Beyond the linear fluctuation-dissipation theorem: the role of causality

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Abstract. In this paper we tackle the traditional problem of relating the fluctuations of a system to its response to external forcings and extend the classical theory in order to be able to encompass also nonlinear processes. With this goal, we try to build on Kubo’s linear response theory and the response theory recently developed by Ruelle for nonequilibrium systems equipped with an invariant Sinai–Ruelle–Bowen (SRB) measure. Our derivation also sheds light on the link between causality and the possibility of relating fluctuations and response, both at the linear and nonlinear level. We first show, in a rather general setting, how the formalism of Ruelle’s response theory can be used to derive in a novel way a generalization of the Kramers–Kronig relations. We then provide a formal extension at each order of nonlinearity of the fluctuation-dissipation theorem for general systems endowed with a smooth invariant measure. Finally, we focus on the physically relevant case of systems weakly perturbed from equilibrium, for which we present explicit fluctuation-dissipation relations linking the susceptibility describing the $n$th order response of the system with suitably defined correlations taken in the equilibrium ensemble.

Keywords: dissipative systems (theory), exact results, fluctuations (theory), stationary states

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1. Introduction

The equilibrium statistical mechanical description of a many-particle system is rooted on the Hamiltonian equations of motion, which feature no dissipation, i.e. a vanishing average phase space contraction rate. This basic tenet of the Hamiltonian dynamics is mirrored, in the Gibbs’ ensemble approach, by the Liouville theorem, which claims the conservation of the probability measure in the phase space. On the other hand, a major endeavor of nonequilibrium statistical mechanics is the investigation of dissipative dynamical systems attaining a steady state. In this case, the mathematical description is richer: besides the many-particle system, one needs to suitably take into account the effects of the external field performing work on the system, and of a thermal reservoir, which absorbs the heat generated within the system by the action of the external field. A milestone of the emerging nonequilibrium theory is represented by the fluctuation relations (FRs), which concern some peculiar symmetry properties of the underlying microscopic (deterministic) dynamics under time reversal, with respect to some specific observables, e.g. the phase space contraction rate [1] or the dissipation function [2] (which can be replaced, in stochastic dynamics, by the entropy production of the system [3]). While the FRs hold for dissipative systems even far from equilibrium, and may essentially be regarded as a large deviation result [4, 5], the fluctuation-dissipation theorem (FDT) addresses systems weakly perturbed from equilibrium [6, 7] and establishes a link between the response of the

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system to an external (possibly time-dependent) perturbation and a correlation function computed in the equilibrium, unperturbed, state. The idea underlying the FDT is simple, yet powerful: for linear deviations from equilibrium, one may compute, for instance, the viscosity of a fluid or the resistance of an electrical wire (which are related to the dissipation produced in the system when an external driver, i.e. a shear stress or a voltage, is switched on) without actually applying the external field, but just through observing suitably defined correlation properties of the fluctuations of the unperturbed system. The practical and conceptual implications of this result can hardly be underestimated.

The problem of determining the response of the system in contact with a thermal reservoir to external perturbations was generalized by Kubo himself in order to study higher-order effects on observables, which become practically relevant in the presence of stronger forcings. This line of investigation has since found relevant applications in fields such as optics, where by the 1960s the revolutionary laser technology allowed the study of intense radiation–matter coupling and the generation of a complex and fascinating phenomenology with wide-ranging theoretical as well as industrial relevance. See the book by Bloembergen [8] for an interesting mix of the early appraisal of Kubo’s work and a fresh outlook on the very first studies in nonlinear optics, and the book by Butcher and Cotter [9] for a more recent point of view. For rather obvious reasons, optics has historically been the scientific context in which the response theory has been developed, extensively focusing on the frequency domain, rather than on the time domain description. This has led to emphasizing the link between the fact that the system obeys causality when responding to an external perturbation and the existence of general integral dispersion relations, commonly known as Kramers–Kronig relations, linking the real and imaginary part of the frequency-dependent response to radiation, and the related sum rules. This has been of great practical relevance for computing and reconstructing the optical properties of matter; natural as well as artificial. An extensive account of this line of work can be found in [10,11].

Along a different route, the investigation of the response to external perturbations has been extended to encompass the case where the unperturbed system attains a nonequilibrium steady state (NESS) [12]. In this case, the dynamical system features a nonvanishing average phase space contraction rate and Sinai–Ruelle–Bowen (SRB) measures [13]–[15] provide the natural mathematical framework for describing its statistical properties. Ruelle [16] recently derived explicit formulas for describing the smooth dependence of the SRB measure on small perturbations of the flow in the case of Axiom A systems [15]. Such a response theory boils down to a Kubo-like perturbative expression connecting the terms describing the linear and nonlinear response of the system as expectation values of observables on the unperturbed SRB measure. This approach is especially useful for studying the impact of changes in the internal parameters of a system or of small modulations to the external forcing, and various studies have highlighted the practical relevance of Ruelle theory for studying what we may call the sensitivity of the system to small perturbations. In some cases, the emphasis has been on providing convincing ways to compute the linear response from the unperturbed motion [17], in other studies, the authors have highlighted the properties of the frequency-dependent linear response of the system [18,19]. Finally, some efforts have been directed at extending the analysis of the frequency-dependent response to the nonlinear case [20] and on testing the robustness of the theory with simple chaotic models [21]. Recently,
response theory has been used to study the impact of stochastic perturbations [22] and derive rigorous parameterizations for reducing the complexity of multiscale systems [23], which provides potentially interesting links to the Mori–Zwanzig projection operator approach [24].

