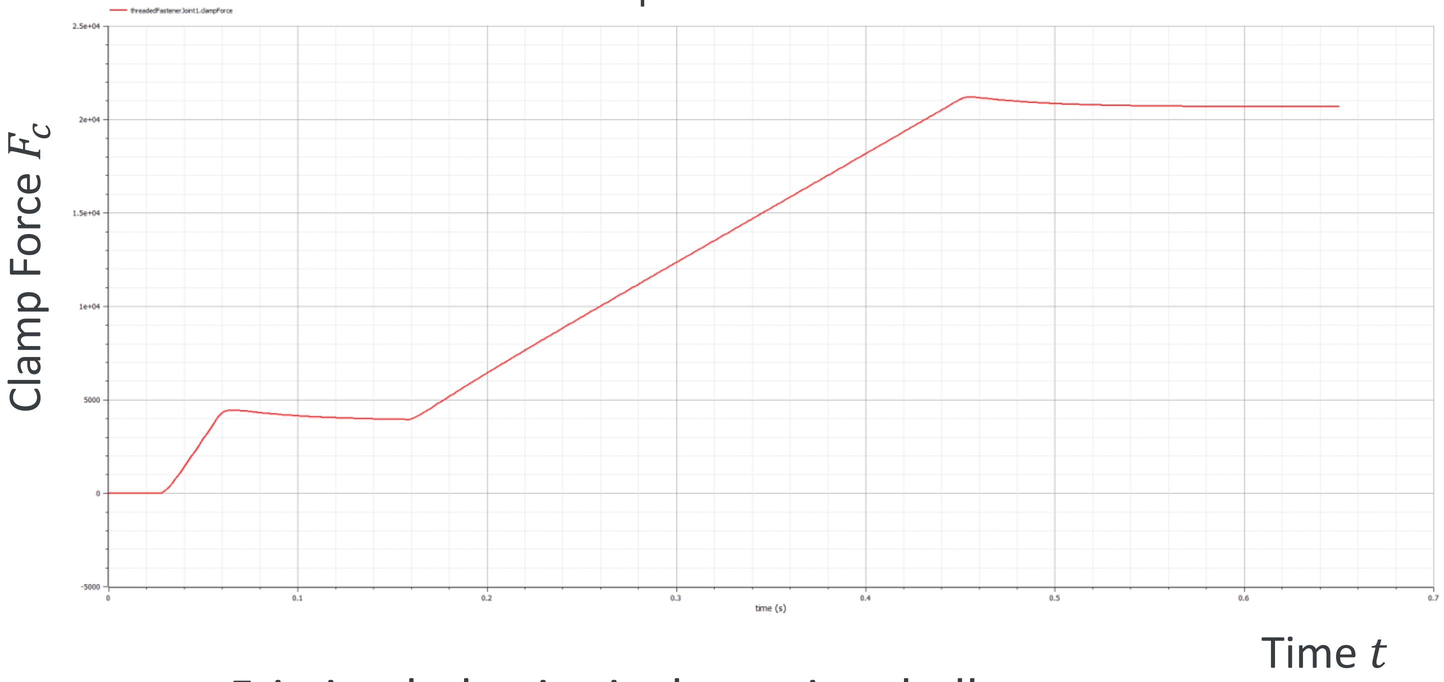
Elasto-Backlash Model

Alignment

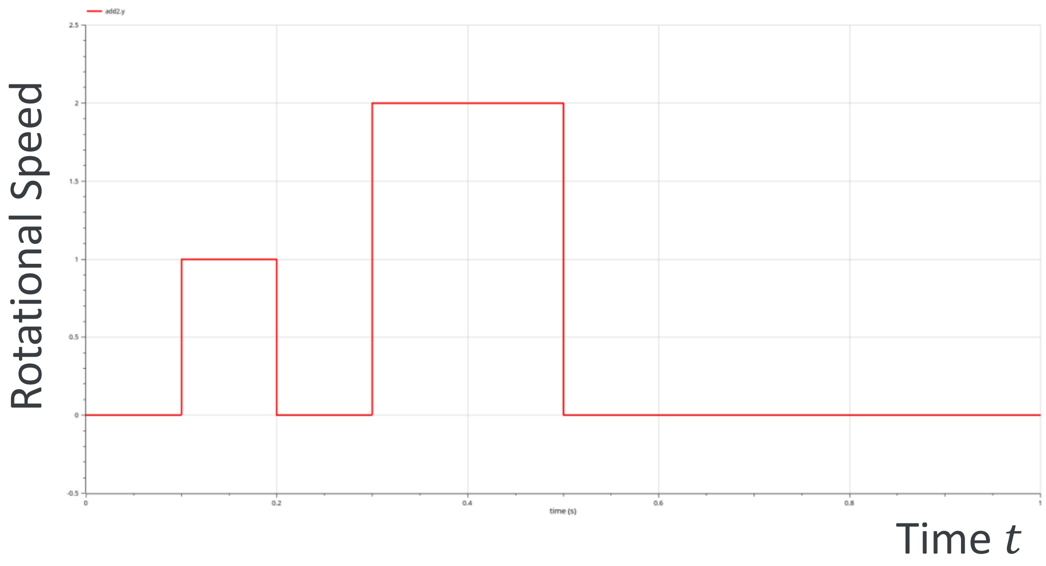
```
model Alignment
"Model to simulate the alignment"
import SI = Modelica.Units.SI;
extends ...Interfaces.PartialCompliant;
  parameter Real c(final min=0, start=1)
    "Spring constant unit in N.m^p/m";
  parameter SI.Distance d(final min=0,start=1)
    "Offset for missalignment";
  parameter Real p(final min=0, start=1)
    "Polynom Degree";
  parameter SI.Distance s_rel0=0
"Unstretched spring length";
equation
  f = -c/d^p*(abs(s_rel - s_rel0))^p;
end Mating;
```

