Electrical characterization of MEMS gyroscopes with fast frequency sweeps

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High-Q, low-f_0 resonator parameter estimation

- Obtaining the steady-state response (e.g. Nyquist diagram) from a high-Q, low-f_0 resonator requires extremely long acquisitions
  - unpractical
  - cost of adequate environmental control
- Ringdown response (linear/nonlinear) is the fastest estimation approach
  - some parameters are not identified (e.g. transduction efficiency)
  - relies on analytical expression of free resonator response
  - embedded/integrated implementation is difficult (in nonlinear case)

Proposed approach (1-DOF resonator with polynomial nonlinearity)

- Excite resonator with

$$v_{exc}(t) = V_{exc}(t) \sin \int \omega(t) dt$$

with slowly-varying $V_{exc}(t)$ and $\omega(t)$

- Measure (complex) resonator output $X(t)$
- Estimate $\dot{X}(t)$, e.g.

$$\hat{\dot{X}}(t_k) = \frac{X(t_{k+1}) - X(t_{k-1})}{t_{k+1} - t_{k-1}}$$

- Determine parameters $\boldsymbol{\theta} = (g, C_0, \dots, C_n)$ in resonator model

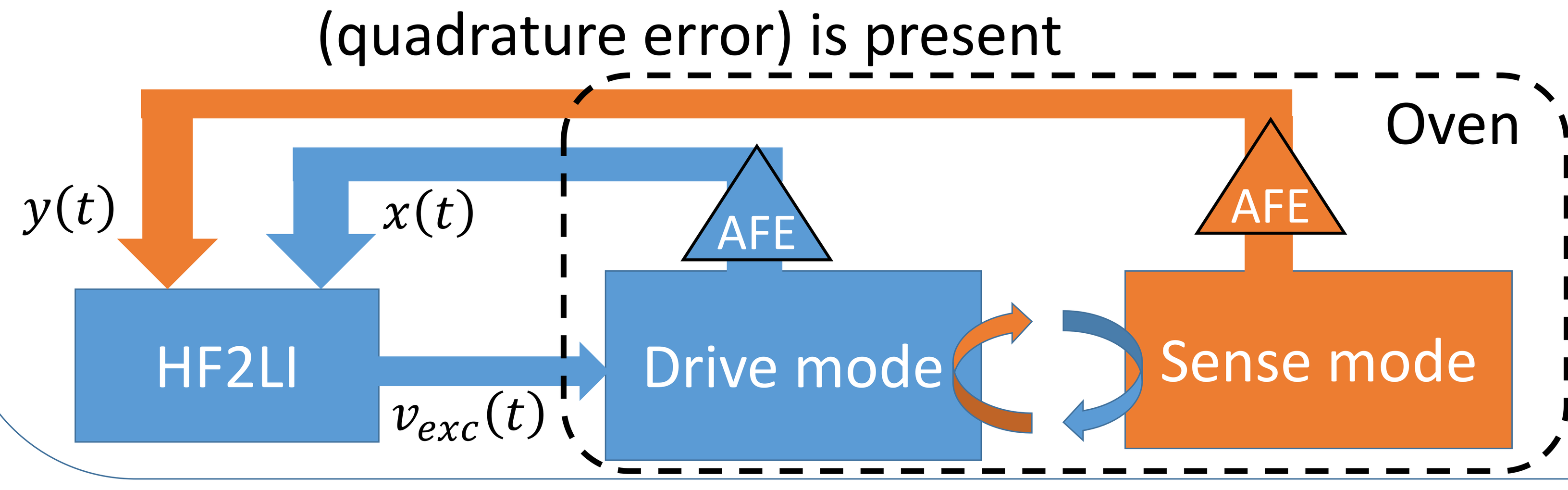
$$F\left(t, \dot{X}(t), X(t), \boldsymbol{\theta}\right) \equiv 2j\omega(t)\dot{X} + \left(C_0 + \sum_{i=1}^{n} C_i |X|^{2i} - \omega(t)^2\right) X - gV_{exc}(t) = 0$$

$$\hat{\boldsymbol{\theta}} = \arg\min \sum_{k=2}^{N-1} \left| F\left(t_k, \hat{\dot{X}}(t_k), X(t_k), \boldsymbol{\theta}\right) \right|^2$$

- Linear LS solution for all $V_{exc}(t)$ and $\omega(t)$, even in nonlinear resonator case!
- Extension to more DOFs is straightforward

Experimental setup and method

- ONERA's VIG gyroscope
  - 2-DOF resonator
  - Drive mode characteristics : $f_0 \approx 5888.2$ Hz, $Q \approx 3.6 \times 10^5$, $\Delta f = f_0/2Q \approx 8.2$ mHz, $\tau \approx 19.5$ s
  - Sense-drive frequency mismatch ≈ 111 Hz
  - Near to no feedthrough, but mechanical coupling (quadrature error) is present