The link between the linear response of the system to external perturbations and its fluctuations is more elusive when the unperturbed state is a NESS. In [16,25], it is shown that, since the invariant measure is singular, the response of the system contains, in general, two qualitatively different contributions. The first term may be expressed in terms of a correlation function evaluated with respect to the unperturbed dynamics along the space tangent to the attractor, and represents the dissipative version of the equilibrium correlation function occurring in Kubo’s theory [19,26]. On the other hand, the second term, which has no equilibrium counterpart, depends on the dynamics along the stable manifold, and, hence, it may not be determined from the unperturbed dynamics and is also quite difficult to compute numerically. When devising algorithms for computing the response of the system, in fact, Majda and collaborators are forced to use different methods for computing the correlation-like and the additional term described above [17]. The relevance of the novel term spoiling the canonical structure of the FDT for dissipative chaotic systems is still a matter of ongoing research. While Majda and collaborators find this term to be of comparable size as the one coming from the usual correlation integral, in [27] it is shown, by means of low-dimensional solvable models, that the novel term introduced by Ruelle is expected to attain its own relevance only in very peculiar situations, such as systems with carefully oriented manifolds in phase space and for initial perturbations chosen along peculiar directions. These results suggest that the fluctuation-dissipation relations may, for practical purposes, hold also outside the standard equilibrium domain and stem from the fact that physics is mainly concerned with smooth observables and with projections from high-dimensional spaces to lower dimensional ones [28,29]. This may also explain why some attempts at reconstructing the response to perturbations of a complex system such as the climate via the application of the classic FDT have enjoyed a reasonable degree of success [30]–[32], even if it is clear that the performance depends critically on the choice of the observable of interest. Moreover, it is important to underline that recent works [33] have emphasized that FDT applies for all systems whose invariant measure is smooth, which is, in particular, the case for deterministic systems perturbed with noise [34].

The purpose of this paper is twofold: we wish emphasize the intimate link existing between the causality of the response of the system and the possibility of connecting response and fluctuations. In section 2, we briefly recapitulate the Kubo linear response theory in order to emphasize some specific formal aspects that will be useful for the subsequent derivations. Then, we show how the Ruelle response theory can be used to derive straightforwardly Kramers–Kronig relations connecting at all orders of nonlinearity the real and imaginary part of the susceptibility—frequency-dependent response of the system to perturbations—and how the susceptibility can be written in terms of unperturbed properties of the system. This is accomplished in section 3. Subsequently, we focus on extending the FDT. In section 4, we derive a nonlinear generalization of the classical FDT by considering higher orders in the standard perturbative expansion around the unperturbed measure, assumed to be absolutely continuous with respect to
Lebesgue. In section 5, we present explicit calculations for the canonical equilibrium reference frame, which provides the natural extension to arbitrary order of the classical Kubo’s FDT. In section 6, we present our conclusions and perspectives for future works. Finally, as a side note, in the appendix we show that, when considering perturbations to a canonical ensemble, at all orders of nonlinearity the imaginary part of the susceptibility of the observable conjugated to the external field is intimately connected to dissipation.

2. Prologue

This work focuses on the general relation between two quantities which play a decisive role in Kubo’s theory of FDT: the
\[ n \text{th order Green function } G^{(n)}(t_1, \ldots, t_n), \]
which modulates the response of the system to an external forcing, and the corresponding response function
\[ R^{(n)}(t_1, \ldots, t_n), \]
which, in the setting illustrated in this work, can be computed from the statistical properties of the unperturbed system. In order to provide a bird’s-eye view upon the meaning of such relation, we will dedicate this short prologue to reviewing the linear response theory introduced by Kubo in his seminal paper [6], so as to pave the basis for the nonlinear extension to be discussed in this paper. Following [6,35], let \( A(x) \) be a (smooth enough) phase space observable (with \( x \) denoting a point in the phase space—we will omit, here, the phase space dependence of the observable, so as not to overload the notation), \( \rho_0(x) \) an equilibrium invariant density and \( \rho(x, t) \) a perturbed density, induced by the action of an external time-dependent field \( T(t) \). Thus, denoting by \( \langle A \rangle_\rho \) the average of \( A \) with respect to the density \( \rho \), by
\[ \delta \bar{A}(t) = \langle A \rangle_\rho - \langle A \rangle_{\rho_0} \]
the difference between the two averages, and by using the shorthand notation \( R(t) = R^{(1)}(t_1) \), \( G(t) = G^{(1)}(t_1) \), the linear response relation reads:

\[
\delta \bar{A}(t) = \int_{-\infty}^{+\infty} G(t - \tau) T(\tau) \, d\tau.
\]

Next, by factorizing the Green function as
\[ G(t - \tau) = \theta(t - \tau) R(t - \tau), \]
where
\[
\theta(t) = \begin{cases} 
0 & \text{if } t < 0 \\
1 & \text{if } t \geq 0 
\end{cases}
\]
denotes the Heaviside distribution, equation (1) may be equivalently written as:

\[
\delta \bar{A}(t) = \int_{-\infty}^{+\infty} \theta(t - \tau) R(t - \tau) T(\tau) \, d\tau = \int_{-\infty}^{t} R(t - \tau) T(\tau) \, d\tau.
\]

The Heaviside distribution is explicitly introduced to take into account the causality of the response: namely, the perturbation \( T(\tau) \) is supposed to induce the response of the observable \( \delta \bar{A}(t) \), and, hence, the Green function \( G(t - \tau) \) must vanish for \( t < \tau \).

The detailed structure of the response function \( R(t) \) may be exposed by using some physical insight on the system under consideration. Kubo showed that, in the case of Hamiltonian particle systems whose unperturbed state is described by the equilibrium canonical ensemble, the function \( R(t) \) can be computed as the expectation value of a given observable with respect to the invariant density \( \rho_0(x) \) alone (which stands, in fact, as one of the outstanding results of Kubo’s linear theory). In particular, \( R(t) \) turns out to be given in terms of a suitable equilibrium correlation function, which, via the Wiener–Khintchine theorem [35], is related, in the Fourier space, to the spectral density of the equilibrium fluctuations \( \hat{C}(\omega) \) (to be defined in section 5).
On the mathematical side, instead, the connection between the response function $R(t)$ and the Green function $G(t)$, highlighted by equations (1) and (2), can be explored further by employing the aforementioned principle of causality, embodied by the function $\theta(t)$. In fact, going to Fourier space, one obtains from equation (1):

$$\delta \tilde{A}(\omega) = \int_{-\infty}^{+\infty} e^{-i\omega t} dt \int_{-\infty}^{+\infty} G(t-\tau)T(\tau) d\tau = \chi(\omega)\tilde{T}(\omega)$$

