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ON-LINE TRACKING OF COGGING STIFFNESS USING THE MULTI-BIN SDFT

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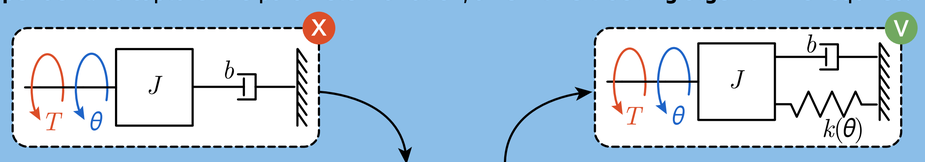
1 MOTIVATION

Cogging stiffness is often forgotten in the case of PMSM-driven mechanisms.

Model-based control design requires an accurate model, otherwise the performance is sub-optimal and speed ripples occur.
Due to changing load conditions (e.g. temperature), the cogging torque and accompanying cogging stiffness is **time-dependent**. To capture this parameter variation, an **on-line tracking algorithm** is required.

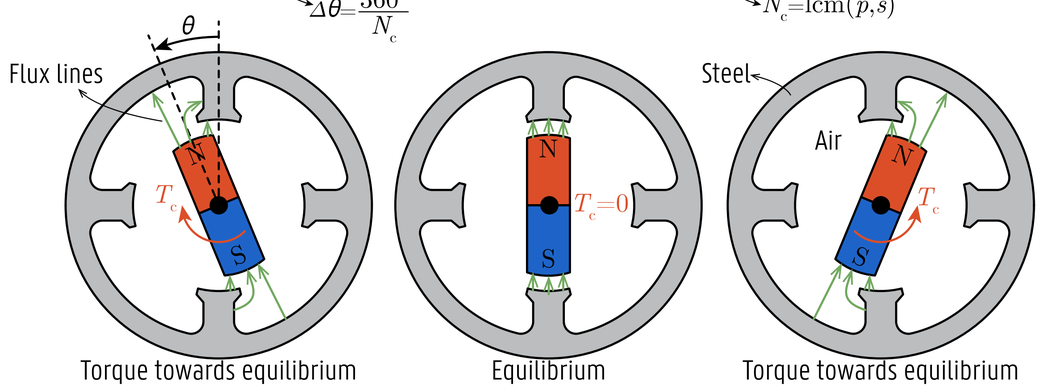


COGGING

Flux prefers path of least reluctance (or highest permeability μ) through the stator teeth: $\mu_{steel} >> \mu_{air}$.
↳ Attractive forces towards an equilibrium where the reluctance is minimum.
↳ Cogging torque T_c: • Position-dependent due to varying reluctance
• Periodic with to the number of equilibrium positions:

$$\Delta\theta = \frac{360°}{N_c} \qquad N_c = \mathrm{lcm}(p,s)$$

(p: number of poles, s: number of slots)



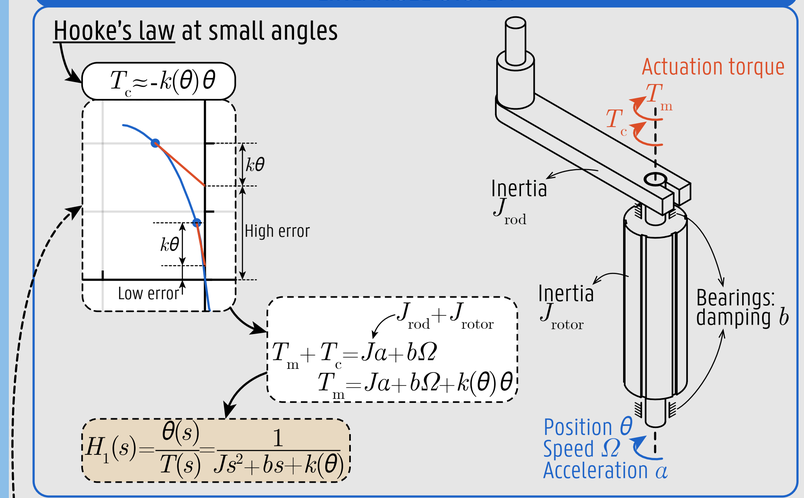
2 CASE

Gravity-free rod driven by a PMSM

LINEARISED SYSTEM

Hooke's law at small angles

$$T_c \approx -k(\theta)\,\theta$$



$$T_m + T_c = J_{rod}+J_{rotor}\,a + b\Omega$$
$$T_m = Ja + b\Omega + k(\theta)\,\theta$$

