ESTIMATION OF TEMPERATURE FLUCTUATIONS HARSHNESS REGARDING STABILITY OF STRUCTURES IN THE NANOMETER RANGE

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OUTLINE

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Mechanical Engineering at SOLEIL
We are here!
NANOMETER STABILITY: SOME CLARIFICATIONS

- Ground motion at SOLEIL = *dozens* of nm (RMS !)
- Absolute stability is **not** required, but
- Mis-alignment **is** critical
- Alignment preserved if:
  - Ground motion is uniform
  - Supports deflections are small
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Compact & stiff support structures => dynamic relative motion << 10nm
BUT for long (1h+) observation time, thermally induced error can be WAY higher
DISTURBANCE SOURCES
CLASSIFICATION

**Thermal mechanical effects**
- Internal:
  - beam heat load
  - motors heat load
  - coolant flow temp
- External:
  - hutch ambient air

**Dynamic effects**
- Internal:
  - motors
  - pressurized air
  - coolant flow
- External:
  - ground transmitted
  - acoustically transmitted
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  - ground transmitted
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Design: no disturbance from heat sink
Reality: no perfect heat sink, non-zero perturbations
THERMAL STABILITY IN NUMBERS (1/2)

Common practice:
use peak-to-peak values

Water buffer - blue=bottom green=top

0.1°C
1 week
THERMAL STABILITY IN NUMBERS

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THERMAL STABILITY IN NUMBERS
(2/2)

AMPLITUDE PP
(millidegree C)
- 9 days => 100 mdeg
- 8 hours => 12 mdeg
- 4 hours => 10 mdeg
- 2 hours => 10 mdeg
- 1 hour => 10 mdeg

SIGNAL TYPE
- Steady trend
- No trend (random)
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A1: our reference fluctuations are 50%
of total error budget, it’s a mess!
## THERMAL STABILITY IN NUMBERS (2/2)

### AMPLITUDE PP

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### SIGNAL TYPE

- Steady trend
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### Q: Where do we stand actually?

- A1: our reference fluctuations are 50% of total error budget, it’s a mess!
- A2: random temperature fluctuations have no effect whatsoever so stop worrying: We’re good!
THERMAL-MECHANICAL SUSCEPTIBILITY : MECHANISMS

Intuition: « fast » temperature oscillation do not propagate very far along support structure

\[ \alpha = \text{thermal diffusivity} \ [\text{Length}^2/\text{Time}] \]

\[ \alpha \left[ \frac{\text{mm}^2}{s} \right] \sim 4 (\text{Invar}) \ldots 100 (\text{Al}) \]
Intuition: « fast » temperature oscillation do not propagate very far along support structure

Analytical solution: exponential decay

\[ T(x, t) - T_i = \exp\left(-\frac{x}{\sqrt{\frac{\omega}{2\alpha}}}\right)\sin(\omega t - x \sqrt{\frac{\omega}{2\alpha}}) \]

\[ T(0,t) = T_i + \Delta T \sin(\omega t) \]

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\[ T(x, t) - T_i \]

\[ \Delta T \]

\[ = \exp(-\frac{x}{\sqrt{\omega}})\sin(\omega t - x \sqrt{\frac{\omega}{2\alpha}}) \]

\[ T_{\text{corner}}[s] \sim 6.3 \frac{L[\text{mm}]}{2}\alpha \]

\[ \delta_{\text{effective}} = \sqrt{\frac{\alpha \cdot T}{2\pi}} \]
THERMAL-MECHANICAL SUSCEPTIBILITY: PRACTICAL ESTIMATION RULES (1/2)

- Random fluctuations ⇔ broadband spectral content
- Hence, harmonic formula not usable « as is »
- Need to SEPARATELY estimate severity of ALL frequency components
- Combine individual components into OVERALL harshness indicator

EXAMPLE: SPECTRAL ANALYSIS OF 8 HOURS TEMPERATURE DRIFT

Need for a simple, automated procedure
Estimate thermal mechanical « frequency response function »
\[ H_{UTc}(f) \]
(structural response / unit temperature fluctuation)

Break down coolant temperature fluctuations into individual frequency components, i.e.
« PSD analysis » \( \hat{\Phi}_{TcTc}(f) \)
(degree\(^2\)/unit frequency bandwith)

Combine to obtain into actual response level
\[ U_{rms} = \left( \int_0^{f_{max}} |H_{UTc}(f)|^2 \cdot \hat{\Phi}_{TcTc}(f) df \right)^{1/2} \]
Application case: Aluminum (CTE=23ppm/K, diffusivity=100mm²/s)

\[ \Delta U_v \sim CTE \times \text{Height} \times \Delta T_{\text{coolant}} \]
Corner period as predicted by hand calc’s matches FEM analysis results 😊 … except for pointing errors ☹️ where AMPLIFICATION occurs
THERMAL-MECHANICAL SUSCEPTIBILITY : VALIDATION

- Benchmark vs direct calculations

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<th>FRF</th>
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Near perfect agreement
PRACTICAL USAGE: RELIABILITY ANALYSIS

RANDOM FLUCTUATIONS
- Deterministic figures of merit (« Peak to peak ») amplitude meaningless
- Need to define amplitude into a probabilistic sense
- Common practice at SOLEIL: Probability Of Exceedance For Given Allowable Drift (AD)

Need to know:
- RMS amplitude $U_{RMS}$
- Observation time $T_s$

\[ P(|Drift(T_s)| > AD) = 1 - \text{erf} \left( \frac{AD}{\sqrt{2}U_{RMS}(T_s)} \right) \]
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NB: Other statistics (mean time between exceedances, etc..) could be estimated
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BUT, for stabilized environments, fluctuations are mostly random
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• Frequency domain approach allows for quicker results and improved understanding
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Severity of random temperature fluctuations cannot readily be assessed at face value.

Using the proposed procedure, a minimum analytical effort can provide reliable quantitative estimates of setup reliability
THANK YOU FOR YOUR ATTENTION

QUESTION & COMMENTS ARE WELCOME