$$= [\text{Re}\{\chi(\omega)\} + i \text{Im}\{\chi(\omega)\}] \tilde{T}(\omega),$$

where $\chi(\omega) = \mathcal{F}(G(t))$ (typically referred to, in the literature, as the dynamic susceptibility) represents the Fourier transform of $G(t)$. Moreover, from equation (2) it also follows:

$$\delta \tilde{A}(\omega) = \left[ \int_{-\infty}^{+\infty} e^{-i\omega t} R(t)\theta(t) dt \right] \tilde{T}(\omega) = \frac{1}{2\pi} \left[ \int_{-\infty}^{+\infty} \tilde{R}(\omega_1)\theta(\omega - \omega_1) d\omega_1 \right] \tilde{T}(\omega)$$

$$= \left[ \int_{-\infty}^{+\infty} \tilde{R}(\omega_1) \left( -\frac{i}{2\pi} \mathcal{P} \left( \frac{1}{\omega - \omega_1} \right) + \frac{1}{2} \delta(\omega - \omega_1) \right) d\omega_1 \right] \tilde{T}(\omega).$$

Equations (3) and (4) entail a relation between $\chi(\omega)$ and $\tilde{R}(\omega)$, which can be made explicit by using the Kramers–Kronig relations [35]. Thus, one obtains the following alternative relations: $\tilde{R}(\omega) = 2 \text{Re}\{\chi(\omega)\}$ or $\tilde{R}(\omega) = 2i \text{Im}\{\chi(\omega)\}$, which correspond to a response function $R(t)$ endowed with, respectively, an even or odd symmetry under time reversal (see also figure 1 in section 5). This can immediately be seen by writing:

$$\tilde{R}(\omega) = \int_{-\infty}^{+\infty} e^{-i\omega t} R(t) dt = \epsilon_R \int_{-\infty}^{+\infty} e^{i\omega(-t)} R(-t) d(-t) = \epsilon_R \tilde{R}(-\omega) = \epsilon_R \tilde{R}^*(\omega),$$

where $\epsilon_R = +1$ (respectively, $-1$) if the response function $R(t)$ is even (odd) under the transformation $t \rightarrow -t$. Thus, if $\epsilon_R = 1$, equation (5) yields $\tilde{R}(\omega) = \tilde{R}^*(\omega)$, i.e. $\tilde{R}(\omega)$ is real; on the other hand, if $\epsilon_R = -1$, equation (5) gives $\tilde{R}(\omega) = -\tilde{R}^*(\omega)$, i.e. $\tilde{R}(\omega)$ is purely imaginary. Therefore, in the linear case, the principle of causality (expressed by the Kramers–Kronig relations) and the symmetry of the response function with respect to the time reversal, lead to a neat relation between $R(t)$ and either the real or the imaginary part of the Fourier transform of the Green function $G(t)$. This is a general (i.e. not restricted to equilibrium or close-to-equilibrium systems), rather abstract result.

By combining such mathematical formalism with some physical description of the system, which allows one to characterize $R(t)$ case by case, Kubo derived his celebrated FDT [6, 16] (which will be discussed extensively in section 5) in the form of a relation between $\chi(\omega)$—in the case of odd $R(t)$—or $\text{Re}\{\chi(\omega)\}$—in the case of even $R(t)$—and $\dot{C}(\omega)$, which is related to the equilibrium fluctuations. In the most common case of odd-valued $R(t)$, the relevant quantity $\text{Im}\{\chi(\omega)\}$ can be associated with the power dissipated within the system (see appendix). Thus, our purpose is to extend this formalism beyond the linear regime discussed by Kubo.

3. Response theory and Kramers–Kronig relations

Axiom A dynamical systems [14, 15] of the form $\dot{x} = F(x)$ possess a very special kind of invariant measure $\rho^{(0)}(dx)$, usually referred to as SRB measure. This is a physical
measure, i.e. for a set of initial conditions of positive Lebesgue measure the time average \( \lim_{T \to \infty} \frac{1}{T} \int dt A(x(t)) \) of any smooth observable \( A \) converges to the expectation value \( \rho^{(0)}(A) = \int \rho^{(0)}(dx) A(x) \). Another crucial property of \( \rho^{(0)}(dx) \) is that it is stochastically stable, i.e. it corresponds to the zero-noise limit of the invariant measure of the random dynamical system whose deterministic component is given by \( \dot{x} = F(x) \).

Ruelle [16] recently derived explicit formulas for describing the smooth dependence of the SRB measure of Axiom A dynamical systems to small perturbations of the flow. Such a response theory boils down to a Kubo-like perturbative expression connecting the terms describing the linear and nonlinear response of the system as expectation values of observables on the unperturbed measure. At order \( n \) of nonlinearity, such expectation values can be written as an \( n \)-tuple convolution of a causal Green function with the time-delayed perturbative fields, so that at every order the Kramers–Kronig relations can be written for the Fourier transform of the Green function, the so-called susceptibility [20].

In particular, Ruelle [26, 36] has shown that if the system is weakly perturbed so that its evolution equation can be written as:

\[
\dot{x} = F(x) + X(x)T(t),
\]

where \( X(x) \) is a weak time-independent forcing and \( T(t) \) is its time modulation, it is possible to write the modification to the expectation value of a general observable \( A \) as

\[
\rho^{(1)}(A) = \rho^{(0)}(A) + \int d^m x \rho^{(0)}(dx) \rho^{(0)}(dx_1) \ldots \rho^{(0)}(dx_{m-1}) X(x) T(t) \ldots T(t_{m-1}) A(x_{m-1}, \ldots, x) \]

where \( m \) is the order of the nonlinearity.
a perturbative series:

\[ \rho(A)_t = \sum_{j=0}^{\infty} \rho^{(n)}(A)_t, \]  

(7)

where \( \rho^{(0)} \) is the unperturbed invariant measure, \( \rho^{(n)}(A)_t \) with \( n \geq 1 \) represents the contribution due to \( n \)th order nonlinear processes and can be expressed as an \( n \)-tuple convolution product:

\[ \rho^{(n)}(A)_t = \int_{-\infty}^{\infty} d\tau_1 \cdots \int_{-\infty}^{\infty} d\tau_n G^{(n)}(\tau_1, \ldots, \tau_n) T(t - \tau_1) \cdots T(t - \tau_n). \]  