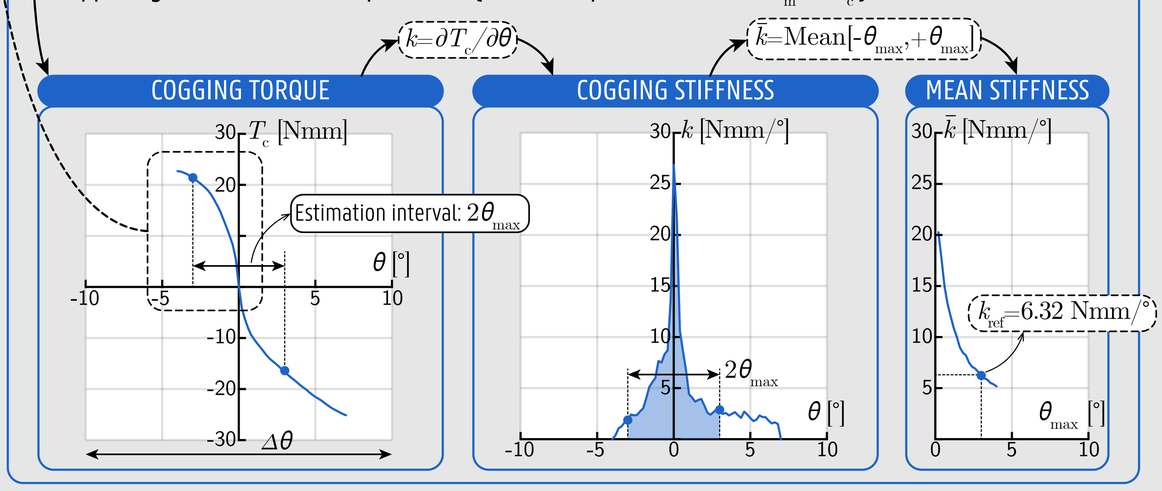
$$H_1(s) = \frac{\theta(s)}{T(s)} = \frac{1}{Js^2+bs+k(\theta)}$$

EXPERIMENTAL SETUP

STATIC CHARACTERIZATION FOR ACHIEVING A REFERENCE VALUE

• Starting from an equilibrium position (θ=0°), the actuation torque T_m is step-wise increased and mapped against the measured position θ (at static equilibrium where $T_m = -T_c$).

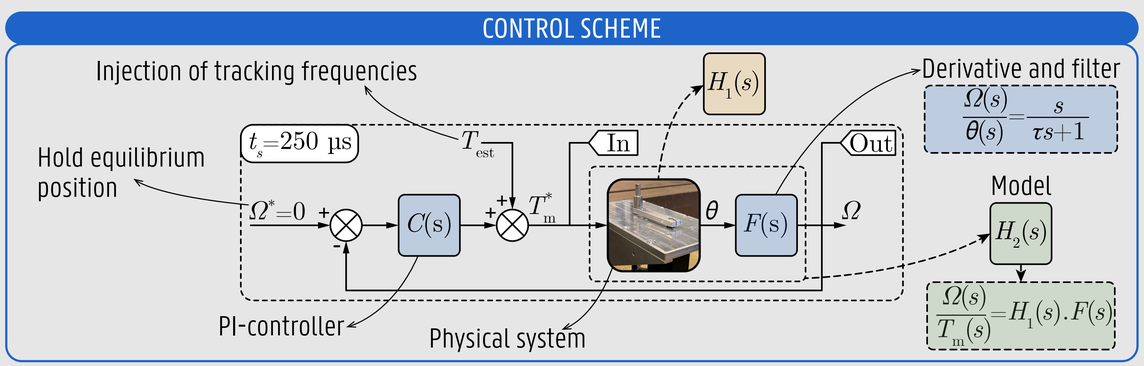
$\bar{k} = \partial T_c / \partial\theta$ → $\bar{k} = \mathrm{Mean}[-\theta_{max}, +\theta_{max}]$



