Outline

- Modified Fluctuation Dissipation Theorems (MFDTs) for Non Equilibrium Steady State (NESS)

- Fluctuation Theorem for systems driven out of equilibrium by a random force.
Modified Fluctuation Dissipation Theorems (MFDT)

Motivation: Test in an experiment the new FDT for an out of equilibrium system

Outline:

- MFDT Three formulations: 1) Lagrangian FDT 2) Frenesy FDT 3) Generalized FDT
- Langevin dynamics
- Experimental realisation
- Results
Fluctuation Dissipation Theorem (FDT)

In equilibrium FDT takes the form:

$$-R(t - s) = \frac{1}{k_B T} \partial_s C(t - s)$$

Observable $O_t(\theta)$ of the dynamical process $\theta$ and its conjugated variable $h$

Correlation function
$$C(t - s) = \langle O_t O_s \rangle$$

Response function to a delta perturbation of $h$
$$R(t - s) = \langle \frac{\delta O_s}{h} \rangle$$
Langevin Dynamics

\[ \nu \dot{x} = -\partial_x U(x) + G + \eta \]

with \( < \eta(t)\eta(t') > = 2k_B T \nu \delta(t - t') \)

\( G \) non conservative force
Langevin Dynamics

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\( G \) non conservative force

with \( G = 0 \) equilibrium FDT holds
Langevin Dynamics

\[ \nu \dot{x} = -\partial_x U(x) + G + \eta \]

with \( \langle \eta(t)\eta(t') \rangle = 2k_B T \nu \delta(t - t') \)

\( G \) non conservative force

with \( G = 0 \) equilibrium FDT holds

with \( G \neq 0 \) the system is driven into a non equilibrium steady state \textbf{(NESS)}

where equilibrium FDT does not hold
Modified Fluctuation Dissipation Theorem (MFDT) for NESS


\[-R^L(t,s) = \frac{1}{k_B T} \partial_s C^L(t,s)\]

$R^L$ and $C^L$ are measured in the Lagrangian frame moving at mean local velocity $v_0(\theta)$

The new observable $O(t, \theta)$ evolves according to:

$$\partial_t O(t, \theta) + v_0(\theta) \cdot \nabla O(t, \theta) = 0$$
The MFDT in the lagrangian frame,

\[ R^L(t, s) = -\frac{1}{k_BT} \partial_s C^L(t, s), \]

can also be written in the laboratory frame, replacing \( \partial_s \) in FDT with the convective derivative \( \partial_s + \nabla \cdot v_0(\theta) \)

MFDT becomes:

\[ R(t - s) \ k_BT = \partial_s C(t - s) - b(t - s) \]

where

\[ b(t - s) = \langle O(t, \theta)v_0(\theta(s))\partial_\theta O(s, \theta) \rangle \]
The MFDT in the lagrangian frame,

\[ R^L(t, s) = -\frac{1}{k_B T} \partial_s C^L(t, s), \]

can also be written in the laboratory frame, replacing \( \partial_s \) in FDT with the convective derivative \( \partial_s + \nabla \cdot v_0(\theta) \)

MFDT becomes:

This is the equality that we want to test

\[ R(t - s) \ k_B T = \partial_s C(t - s) - b(t - s) \]

where

\[ b(t - s) = \langle O(t, \theta)v_0(\theta(s))\partial_\theta O(s, \theta) \rangle \]
MFDT for NESS

In experiments is much safe to use the integral form:

\[ \chi(t - s) k_B T = [C(0) - C(t - s)] - B(t - s) \]

\( \chi(t - s) \) is the integrated response and

\[ B(t - s) = \int_0^s b(t - t') dt' \]

We test this equality on the Langevin dynamics

\[ \gamma \dot{x} = -\partial_x U(x) + G + \eta \]

with \( < \eta(t) \eta(t') > = 2k_B T \nu \delta(t - t') \)

\( G = \text{constant} \neq 0 \) non conservative force

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Experiment with optical trap