(8)

The integration kernel \( G^{(n)}(\tau_1, \ldots, \tau_n) \) is the \( n \)th order Green function, which can be written as:

\[ G^{(n)}(\tau_1, \ldots, \tau_n) = \int \rho^{(0)}(dx) \Theta(\tau_1) \Theta(\tau_2 - \tau_1) \cdots \Theta(\tau_n - \tau_{n-1}) \Lambda(\tau_n - \tau_{n-1}) \]

\[ \times \Lambda(\tau_{n-1} - \tau_{n-2}) \Lambda(\tau_1) A(x) \Theta(\tau_n - \tau_{n-1}) R(\tau_1, \ldots, \tau_n), \]  

(9)

where \( \Lambda(\bullet) = X \cdot \nabla(\bullet) \) describes the impact of the perturbation field and \( \Pi(\sigma) \) is the unperturbed time evolution operator such that \( \Pi(\sigma)K(x) = K(x(\sigma)) \). The Green function obeys two fundamental properties:

- its variables are time-ordered: if \( j < k, \tau_j > \tau_k \rightarrow G^{(n)}(\tau_1, \ldots, \tau_n) = 0; \)
- the function is causal: \( \tau_1 < 0 \rightarrow G^{(n)}(\tau_1, \ldots, \tau_n) = 0. \)

Obviously, in the linear case only the second condition applies. These properties allow the Green function to be rewritten as \( G^{(n)}(\tau_1, \ldots, \tau_n) = \Theta(\tau_1) \Pi^{n}_{j=2} \Theta(\tau_j - \tau_{j-1}) R(\tau_1, \ldots, \tau_n) \), where the Heaviside distribution \( \Theta(\tau_1) \) takes care of guaranteeing the causality, the terms of the form \( \Theta(\tau_j - \tau_{j-1}) \) enforce the time-ordering, while \( R(\tau_1, \ldots, \tau_n) \) is the response function, which contains the information about the microscopic dynamics of the system. By applying the Fourier transform to equation (8), with \( \hat{Y}(\omega) = \mathcal{F}(Y(t)) = \int_{-\infty}^{\infty} dt \exp[-i\omega t]Y(t) \) one obtains the following expression [20]:

\[ \rho^{(n)}(\hat{A})(\omega) = \int_{-\infty}^{\infty} d\omega_1 \cdots \int_{-\infty}^{\infty} d\omega_n \chi^{(n)}(\omega_1, \ldots, \omega_n) \hat{T}(\omega_1) \cdots \hat{T}(\omega_n) \delta \left( \omega - \sum_{j=1}^{n} \omega_j \right), \]  

(10)

where \( \rho^{(n)}(\hat{A})(\omega) = \mathcal{F}(\rho^{(n)}(A)_t), \hat{T}(\omega_j) = \mathcal{F}(T(\tau_j)) \), and the susceptibility \( \chi^{(n)}(\omega_1, \ldots, \omega_n) \) is the \( n \)-dimensional Fourier transform of \( G^{(n)}(\tau_1, \ldots, \tau_n) \) defined as:

\[ \chi^{(n)}(\omega_1, \ldots, \omega_n) = \int_{-\infty}^{\infty} d\tau_1 \cdots d\tau_n \exp[-i\omega_1 \tau_1] \cdots \exp[-i\omega_n \tau_n] G^{(n)}(\tau_1, \tau_2, \ldots, \tau_n), \]  

(11)

while the term containing the Dirac \( \delta \) ensures that the frequency of the output is identical to the sum of the input frequencies. Note that we use the same definition for the Fourier transform as in [6], while the sign of the frequency variable in the integration is opposite to what was used in [11, 20], which is more common in the optical literature. We define

\[ G^{(n)}_S(\tau_1, \ldots, \tau_n) = G^{(n)}(\tau_1, \ldots, \tau_n) + G^{(n)}(-\tau_1, \ldots, -\tau_n) \]  

(12)

\[ G^{(n)}_A(\tau_1, \ldots, \tau_n) = G^{(n)}(\tau_1, \ldots, \tau_n) - G^{(n)}(-\tau_1, \ldots, -\tau_n) \]  

(13)
which are different from zero for \( \tau_n > \tau_{n-1} > \cdots > \tau_1 > 0 \) and \( \tau_n < \tau_{n-1} < \cdots < \tau_1 < 0 \) and have opposite parity with respect to exchange of the sign of all of the variables, \( G_S^{(n)}(\tau_1, \ldots, \tau_n) \) being even and \( G_A^{(n)}(\tau_1, \ldots, \tau_n) \) odd with respect to this symmetry. We have that:

\[
2 \text{Re}\{\chi^{(n)}(\omega_1, \ldots, \omega_n)\} = \int_{-\infty}^{\infty} \text{d}\tau_1 \cdots \text{d}\tau_n \exp[-i\omega_1\tau_1] \cdots \exp[-i\omega_n\tau_n] G_S^{(n)}(\tau_1, \ldots, \tau_n) \tag{14}
\]

\[
2i \text{Im}\{\chi^{(n)}(\omega_1, \ldots, \omega_n)\} = \int_{-\infty}^{\infty} \text{d}\tau_1 \cdots \text{d}\tau_n \exp[-i\omega_1\tau_1] \cdots \exp[-i\omega_n\tau_n] G_A^{(n)}(\tau_1, \ldots, \tau_n). \tag{15}
\]

Thanks to causality \( \forall \, j \) we have that

\[
G^{(n)}(\tau_1, \ldots, \tau_n) = \Theta(\tau_j) G^{(n)}(\tau_1, \ldots, \tau_n)
= \Theta(\tau_j) G_S^{(n)}(\tau_1, \ldots, \tau_n)
= \Theta(\tau_j) G_A^{(n)}(\tau_1, \ldots, \tau_n). \tag{16}
\]