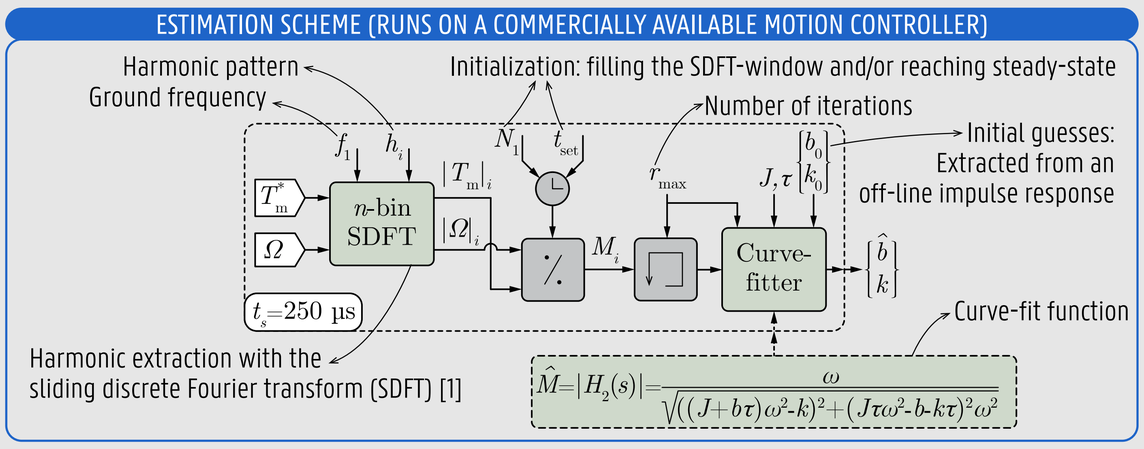
3 APPROACH

Whenever tracking is desired, the machine task is interrupted, the load moves to an equilibrium position and tracking frequencies are injected for subsequent parameter estimation.

CONTROL SCHEME



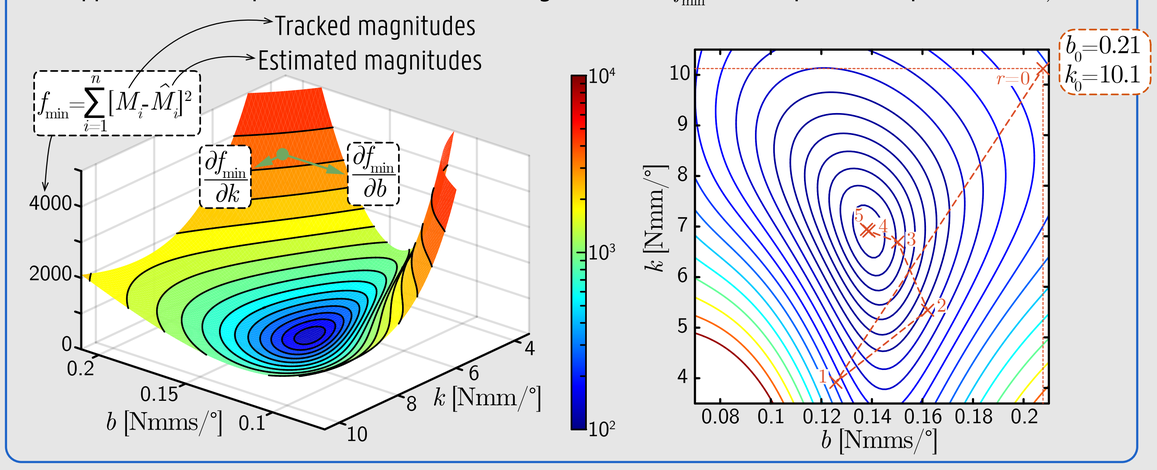
ESTIMATION SCHEME (RUNS ON A COMMERCIALLY AVAILABLE MOTION CONTROLLER)



$$\hat{M} = |H_2(s)| = \frac{\omega}{\sqrt{((J+b\tau)\omega^2-k)^2+(J\tau\omega^2-b-k\tau)^2\omega^2}}$$