Let us consider first the case with $U = 0$

$$\nu \dot{x} = G + \eta$$

$G = constant \neq 0$ non conservative force

We use a Brownian particle confined in an optical trap

The experimental set up
Optical traps

Camera rapide

AOD 75 MHz

Diode Laser
\( \lambda = 980 \text{ nm} \)

Condenser
20 \( \mu \text{m} \)

Objective 63x N.A. 1.3

Nano-Max Pizo-stage

He-Ne
\( \lambda = 633 \text{ nm} \)

LS white light source
DM dichroic mirror
M mirror
IRF infrared filter
IF interference filter
P polarizer
A analyzer
QD quadrant photo diode

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Optical traps

\[ U = \frac{K}{2} (x^2 + y^2) \]
Examples of traps

The Kramer rate is

$$r_k = \tau_0^{-1} \exp\left(-\frac{\delta U}{k_B T}\right)$$
Experiment with optical trap

Let us consider first the case with $U = 0$

$$\nu \dot{x} = G + \eta$$

$G = \text{constant} \neq 0$ non conservative force

The motion of the particle is confined on a circle of radius $a$

$$x = a \theta \quad \text{with} \quad 0 \leq \theta \leq 2\pi$$

This is achieved by a circular sweeping of the laser beam

How $G$ is obtained?
Particle motion with $U=0$

\[

\nu \alpha \dot{\theta} = G + \eta \\
\nu = 6\pi \ r \ \mu \\
\nu_0 = \langle \dot{\theta} \rangle = \frac{G}{\nu}
\]
Particle motion with $U=0$

$$\nu \ a \ \dot{\theta} = G + \eta$$

$$\nu = 6\pi \ r \ \mu$$

$$\nu_0 = \langle \dot{\theta} \rangle = \frac{G}{\nu}$$
Particle motion with $U=0$

\[ \nu \ a \ \dot{\theta} = G + \eta \]

\[ \nu = 6\pi \ r \ \mu \]

\[ \nu_0 = \langle \dot{\theta} \rangle = G / \nu \]

\[ a = 4.5 \mu m, \ r = 1 \mu m, \ \mu = 10^{-3} Pa \]

We obtain $G = 6.60 \times 10^{-14} N$ from the measure of $\nu_0 = 0.85 rad/s$
Particle motion with potential

Periodic potential \( U = A \sin(\theta + \varphi) \)

\[
\nu a^2 \dot{\theta} = -\partial_\theta U(\theta) + F + \eta a
\]

\( F = G a \) = constant non conservative torque

The potential \( U \) is produced by a modulation (5%) of the laser intensity
PDF of the particle position

\[ j = \text{probability current} = \frac{\langle \dot{\theta} \rangle_0}{(2\pi)} \]

\[ \rho(\theta) = \text{probability density} \]

\[ v_0(\theta) = \frac{j}{\rho(\theta)} \]
Local mean velocity

\[ j = \text{probability current} = \frac{< \dot{\theta} >_0}{(2\pi)} \]
\[ \rho(\theta) = \text{probability density} \]
\[ v_0(\theta) = \frac{j}{\rho(\theta)} \]
The observable \( O(\theta) \)

To measure the response, the perturbation is applied in the following way:

\[
U(\theta) \rightarrow U(\theta) + \delta A \sin(\theta + \varphi)
\]

Thus the observable is \( O(\theta(t)) = \sin(\theta(t) + \varphi) \)

![Graph](image_url)
Time evolution of $O(t)$
The observable is: \[ O(\theta(t)) = \sin(\theta(t) + \varphi) \]

\[ \chi(t) \ k_B T = [C(0) - C(t)] - B(t) \]

with

\[ B(t) = \int_0^t <O(\theta(t'))v_0(\theta(t'))\partial_\theta O(\theta(0))> \ dt' \]

\[ C(t) = <O(\theta(t))O(\theta(0))> \]