By applying the Fourier transform to these identities and using the convolution theorem we obtain:

\[
\chi^{(n)}(\omega_1, \ldots, \omega_n) = \frac{1}{2\pi} \left( \hat{\Theta}(\omega_j) * (2 \text{Re}\{\chi^{(n)}(\omega_1, \ldots, \omega_j, \ldots, \omega_n)\}) \right)
= \frac{1}{2\pi} \left( \hat{\Theta}(\omega_j) * (2i \text{Im}\{\chi^{(n)}(\omega_1, \ldots, \omega_j, \ldots, \omega_n)\}) \right)
= \frac{1}{2\pi} \left( \hat{\Theta}(\omega_j) * (\chi^{(n)}(\omega_1, \ldots, \omega_j, \ldots, \omega_n)) \right)
= \left( -\frac{i}{\pi} \mathcal{P} \left( \frac{1}{\omega_j} \right) + \delta(\omega_j) \right) * \left( \text{Re}\{\chi^{(n)}(\omega_1, \ldots, \omega_j, \ldots, \omega_n)\} \right)
= \left( -\frac{i}{\pi} \mathcal{P} \left( \frac{1}{\omega_j} \right) + \delta(\omega_j) \right) * \left( \text{Im}\{\chi^{(n)}(\omega_1, \ldots, \omega_j, \ldots, \omega_n)\} \right)
= \left( -\frac{i}{\pi} \mathcal{P} \left( \frac{1}{\omega_j} \right) + \delta(\omega_j) \right) * \left( \frac{1}{2} \chi^{(n)}(\omega_1, \ldots, \omega_j, \ldots, \omega_n) \right), \tag{17}
\]

where \( \mathcal{P} \) indicates that the integral must be computed considering the principal part and * indicates the operation of the convolution product. As the same causality argument given in equation (16) can be repeated for any time variable \( \tau_k \), we have that:

\[
G^{(n)}(\tau_1, \ldots, \tau_n) = \prod_{i=1}^{k} \Theta(\tau_{j_i}) G^{(n)}(\tau_1, \ldots, \tau_n)
= \prod_{i=1}^{k} \Theta(\tau_{j_i}) G_S^{(n)}(\tau_1, \ldots, \tau_n)
= \prod_{i=1}^{k} \Theta(\tau_{j_i}) G_A^{(n)}(\tau_1, \ldots, \tau_n), \tag{18}
\]

where \( j_1, \ldots, j_k \) runs over some or all of the indices 1, \ldots, n. When taking the Fourier transform of the previous identities, we obtain:

\[
\chi^{(n)}(\omega_1, \ldots, \omega_n) = \prod_{i=1}^{k} \left( -\frac{i}{\pi} \mathcal{P} \left( \frac{1}{\omega_{j_i}} \right) + \delta(\omega_{j_i}) \right) * \left( \frac{1}{2^{k-1}} \text{Re}\{\chi^{(n)}(\omega_1, \ldots, \omega_{j_i}, \ldots, \omega_n)\} \right)
= \prod_{i=1}^{k} \left( -\frac{i}{\pi} \mathcal{P} \left( \frac{1}{\omega_{j_i}} \right) + \delta(\omega_{j_i}) \right) * \left( \frac{i}{2^{k-1}} \text{Im}\{\chi^{(n)}(\omega_1, \ldots, \omega_{j_i}, \ldots, \omega_n)\} \right)
= \prod_{i=1}^{k} \left( -\frac{i}{\pi} \mathcal{P} \left( \frac{1}{\omega_{j_i}} \right) + \delta(\omega_{j_i}) \right) * \left( \frac{1}{2^k} \chi^{(n)}(\omega_1, \ldots, \omega_{j_i}, \ldots, \omega_n) \right), \tag{19}
\]
where * must be intended as a multiple convolution product of the variables $\omega_{j_1}, \ldots, \omega_{j_k}$. Equations (19) provide an alternative expression of the generalized Kramers–Kronig relations for nonlinear susceptibilities, first presented in the special case of optical processes in [11].

We emphasize that equations (13)–(19) provide a fundamental connection between the time-dependent response of the system to perturbations and the real and imaginary part of the susceptibility. The Kramers–Kronig relations establish the correspondence between the fundamental property of causality in the response with the fact that the knowledge of only either the real or the imaginary part of the susceptibility is sufficient to reconstruct the full frequency-dependent response of the system, both in the linear and in the nonlinear regime.

3.1. Response function

We now take a slightly different point of view to analyze the frequency-dependent response of the system by focusing on the Fourier transform of the response function $R^{(n)}(\tau_1, \ldots, \tau_n)$. We rewrite the definition of the $n$th order susceptibility as follows:

$$
\chi^{(n)}(\omega_1, \ldots, \omega_n) = \int_{-\infty}^{\infty} d\tau_1 \cdots d\tau_n \exp[-i\omega_1 \tau_1] \cdots \exp[-i\omega_n \tau_n] \Theta(\tau_1) \cdots \Theta(\tau_n - \tau_{n-1}) R^{(n)}(\tau_1, \ldots, \tau_n)
$$

$$
= \int_{-\infty}^{\infty} d\sigma_1 \cdots d\sigma_n \exp[-i\omega_1 \sigma_1] \exp \left[-i\omega_2 \sum_{j=1}^{n} \sigma_j \right] \cdots \exp[-i\omega_n \sum_{j=1}^{n} \sigma_j] \Theta(\sigma_1) \cdots \Theta(\sigma_n) S^{(n)}(\sigma_1, \ldots, \sigma_n)
$$

$$
= \int_{-\infty}^{\infty} d\sigma_1 \cdots d\sigma_n \exp[-i\sigma_1 \sum_{j=1}^{n} \omega_j] \exp \left[-i\sigma_2 \sum_{j=2}^{n} \omega_j \right] \cdots \exp[-i\omega_n \sigma_n] \Theta(\sigma_1) \cdots \Theta(\sigma_n) S^{(n)}(\sigma_1, \ldots, \sigma_n),
$$