Simulation Results

Clamp Force Generated



At given reference speed



- Friction behavior is the major challenge
- Replacing friction models in theory simple
- Practically often other adoptions to the model are needed
- Simple friction model → Execution time in range of 10^{th} of seconds
- Complex friction model → Execution time in range of 10^{th} of minutes

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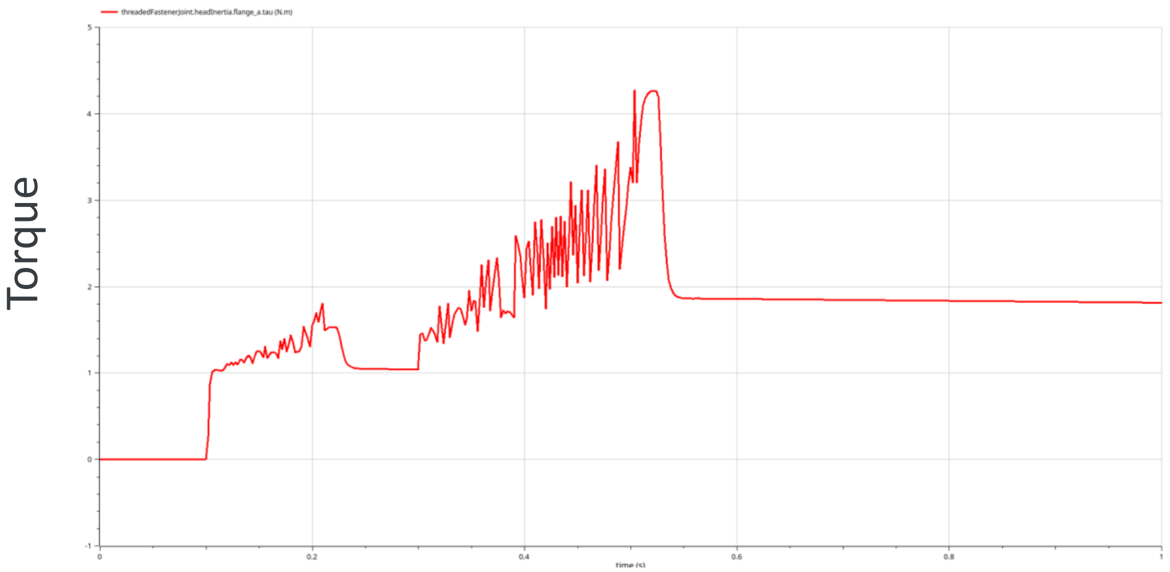
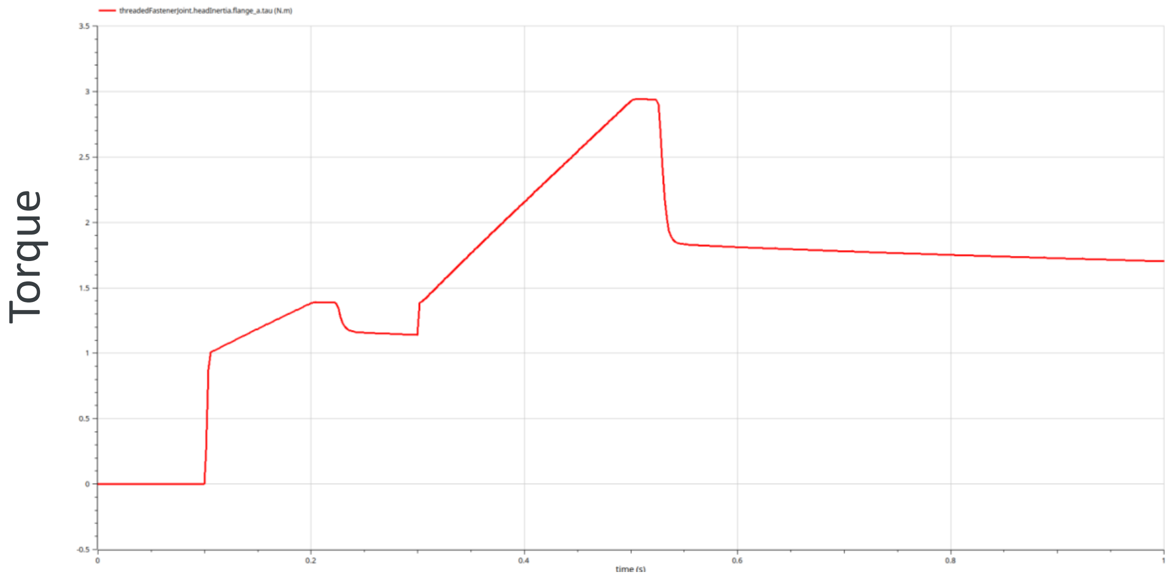
Simulation Performance – Main Challenges

Friction Model has high impact on simulation performance



- Issues
  - Singular matrix (cause friction and spring models)
  - Initialization problems
  - Failure to solve system of linear equations
- Errors on system level
  not when models are investigated separate

Problematic Torque behavior at 0 speed



Many zero crossings

Method of drive changes system behavior
Additional states need to be added

Debugging model very challenging

Insights from Model

- Most important model parameter
  - Translational stiffness of bolt
  - Translational stiffness of clamped parts
- In the current modeling approach for embedment
  - Low impact on tightening result ↔ In contrast to findings in literature
- Good friction models are essential
  - Focus on friction behavior at low speeds and 0-speed