The integrated response \( \chi(t) \)

to a Heaviside perturbation of \( A \), switched on at \( t = 0 \), is:

\[ \chi(t) = \frac{<O(\theta(t))\delta_A - O(\theta(t+t*))_0>}{\delta A} \]

such that \( O(\theta(0))\delta_A = O(\theta(t*))_0 \)
Correlation function and $B(t)$
The integrated response
to a Heaviside perturbation of $A$, switched on at $t = 0$, is:

$$\chi(t) = \frac{<O(\theta(t))\delta_A - O(\theta(t+t^*))_0>}{\delta A}, \text{ with } O(\theta(0))\delta_A = O(\theta(t^*))_0$$

- Select 200 unperturbed trajectories such that at time $t^*$
  $$O(\theta(0))\delta_A = O(\theta(t^*))_0$$

- Compute the mean of
  $$O(\theta(t))\delta_A - O(\theta(t+t^*))_0$$
on the 200 trajectories

- Repeat the procedure on several perturbations and make the average

Perturbed trajectory
The integrated response to a Heaviside perturbation of $A$, switched on at $t = 0$, is:

$$\chi(t) = \frac{< O(\theta(t))_A - O(\theta(t + t^*))_0 >}{\delta A}, \text{ with } O(\theta(0))_A = O(\theta(t^*))_0$$
MFDT

\[ \chi(t) k_B T = [C(0) - C(t)] - B(t) \]

![Graph showing](image)
\[ \chi(t) \ k_B T = [C(0) - C(t)] - B(t) \]
Conclusions on MFDT

based on a Lagrangian formulation

• We have shown that MFDT holds for a bead moving in a toroidal optical trap and submitted to a non conservative force and to a periodic potential.

• The results can be interpreted as an equilibrium like FDT in the Lagrangian frame moving at the velocity determined by the probability current.

• The main drawback of the method is the knowledge of the probability current which is not always obvious to measure.
MFDT based on frenesy


\[ U(q) \rightarrow U(q) - h_s V(q) \]

\[ \chi_{OV}(t) = \int_0^t R_{OV}(t, s) \, ds = \frac{\langle O(q_t) \rangle_h - \langle O(q_t) \rangle_0}{h}, \]

\[ \chi_{QV}(t) = \frac{\beta}{2} [C_{OV}(0) - C_{OV}(t) + K(t)], \]

\[ C_{OV}(t) = \langle V(q_0) O(q_t) \rangle_0, \]

\[ K(t) = -\int_0^t \langle LV(q_s) O(q_t) \rangle_0 \, ds, \]

The frenesy \( \beta LV(q) \) can be regarded as a generalized escape rate of a trajectory from a given phase-space point \( q \) \((\text{Baiesi et al})\).
MFDT based on frenesy

In our experiment

\[ \nu a^2 \dot{\theta} = -A \frac{\partial O(\theta)}{\partial \theta} + F + \eta a \]

\[ U(\theta) = A O(\theta) \text{ with } O(\theta) \simeq \sin(\theta + \varphi) \]

and \[ V(\theta) = U(\theta) \]

\[ U(\theta) \rightarrow U(\theta) - \frac{\delta A}{A} U(\theta) \]

\[ \chi_{OV}(t) = \frac{A(\langle O(\theta(t)) \rangle_h - \langle O(\theta(t+t^*)) \rangle_0)}{\delta A} = A \chi(t) \]

with \[ O(\theta(0))_{\delta A} = O(\theta(t^*))_0 \]
MFDT based on frenesy

\[ \chi_{QV}(t) = \frac{\beta}{2} [C_{OV}(0) - C_{OV}(t) + K(t)], \]

\[ K(t) = - \int_0^t \langle LV(q_s)O(q_t)\rangle_0 \, ds, \]

For the Langevin dynamics of \( \theta \) the analytical expression of the generator \( L \) is

\[ L = \frac{1}{\nu a^2} \left[ (F - AO'(\theta)) \partial_\theta + k_BT \partial_\theta^2 \right]. \]