(20)

where we have performed the change of variables $\sigma_1 = \tau_1$ and $\sigma_j = \tau_j - \tau_{j-1}$ $\forall j \geq 2$ and we have defined $S^{(n)}(\sigma_1, \ldots, \sigma_n) = R^{(n)}(\sigma_1, \ldots, \sum_{j=1}^{n} \sigma_j)$. Defining $\Delta^{(n)}(\sigma_1, \ldots, \sigma_n) = \Theta(\sigma_1) \cdots \Theta(\sigma_n) S^{(n)}(\sigma_1, \ldots, \sigma_n)$, we obtain that:

$$
\chi^{(n)}(\omega_1, \ldots, \omega_n) = \Delta^{(n)} \left( \sum_{j=1}^{n} \omega_j, \sum_{j=2}^{n} \omega_j, \ldots, \omega_n \right),
$$

(21)

or, in other terms:

$$
\chi^{(n)}(\nu_1 - \nu_2, \nu_2 - \nu_3, \ldots, \nu_n) = \Delta^{(n)}(\nu_1, \nu_2, \ldots, \nu_n).
$$

(22)

Along the lines of the derivation proposed in equations (16)–(20), we obtain:

$$
\hat{\Delta}^{(n)}(\omega_1, \ldots, \omega_n) = \Pi_{i=1}^{n} \left( -\frac{i}{\pi} \frac{1}{\omega_i} \delta(\omega_i) + \delta(\omega_i) \right) * \left( -\frac{1}{2^{n-1}} \text{Re}\{\hat{\Delta}^{(n)}(\omega_1, \ldots, \omega_i, \ldots, \omega_n)\} \right)
$$

$$
= \Pi_{i=1}^{n} \left( -\frac{i}{\pi} \frac{1}{\omega_i} \delta(\omega_i) + \delta(\omega_i) \right) * \left( \frac{i}{2^{n-1}} \text{Im}\{\hat{\Delta}^{(n)}(\omega_1, \ldots, \omega_i, \ldots, \omega_n)\} \right)
$$

doi:10.1088/1742-5468/2012/05/P05013
Beyond the linear fluctuation-dissipation theorem: the role of causality

\[
\begin{align*}
\hat{\Delta}^n(\omega_1, \ldots, \omega_n) &= \Pi_{i=1}^n \left( -\frac{i}{\pi} \mathcal{P} \left( \frac{1}{\omega_i} \right) + \delta(\omega_i) \right) * \left( \frac{1}{2n} \hat{S}^n(\omega_1, \ldots, \omega_i, \ldots, \omega_n) \right) \\
&= \Pi_{i=1}^n \left( -\frac{i}{\pi} \mathcal{P} \left( \frac{1}{\omega_i} \right) + \delta(\omega_i) \right) * \left( \frac{1}{2n} \hat{\Delta}^n(\omega_1, \ldots, \omega_i, \ldots, \omega_n) \right),
\end{align*}
\]

which highlights the fundamental connection, made possible by causality, between the spectral properties of the response function and the corresponding susceptibility, at all orders of nonlinearity. Equation (23) suggests that the poles of \( \hat{\Delta}^n(\omega_1, \ldots, \omega_n) \) are, at most, those of \( \hat{S}^n(\omega_1, \ldots, \omega_n) \); moreover, the multiple convolution product ensures that all the singularities in the right-hand side terms which are not compatible with causality are removed.

Furthermore, if \( S^{(n)}(\sigma_1, \ldots, \sigma_n) \) is even with respect to the change of sign of all variables, so that \( \hat{S}^n(\omega_1, \ldots, \omega_n) \) is even and real, we have that the real part of \( \hat{\Delta}^n(\omega_1, \ldots, \omega_n) \) will be given by the sum of all contributions in equation (23) including an even number of convolutions between \( \hat{S}^n(\omega_1, \ldots, \omega_n) \) and terms of the form \( \mathcal{P}(1/\omega_i) \), whereas the imaginary part, conversely, will result from the remaining terms. Note that each time the convolution product is applied, the parity of the function is exchanged. The same result will hold if \( S^{(n)}(\sigma_1, \ldots, \sigma_n) \) is odd: in this case, \( i \) times the imaginary part of the \( \hat{\Delta}^n(\omega_1, \ldots, \omega_n) \) will be given by the sum of all contributions where \( \hat{S}^n(\omega_1, \ldots, \omega_n) \) (which is odd and purely imaginary) is convolved an even number of times with the factors \( \mathcal{P}(1/\omega_i) \), and the real part of \( \hat{\Delta}^n(\omega_1, \ldots, \omega_n) \) will come from the remaining terms.

In the linear \( n = 1 \) case, \( \chi^{(1)}(\omega) = \hat{\Delta}^{(1)}(\omega) \), and the results presented in equations (19) and (23) lead us to the classical results presented by Kubo in the case of perturbations to Hamiltonian systems immersed in a thermal bath [6]. In fact, we obtain that, if \( S^{(1)}(\tau_1) \) is even, it is equal to \( G_{\tilde{S}}^{(1)}(\tau_1) \), so that its Fourier transform \( \hat{S}^{(1)}(\omega_1) \) is equal to \( 2\text{Re}\{\chi^{(1)}(\omega)\} \). Instead, if \( S^{(1)}(\tau_1) \) is odd, it is equal to \( G_{\tilde{A}}^{(1)}(\tau_1) \), and we have that \( \hat{S}^{(1)}(\omega_1) = 2\text{Im}\{\chi^{(1)}(\omega)\} \). Obviously, the parity properties of \( S^{(1)}(\tau_1) \) depend critically on the unperturbed invariant measure and on the way the flow is perturbed, and so on the choice of \( X(x) \). When nonlinear processes are considered, the link between \( \hat{S}^{(n)}(\omega_1, \ldots, \omega_n) \) and \( \chi^{(n)}(\omega_1, \ldots, \omega_n) \) is indeed less trivial, even if equations (22) and (23) provide an algorithmically feasible way to unperturbed properties of the system to its response to external perturbations.

