Friction Mapping for Clamp Force Estimation

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Abstract

Friction variability drives torque $\rightarrow$ force scatter in threaded joints, limiting clamp-force accuracy. We map thread and under-head friction across **load** and **speed** to
(i) provide **priors/initial guesses** for clamp-force estimators
(ii) **quantify spread** as an uncertainty indicator.
The map shows that friction and its variability are not constant: certain load–speed regions are stable, others exhibit large spread.

Motivation & Objective

Clamp force is highly sensitive to friction in both threads and at the bearing surface; variability in the coefficient of friction (COF) is a primary source of torque$\rightarrow$force scatter (reports up to $\pm 40\%$ when inferring F from torque alone). Standards (ISO 16047; VDI 2230) specify how to determine friction at prescribed proof load and speed, but they do not provide load–speed–resolved priors or quantify spread for a specific joint.

Objective: Quantify how COF changes with load and speed for a specific **joint** (bolt–nut–washer + joint members), delivering an operating-point COF and its uncertainty to improve estimator convergence and enable optimization of tightening profiles.

Operating-point prior. At the current load F and speed v, we model COF as approximately Gaussian,

$$\mu(F, v) \sim \mathcal{N}\big(\mu_0(F, v),\ \sigma^2(F, v)\big),$$

where $\mu_0(F, v)$ is the map value (median) and $\sigma(F, v)$ as the standard deviation of the samples.

How we use it

- Use the friction map to set the estimator's starting value (median COF) and confidence (σ) at the current (F, v).
- Predict how COF changes with speed under load to plan/optimise tightening trajectories towards the target clamp force under quantified uncertainty.

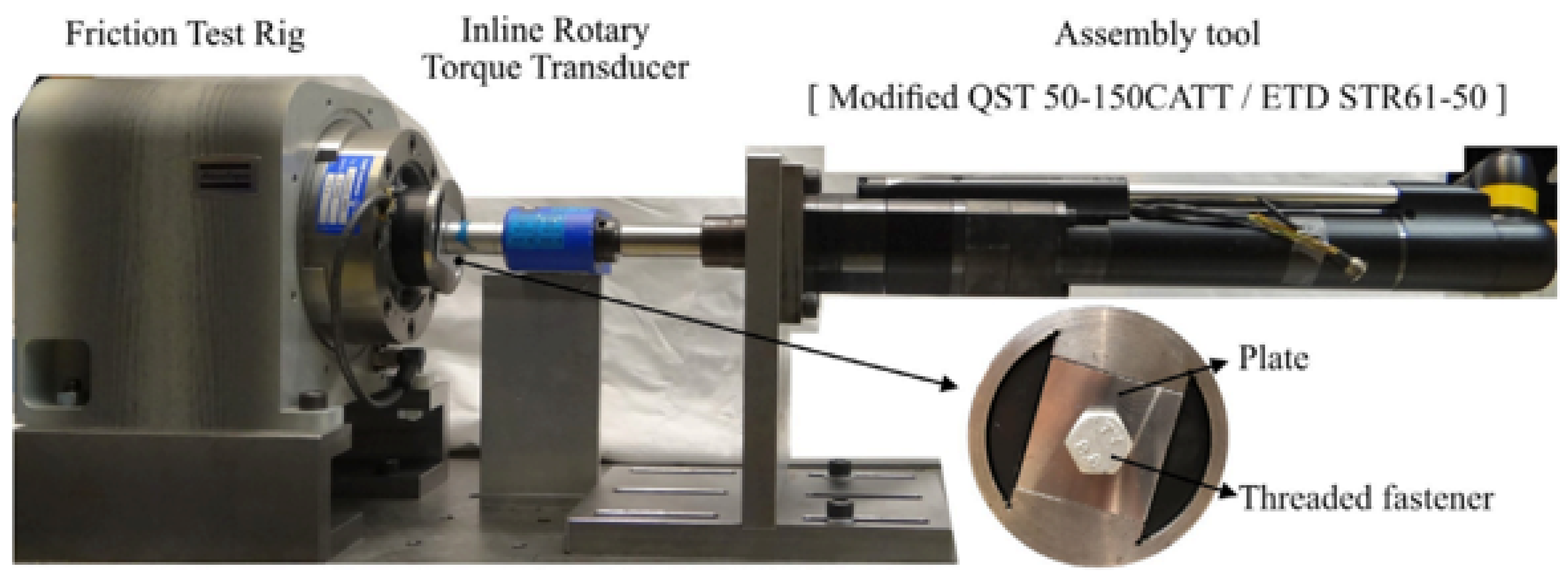
Methods

At discrete speed setpoints v_s, a fixed number of tightenings were recorded from near-zero load to F_{max} on a friction test rig (FTR) with an inline rotary torque transducer.
Signals: total torque $T(t)$; thread torque $T_{\text{th}}(t)$; angular position $\theta(t)$; clamp force $F(t)$.

Resampling, map construction & smoothing

We define a common load grid $\{F_k\}$. For each run and each F_k, we identify (or interpolate) the time where $F(t) = F_k$, read T and T_{th}, and compute $\mu_{\text{thread}}(F_k, v_s)$ and $\mu_{\text{bearing}}(F_k, v_s)$. Aggregating across runs at each (v_s, F_k), we report the *median* $\tilde{\mu}$ and the across-run *standard deviation* (SD), which form the 3-D friction map.