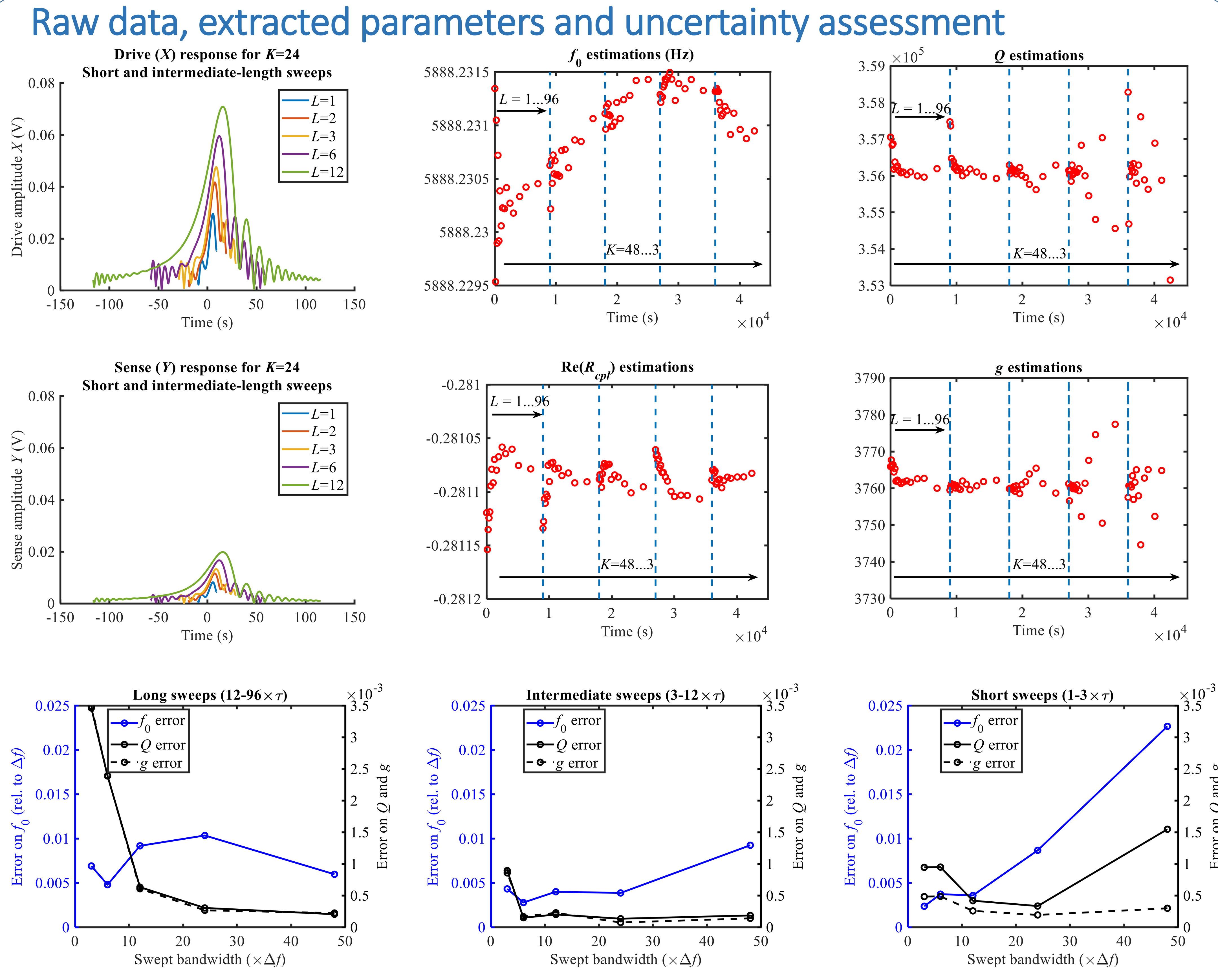


- Resonator is placed inside ± 0.1 °C regulated oven
- Drive mode is harmonically excited with lock-in amplifier, both drive (X) and sense (Y) modes are detected
  - « Fast » linear frequency sweeps around f_0
  - Sweep bandwidth $K \times \Delta f$, $K = 48, 24, 12, 6, 3$
  - Sweep duration $L \times \tau$, $L = 1, 2, 3, 6, 12, 24, 48, 96$
  - 2 sweeps performed for each $\{K, L\}$

➔estimate drive mode parameters with proposed approach
➔estimate coupling coefficient R_{cpl} from

$$(\hat{R}_{cpl}, \hat{R}_{FT}) = \arg\min \sum_{k=1}^{N} \left| Y(t_k) - R_{cpl} X(t_k) - R_{FT} V_{exc} \right|^2$$

Raw data, extracted parameters and uncertainty assessment



- Visible drift in f_0 over time (follows temperature regulation)
- Overall excellent estimation of resonator parameters (better than 0.1% for Q and g, than 1% for f_0 w.r.t. Δf)
  - For small bandwidths / long durations, Q and g estimations have « large » variance, with strong correlation
  - For large bandwidths / small durations, errors result from finite difference approximation and from reduced SNR
- 1st coefficient of nonlinearity (C_1) is close to zero

Conclusion

Experimental validation of a transient parameter estimation approach
- nearly as fast as ringdown
- model- and response-agnostic
- yielding all resonator parameters
- small computational and integration complexity
- moderate hardware requirements