Closed-loop simulations of the thermal experiments in LISA Pathfinder

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9th LISA Symposium
APC Paris, 23rd May 2012
Organisation of the talk

1. Thermal Diagnostic Experiments
2. Models for the experiments
3. Injection to the LTP model
4. Simulations
   - Electrode Housing (EH) heating case
   - Optical Window (OW) heating case
   - Temperature noise injection
5. Summary
The performance LISA Pathfinder's (LPF) Interferometer (IFO) is sensitive to thermal fluctuations in the environment.

Motivation:

A series of Thermal Diagnostic experiments are planned to be done in-flight in order to study the system response in front of different thermal fluctuations.
LTP Thermal Diagnostics experiments

Different experiments for each thermal-sensitive elements in the LTP

- **Optical Window (OW)**
  - Thermal experiments
  - Optical path length modification of the Optical Window glass.

- **Struts (STR)**
  - Thermal experiments
  - Thermo-elastic distortions of the Optical Bench

- **Electrode Housing (EH)**
  - Thermal experiments
  - Forces and Torques on the Test Masses. (through different thermal effects)

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LTP Thermal Diagnostics experiments

14 Heaters
24 Temperature Sensors

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Models for the experiments

How are we modelling them?

**OW Thermal experiments**
- Model based on data from OW campaign in AEI Hanover (2007)

**STR Thermal experiments**
- Model will be based on data from Thermo-Optical Qualification Model tests

**EH Thermal experiments**
- Both theoretical expressions and data from Torsion Pendulum from UTN should be used for modelling.
Modelling: EH experiments

*Temperatures gradients cause forces through different thermal effects*

- **Radiometer effect.** In rarefied atmospheres, where the particles' mean free path is much longer than the system distance
  
  \[
  \Delta F_{ij}^{RM} = w_{rm} \frac{1}{4} \frac{A_j p}{T} \Delta T_{ij}
  \]

- **Differential radiation pressure.** Infrared radiation
  
  \[
  \Delta F_{ij}^{RP} = w_{rp} \frac{8}{3} \frac{\epsilon_{ij} A_j \sigma T^3}{c} \Delta T_{ij}
  \]

- **Asymmetric outgassing.** Particles flow emitted by surfaces exposed to low pressure
  
  \[
  \Delta F_{ij}^{OG} = w_{og} \frac{-\Theta_{OG}}{T_0} \frac{Q_0 \Theta_{OG} e}{C_{\text{eff}} T_0^2} \Delta T_{ij}
  \]
Modelling: EH experiments

So, first of all, temperatures...

- An accurate **thermal model** required, coded in ESATAN Software.

- **Transfer function samples** from the temperature response at a node due to heat application to other nodes.
  - **Inputs**: heater location nodes.
  - **Outputs**: TS location nodes and nodes inside the Electrode Housing.
Modelling: EH experiments

- EH inner faces and TM surfaces discretised into isothermal facets

- Force contributions between each pair of EH-TM surfaces are computed individually
  - Multi-reflections treatment of such contributions
    - Assumption: *diffuse reflection*
    - Each force contributions expressed as *vectors*.

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Simulation: Injection to model

- Modelling of both EH and OW experiments by means of **State-Space Models (SSM)** blocks in the **LTPDA Toolbox** environment.

- Simulations by two steps:
  1. Computation of time series of temperatures, forces, torques, phase shifts caused by the activation of any combination of heaters.
  2. Injection of the outputs to the global SSM object of the LTP.
Example 1: EH experiment

Typical input:
- Alternative pulses on H1 and H2
- Power: 10mW
- Frequency: 0.5mHz (pulses of 1000s)

Nominal values:
\[ T_{\text{system}} = 293\text{K} \]
\[ P_{\text{static}} = 10^{-5}\text{ Pa} \]
Example 1: EH experiment

X axis:

Temperature increments of EH1 X-axis facets

Temperature difference between +X and -X sides

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Example 1: EH experiment

Y axis:

Z axis:
Example 1: EH experiment

Force on X axis:

- Forces of $\sim \text{pN}$ on the X axis!

Torque on X axis (theta):

- Torques around $\sim 10^{-17}$ Nm on the X axis, negligible.

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Example 1: EH experiment

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Example 2: OW experiment

Typical input:
- 5 pulses simultaneously on H5 and H6
- Power: 1W
- Pulse frequency: 1mHz
- Pulse length: 50s (duty cycle: 5%)
Example 2: OW experiment

**OW1 - Temperature Sensor readouts**

- TS9
- TS11

**IFO Phase shifts due OW1 heating**

- OW1 contribution
- OW2 contribution

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Example 2: OW experiment

![Graphs showing OW experiment results for IFO x1 and IFO x12 over time.](image)
Example 3: Injecting noise

Other experiment: injecting temperature white noise at inputs. \((10^{-4} \text{ K/sqrt(Hz)})\)
Summary & Future work

- Models for the simulation of the EH and OW experiments have been presented.
- ESATAN data from thermal model adapted to the LTPDA frame.
- Closed-loop simulations of the EH and OW Thermal Experiments ready.
- Different parameters need still to be adjusted.
- Analysis and model extraction from the TOQM data, required to model the thermal STR experiments.
Thanks for your attention!
Extra slides
Example 1: EH experiment

Y axis: (eta)

Z axis: (phi)
EH experiment: Z axis displacement
EH experiment: eta rotation (Y axis)