Hence in this case

\[ k_BT \chi(t) = \frac{C(0) - C(t) + \tilde{K}(t)}{2}, \]

where the entropic and frenetic terms are

\[ A \, C(t) = A \langle O(\theta_0)O(\theta_t)\rangle_0 = C_{OV}(t) \]

\[ K(t) = A\tilde{K}(t) = - \frac{A}{\nu a^2} \int_0^t ds \langle [k_BT \, O''(\theta_s) + (F - A \, O'(\theta_s)) \, O'(\theta_s)]O(\theta_t)\rangle_0, \]
Results on the FDT based on frenesy

- The method is sensitive to the values of the experimental derivative of the potential
- Two drawbacks:
  a) the knowledge of the generator of the dynamics;
  b) The Markofian nature of the system
Generalized FDT

The starting point is the Hatano-Sasa relation for Markofian process

\[ \rho_{ss}(c, \lambda^{ss}) = \exp[-\phi(c, \lambda^{ss})]. \]

\[ \phi(c; \lambda) = -\log[\rho_{ss}(c; \lambda)] \]

Probability density for a NESS
Pseudo-potential

\[ \langle \exp\left\{ - \int_{t_i}^{t_f} dt \dot{\lambda}_\alpha(t) \frac{\partial \phi(c(t); \lambda(t))}{\partial \lambda_\alpha} \right\} \rangle = 1, \]

The average is taken over a large number of realizations of a given dynamical process defined by the variation of \( \lambda(t) \)

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**Hatano-Sasa**

The average is taken over a large number of realizations of a given dynamical process defined by the variation of \( \lambda(t) \)
Generalized FDT

\[ \langle \exp \left\{ - \int_{t_i}^{t_f} dt \dot{\lambda}_\alpha(t) \frac{\partial \phi(c(t); \lambda(t))}{\partial \lambda_\alpha} \right\} \rangle = 1 , \]

Consider small variations of the control parameters around a steady-state value \( \lambda^{ss} \).

\[ \delta \lambda(t) = \lambda(t) - \lambda^{ss} \]

with \( \delta \lambda(t_i) = 0 \)

Expanding to second order in the integrand and taking into account the normalisation conditions one obtains:

Generalized FDT

\[ \left< \frac{\partial \phi(c(t); \lambda^{ss})}{\partial \lambda_{\alpha}} \right> = \int_{t_i}^{t} R_{\alpha\gamma}(t - t') \delta \lambda_{\gamma}(t') dt', \]

\[ R_{\alpha\gamma}(t - t') = \frac{d}{dt} C_{\alpha\gamma}(t - t') \]

\[ = \frac{d}{dt} \left< \frac{\partial \phi(c(t); \lambda^{ss})}{\partial \lambda_{\alpha}} \frac{\partial \phi(c(t'); \lambda^{ss})}{\partial \lambda_{\gamma}} \right>_{ss}. \]

Where now \(<.>_{ss}\) is computed on the stationary state

\[ X_{\alpha}(t) = \frac{\partial \phi(t)}{\partial \lambda_{\alpha}} \] is the observable


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Generalized FDT

In the experiment

\[ X(t) = \frac{\partial \phi(\theta(t), A)}{\partial A} \]
Generalized FDT

In the experiment

\[ X(t) = \frac{\partial \phi(\theta(t), A)}{\partial A} \]

Time evolution of X
Generalized FDT

The response function in the experiment

$$\left\langle \frac{\partial \phi(\theta(t))}{\partial A} \right\rangle = \int_0^t R(t - t') \, \delta A(t') \, dt'$$

If $\delta A$ is an Heaviside perturbation

$$\left\langle \frac{\partial \phi(\theta(t))}{\partial A} \right\rangle = (C(0) - C(t)) \delta A$$

where

$$C(t) = \left\langle \frac{\partial \phi(\theta(t))}{\partial A} \frac{\partial \phi(\theta(0))}{\partial A} \right\rangle_{ss}$$
Generalized FDT