4. Extending the FDT beyond the linear response: general treatment

We now wish to explore how to link the (real or imaginary part) of the susceptibility function at various orders of nonlinearity to the Fourier transform of correlations of the system in the unperturbed state. In the linear case, this is the fundamental content of the fluctuation-dissipation theorem. In order to pursue this line, following Ruelle [16], we must assume that the unperturbed invariant measure \( \rho^{(0)}(dx) \) is absolutely continuous with respect to Lebesgue, so that it can be expressed as \( \rho^{(0)}(dx) = \rho^{(0)}(x) \, dx \). In this case, we can rewrite the linear Green function given in equation (9) for the case \( n = 1 \) as a simple lagged correlation between a function \( C(x) \) and the observable at a later time.
Beyond the linear fluctuation-dissipation theorem: the role of causality

\( A(x(\tau_1)) \) evolved according to the unperturbed dynamics:

\[
G(\tau_1) = \int dx \bar{\rho}^{(0)}(x) \Theta(\tau_1) X(x) \cdot \nabla \Pi(\tau_1) A(x)
\]

\[
= - \int dx \Theta(\tau_1) \bar{\rho}^{(0)}(x) \frac{\nabla \cdot (\bar{\rho}^{(0)}(x) X(x))}{\bar{\rho}^{(0)}(x)} \Pi(\tau_1) A(x)
\]

\[
= \int dx \Theta(\tau_1) \bar{\rho}^{(0)}(x) C(x) A(x(\tau_1)) = \int dx \Theta(\tau_1) \bar{\rho}^{(0)}(x) C(x(-\tau_1)) A(x).
\] (24)

because \( \int dx (\nabla \cdot (\bar{\rho}^{(0)}(x) \Theta(\tau_1) X(x) \cdot \Pi(\tau_1) A(x))) = 0 \), and where we have used the time invariance of the measure \( \bar{\rho}^{(0)}(x) \) \( dx \) in the last step of the derivation. Note that equation (25) provides a very general form of the linear fluctuation-dissipation theorem for dynamical systems endowed with a smooth invariant measure.

In order to generalize this procedure for the \( n \)th order Green function, we define the adjoint operators for the operators \( \Lambda \) and \( \Pi(\sigma) \):

\[
\langle \alpha(\sigma), \Lambda \beta(x) \rangle = \langle \Lambda^+ \alpha(x), \beta(x) \rangle \quad \langle \alpha(\sigma), \Pi(\sigma) \beta(x) \rangle = \langle \Pi(\sigma)^+ \alpha(x), \beta(x) \rangle
\] (26)

where the scalar product \( \langle \bullet, \bullet \rangle \) is the ordinary integral evaluated on the support of \( \bar{\rho}^{(0)}(x) \):

\[
\langle \alpha(x), \beta(x) \rangle = \int_{\bar{\rho}^{(0)}(x) > 0} dx \alpha(x) \beta(x).
\] (27)

Assuming that such support is compact or that the functions we consider vanish sufficiently fast at infinity, we obtain that:

\[
\Lambda(\beta(x)) = X(x) \cdot \nabla \beta(x) \rightarrow \Lambda^+ (\alpha(x)) = - \nabla \cdot (X(x) \alpha(x)),
\] (28)

while the adjoint of the unperturbed evolution operator \( \Pi(\tau_1) \) is given by:

\[
\Pi(\sigma)(\beta(x)) = \beta(x(\sigma)) \rightarrow \Pi(\sigma)^+ (\alpha(x)) = \alpha(x(-\sigma)).
\] (29)

With these definitions, we derive formally from equation (9) the following expression:

\[
R^{(n)}(\tau_1, \ldots, \tau_n) = \langle \bar{\rho}^{(0)}(x), \Lambda \Pi(\tau_n - \tau_{n-1}) \cdots \Lambda \Pi(\tau_1) A(x) \rangle
\]

\[
= \langle \Pi(\tau_1)^+ \Lambda^+ \cdots \Pi(\tau_n - \tau_{n-1})^+ \Lambda^+ \bar{\rho}^{(0)}(x), A(x) \rangle,
\] (30)

which gives the \( n \)th order response function (and consequently, the Green function) as a \( n \)-times correlation. Interestingly, when considering equation (30), one notes that the dual function \( \Pi(\tau_1)^+ \Lambda^+ \cdots \Pi(\tau_n - \tau_{n-1})^+ \Lambda^+ \bar{\rho}^{(0)}(x) \) generates the Green functions corresponding to the perturbation flow \( X(x) \) (given the unperturbed variant measure \( \bar{\rho}^{(0)}(x) \)) for any considered observable, \( A(x) \). Furthermore, following from the definition given in equation (20), we obtain the following expression for \( S^{(n)}(\sigma_1, \ldots, \sigma_n) \):

\[
S^{(n)}(\sigma_1, \ldots, \sigma_n) = \langle \bar{\rho}^{(0)}(x), \Lambda \Pi(\sigma_n) \cdots \Lambda \Pi(\sigma_1) A(x) \rangle
\]

\[
= \langle \Pi(\sigma_1)^+ \Lambda^+ \cdots \Pi(\sigma_n)^+ \Lambda^+ \bar{\rho}^{(0)}(x), A(x) \rangle.
\] (31)

Combining equations (13)–(19), or, alternatively, equations (20)–(23) with the previous equation (30) and considering the physical link between the imaginary part of the \( n \)th order susceptibility and dissipation described in equation (A.4) in the appendix, we obtain a generalized version of the FDT at all orders of nonlinearity and for rather general statistical dynamical systems, specifically for those possessing a smooth invariant measure. In section 5, we will show how to derive an actual explicit expression for the FDT in the special, albeit most relevant, case of the canonical ensemble.
5. Extending the FDT beyond the linear response: canonical ensemble

Following Kubo [6], we now address explicitly the case of an interacting many-particle system whose unperturbed state is described by the canonical ensemble generated by the Hamiltonian \( H_0(x) \), which takes into account only the internal degrees of freedom, and analyze the impact of adding a weak perturbation Hamiltonian \( H'(x, t) = B(x)T(t) \), where \( B(x) \) is an observable conjugated to the external field \( T(t) \) [27, 34, 35]. In the Kubo framework, the perturbed equations of motions can be written as \( \dot{x} = F(x) + X(x)T(t) \), where \( F(x) = S \cdot \nabla H_0(x) \) and \( X(x) = S \cdot \nabla B(x) \), where \( S \) is the symplectic matrix.