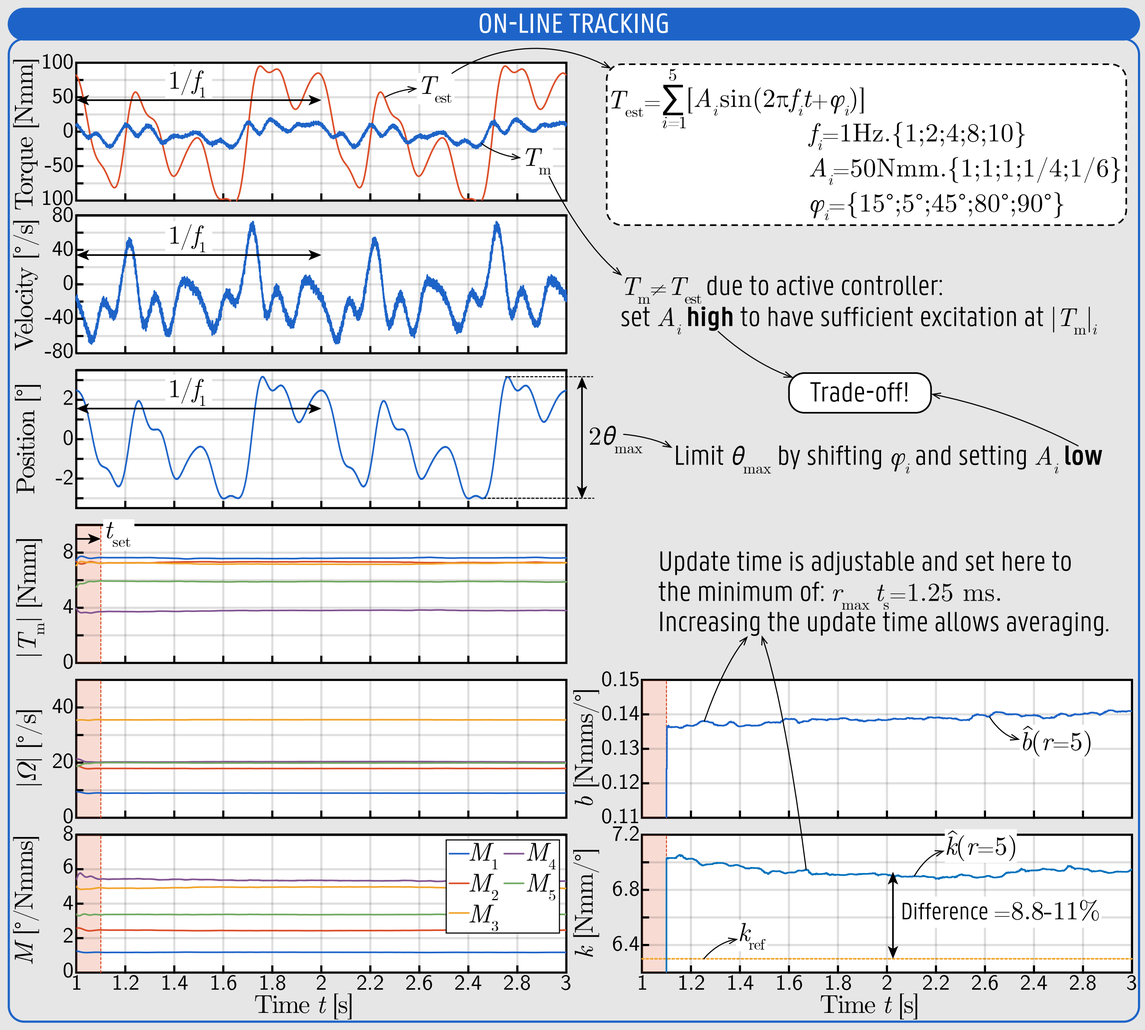
GAUS-NEWTON (GN) ALGORITHM FOR NON-LINEAR CURVE FITTING

Parameters k,b are iteratively updated assuming that the objective function f_{min} is approximately quadratic. This approximation requires the calculation of the **gradients** of f_{min} with respect to the parameters k,b.



4 VALIDATION

ON-LINE TRACKING



$$T_{est} = \sum_{i=1}^{5} [A_i \sin(2\pi f_i t + \varphi_i)]$$
f_i=1Hz.{1;2;4;8;10}
A_i=50Nmm.{1;1;1;1/4;1/6}
φ_i={15°;5°;45°;80°;90°}

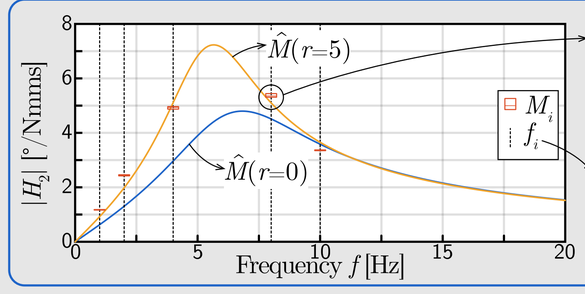
$T_m \neq T_{est}$ due to active controller:
set A_i **high** to have sufficient excitation at $|T_m|_i$

Trade-off!

$2\theta_{max}$ → Limit θ_{max} by shifting φ_i and setting A_i **low**

Update time is adjustable and set here to the minimum of: r_{max} t_s=1.25 ms.
Increasing the update time allows averaging.

CONVERGENCE FROM INITIAL TO FINAL CURVE-FIT



Optionally, a moving averager can be included to avoid outliers. The averaged magnitudes are then used for curve-fitting instead of the instant ones.

Avoid leakage by choosing f_i with an integer period N.

$$N = \frac{1}{f_i t_s}$$

5 CONCLUSION

- SDFT for harmonic extraction combined with GN for curve-fitting is suited for on-line tracking of the cogging stiffness and accompanying damping.
  - Initial guesses are required, but these can be very rough.
- The accuracy is acceptable and tuning rules for increasing the accuracy are presented in the paper.
- Algorithms are based on available control data, requiring no additional hardware.
- Drawback: The machine task must be interrupted when tracking is desired.

REFERENCES

[1] E. Jacobsen and R. Lyons, The sliding DFT, IEEE Signal Processing Magazine, 2003

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FLANDERS MAKE MANUFACTURING INNOVATION NETWORK