The response function in the experiment

\[
\left< \frac{\partial \phi(\theta(t))}{\partial A} \right> = \int_0^t R(t - t') \, \delta A(t') \, dt'
\]

If \( \delta A \) is an Heaviside perturbation

\[
\left< \frac{\partial \phi(\theta(t))}{\partial A} \right> = (C(0) - C(t)) \delta A
\]

where

\[
C(t) = \left< \frac{\partial \phi(\theta(t))}{\partial A} \, \frac{\partial \phi(\theta(0))}{\partial A} \right>_{ss}
\]

Experimentally it does not work
Generalized FDT

The response function in the experiment

\[ \langle \frac{\partial \phi(\theta(t))}{\partial A} \rangle = \int_{0}^{t} R(t - t') \delta A(t') \, dt' \]
Generalized FDT

The response function in the experiment

\[
\left\langle \frac{\partial \phi(\theta(t))}{\partial A} \right\rangle = \int_0^t R(t - t') \delta A(t') \, dt'
\]

\[
\left\langle \frac{\partial \phi(\theta(t))}{\partial A} \right\rangle - \left\langle \frac{\partial \phi(\theta(t))}{\partial A} \right\rangle_{ss} = \int_0^t R(t - t') \delta A(t') \, dt'
\]
Generalized FDT

The response function in the experiment

\[
\left\langle \frac{\partial \phi(\theta(t))}{\partial A} \right\rangle = \int_0^t R(t - t') \, \delta A(t') \, dt'
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This is zero in the case of infinite sampling
Generalized FDT

The response function in the experiment

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This is zero in the case of infinite sampling

In the case of finite sampling two effects have to be taken into account
Generalized FDT

In the case of finite sampling two effects has to be taken into account.

The Hatano-Sasa relation is not exactly 1

and

\[ \left\langle \frac{\partial \phi(\theta(t))}{\partial A} \right\rangle_{ss} \neq 0 \]
In the case of finite sampling two effects have to be taken into account

The Hatano-Sasa relation is not exactly 1

\[ \left\langle \frac{\partial \phi(\theta(t))}{\partial A} \right\rangle_{ss} \neq 0 \]

The integrated response must be computed:

\[ \frac{\left\langle \frac{\partial \phi(\theta(t))}{\partial A} \right\rangle - \left\langle \frac{\partial \phi(\theta(t+t^*))}{\partial A} \right\rangle_{ss}}{\delta A} = \chi(t) \]

under the condition

\[ \left\langle \frac{\partial \phi(\theta(0))}{\partial A} \right\rangle = \left\langle \frac{\partial \phi(\theta(t^*))}{\partial A} \right\rangle_{ss} \]
Generalized FDT

\[ C(t) = \left\langle \frac{\partial \phi(\theta(t))}{\partial A}, \frac{\partial \phi(\theta(0))}{\partial A} \right\rangle_{ss} \]

\[ \chi(t) = (C(0) - C(t)) \]
Generalized FDT

\[ C(t) = \left\langle \frac{\partial \phi(\theta(t))}{\partial A} \right\rangle_{ss} \]

\[ \chi(t) = (C(0) - C(t)) \]

Conclusions

- GFDT as been checked on the experimental data taking into account the finite sampling.

- It is certainly the more general formulation for a Markofian dynamics
Conclusions on FDT on NESS

- We checked three formulations of FDT for NESS.

- The Langrangian formulation can be applied to any process but the knowledge of the current is needed.

- The frenesy formulation needs the knowledge of the generator of the dynamics, but it can in principle be applied to non-stationary cases. It is limited to Markofian systems.