To reduce non-physical oscillations between grid points, we are testing light 2-D smoothers on (F, v_s) to suppress ripple while preserving trends; the final choice is pending. Uncertainty uses per-cell SD with minimal or no smoothing.



Friction test rig with inline rotary torque transducer and electric assembly tool.

From Kumar, Persson, Sherrington & Glavatskih (2022), Tribology International 170:107498.

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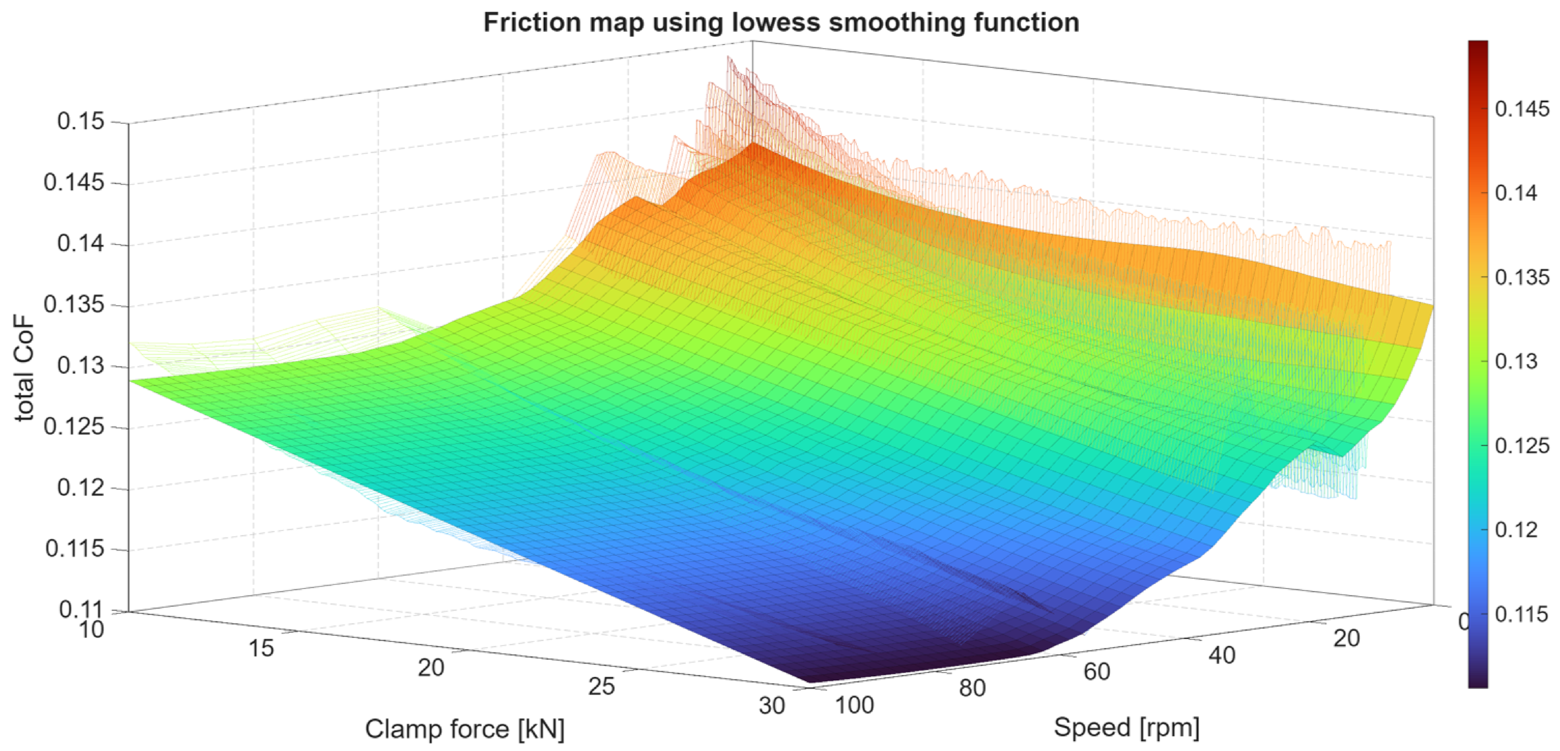
Results

We analyse only the steady regime of continuous tightening, windowed to $F \in [10, 30]$ kN; early seating and the stop event are excluded. We then solve the torque–tension balance to estimate thread and under-head COF and build load–speed maps from per-cell *medians* and *SDs* across runs.



- ✗ **Material dependence:** Stability and trend strength vary strongly with different materials; maps are joint-specific.
- ✗ **Speed effect:** COF is high at very low speed (stick–slip risk); above ~10 rpm COF decreases with speed.
- ✗ **Load effect:** COF decreases with clamp force across speed ranges.
- ✗ **Variability:** Within-cell scatter often exceeds differences between neighboring cells—hotspots.
- ✗ **Stick–slip zone:** Below ~10 rpm non-physical ripples appear with current sample size; denser sampling and careful feature extraction (peaks/valleys/mean) are needed.

Conclusions

- COF map gives operating-point value + uncertainty for the joint.
- Map-based init improves estimator convergence/confidence; useful for friction-model parametrisation.
- Robust maps need repeats per cell and clear stick–slip rules; ISO 16047/VDI 2230-aligned.

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