- The formulation based on Hatano-Sasa relation is certainly the most general of the three if the dynamics is Markofian.
FR for NESS driven by a random forcing

Motivation:

We consider a Langevin dynamics driven out of equilibrium

\[ m\ddot{x} + \gamma \dot{x} = -kx + \zeta_T + f_0. \]

and

\[ w_\tau = \frac{1}{k_B T} \int_t^{t+\tau} \dot{x}(t')f_0(t') \, dt'. \]

\[ \ln \frac{P(W_\tau = W)}{P(W_\tau = -W)} \to \frac{W}{k_B T}, \quad \tau \to -\infty \]
FR for NESS driven by a random forcing

Motivation:

We consider a Langevin dynamics driven out of equilibrium

\[ m\ddot{x} + \gamma \dot{x} = -kx + \zeta_T + f_0. \]

and

\[ w_\tau = \frac{1}{k_B T} \int_t^{t+\tau} \dot{x}(t') f_0(t') \, dt'. \]

What happens if the external force is random?
FR for NESS driven by a random forcing

AFM cantilever

The experiment

\[ m\ddot{X} + \gamma \dot{X} = -kX + \zeta_T \]

\[ E_c = \frac{1}{2} C(X)V^2 \]

\[ F = -\partial_X E_c = -\alpha V^2 \]

\[ \alpha = 15 \text{ pN/V}^2 \]
FR for NESS driven by a random forcing

The experiment

\[ m\ddot{X} + \gamma \dot{X} = -kX + \zeta_T + F \]

\[ F = \overline{F} + f_0 \]

with

\[ \overline{X} = \overline{F}/k \]

\[ m\ddot{x} + \gamma \dot{x} = -kx + \zeta_T + f_0. \]

\[ E_c = \frac{1}{2} C(X)V^2 \]

\[ F = -\partial_X E_c = -\alpha V^2 \]

\[ \alpha = 15 \text{ pN/V}^2 \]

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FR for NESS driven by a random forcing

The relevant control parameter is

\[ \alpha = \frac{\langle x^2 \rangle}{\langle x^2 \rangle_{eq}} - 1, \]

where \( \langle x^2 \rangle_{eq} = k_B T / k \)

\( \alpha = 0.19 \)

\( \alpha = 3 \)

\( \alpha = 19 \)
FR for NESS driven by a random forcing

\[ \rho(w) = \ln \left( \frac{P(w_\tau = w)}{P(w_\tau = -w)} \right) \]
FR for NESS driven by a random forcing

\[ w^*_\tau = \frac{\tau_c}{\tau} \frac{w_\tau}{1 + \alpha} \]

\[ k\langle x^2 \rangle / k_B = (1 + \alpha)T \approx \alpha T \]

\[ \rho^*(w^*) = \lim_{\tau/\tau_c \to \infty} \frac{\tau_c}{\tau} \ln \frac{P(w^*_\tau = w^*)}{P(w^*_\tau = -w^*)} \]
FR for NESS driven by a random forcing

\[ w_\tau^* = \frac{\tau_c}{\tau} \frac{w_\tau}{1 + \alpha} \]

\[ k\langle x^2 \rangle / k_B = (1 + \alpha)T \approx \alpha T \]

\[ \rho^*(w^*) = \lim_{\tau/\tau_c \to \infty} \frac{\tau_c}{\tau} \frac{\ln \frac{P(w_\tau^* = w^*)}{P(w_\tau^* = -w^*)}} \]

\[ \rho^*(w^*) = \begin{cases} 
\frac{7}{4}w^* + \frac{3}{2} - \frac{1}{4w^*} & w^* < 1/3 \\
\frac{1}{4w^*} & w^* \geq 1/3 
\end{cases} \]

FR for NESS driven by a random forcing

Conclusions

- We have studied the FT for the work fluctuations in two experimental systems in contact with a thermal bath and driven out of equilibrium by a stochastic force.

- The main result of our study is that the validity of FT is controlled by the parameter $\alpha$. For $\alpha < 1$ we have shown that the validity of the steady-state FT is a very robust result.

- In contrast for $\alpha > 1$, when the randomness of the system becomes dominated by the external stochastic forcing, we have shown that FT is violated.

- For $\alpha >> 1$ the data can be described by a master curve with a suitable effective temperature.