Following the approach highlighted in [11], one may adopt a perturbative technique to solve the Liouville equation for the probability density \( \rho_t \). To this aim, one may formally write

\[
\rho_t = \sum_{k=0}^{\infty} \rho_t^{(k)}.
\]

This leads to the equation, valid for arbitrary order \( n \):

\[
\frac{\partial \rho^{(n)}}{\partial t} = [H_0, \rho^{(n)}] + [B(x), \rho^{(n-1)}]T(t),
\]

where, in the classical case \([\bullet, \bullet]\) indicate the Poisson brackets \( \rho^{(0)} = e^{-\beta H_0}/Z \) denoting the (time-independent) equilibrium canonical density, with \( Z \) the canonical partition function, and where equation (32) is supplemented with the initial condition \( \rho_{t=0} = \rho^{(0)} \). In the case of a quantum system, we can interpret \([\bullet, \bullet]\) as \( 1/(i\hbar)\{\bullet, \bullet\} \), where \( \{\bullet, \bullet\} \) is the canonical commutator, and \( \rho^{(0)} = \sum_a 1/Z \exp[-\beta E_a]|a\rangle\langle a| \), where the \( |a\rangle \)s constitute a complete set of eigenvectors of \( H_0 \). As a result, one obtains that the expectation value of a given observable \( A \) can be written as [37]:

\[
\langle A \rangle_t = \langle A \rangle_0 + \sum_{n=1}^{\infty} \langle A \rangle_t^{(n)},
\]

where we revert to the notation \( \langle \bullet \rangle_0 = \text{Tr}\{\rho^{(0)}\bullet\} \), which is more common in the statistical physical literature, for indicating the expectation value \( \rho^{(0)}(\bullet) \), in both the classical and quantum cases. The following expression holds for the terms \( n \geq 1 \):

\[
\langle A \rangle_t^{(n)} = (-1)^n \int_{-\infty}^{\infty} d\tau_0 \cdots \int_{-\infty}^{\infty} d\tau_n \Theta(\tau_1) \Theta(\tau_2 - \tau_1) \cdots \Theta(\tau_n - \tau_{n-1})
\times \langle [B(-\tau_0), \ldots [B(-\tau_1), A] \cdots ]_0 T(t - \tau_1) \cdots T(t - \tau_n)\rangle
\]

so that, following equations (8) and (9), we can express the \( n \)th order Green function as:

\[
G_{A,B}^{(n)}(\tau_1, \ldots, \tau_n) = (-1)^n \Theta(\tau_1) \Theta(\tau_2 - \tau_1) \cdots \Theta(\tau_n - \tau_{n-1})
\times \langle [B(-\tau_0), \ldots [B(-\tau_1), A] \cdots ]_0 \rangle
\]

where the lower index of the Green function refers to the fact that we are considering the perturbation to the observable \( A \) due to the coupling with the \( B \) field, whereas the response function \( R_{A,B}^{(n)} \) is:

\[
R_{A,B}^{(n)}(\tau_1, \ldots, \tau_n) = (-1)^n \langle [B(-\tau_0), \ldots [B(-\tau_1), A] \cdots ]_0 \rangle
\]
Beyond the linear fluctuation-dissipation theorem: the role of causality

while the variable-wise rearranged function $S_{A,B}^{(n)}$ is:

$$S_{A,B}^{(n)}(\tau_1, \ldots, \tau_n) = (-1)^n \left\langle \left[ B \left( -\sum_{j=1}^{n} \tau_j \right), \ldots, [B(-\tau_1), A] \ldots \right] \right\rangle_0. \quad (37)$$

In the following, we will find a compact expression for its Fourier transform $\hat{S}_{A,B}^{(n)}$, which, combined with what discussed in the previous sections, provides the generalization of the FDT in the case of perturbed Hamiltonian systems in contact with a thermostat at an inverse temperature $\beta$. time correlation functions defined in equations (36) and (37). In particular, under an equilibrium dynamics, the time reversal symmetry yields [6]: $B$ is even or odd under the time reversal.

5.1. Equilibrium correlation functions: linear case

Let us now examine, order by order, how a general expression for the FDT emerges from the previous results. We first consider the linear response:

$$S_{A,B}^{(1)}(t_1) = \mathcal{R}_{A,B}^{(1)}(t_1) = -\left\langle [B(-t_1), A(0)] \right\rangle_0 = -\frac{1}{\hbar} (\langle B(-t_1)A(0) \rangle_0 - \langle A(0)B(-t_1) \rangle_0)$$

$$= -\frac{1}{\hbar} (C_{A,B}(-t_1) - C_{A,B}(-t_1 - \tau)) \quad (38)$$

with $\tau = i\hbar\beta$, and where $C_{A,B}(t_1) = \langle B(t_1)A(0) \rangle_0$ denotes the two-time equilibrium correlation function. Moreover, in order to obtain the last equality in (38), we employed the invariance of the trace under cyclic permutations and the fact that the operator $e^{i\beta H_0}$ effects a time translation by the imaginary time ($-\tau$). Then, following Kubo [6], when going to the Fourier space, it proves convenient to evaluate the complex conjugates of the various Fourier transforms. Thus, for instance, one considers:

$$\mathcal{F}(C_{A,B}(-\tau_1))^* = \hat{C}_{A,B}(-\omega_1)^* = \hat{C}_{A,B}(\omega_1), \quad (39)$$

where $\hat{C}_{A,B}(\omega_1)$ is the spectral density [38] and where the last equality follows from the fact that $C_{A,B}(-t_1)$ is real. By Fourier transforming and taking the complex conjugate on both sides of equation (38), we obtain:

$$\hat{S}_{A,B}^{(1)}(\omega_1) = -\frac{1}{i\hbar} (1 - e^{-\beta \omega_1}) \hat{C}_{A,B}(\omega_1). \quad (40)$$

If, $S_{A,B}(t_1)$ is odd under time reversal, as it is commonly assumed, we have, as discussed in section 2, that $\hat{S}_{A,B}^{(1)}(\omega_1) = 2i \text{Im}\{\chi_{A,B}^{(1)}(\omega_1)\}$, so that:

$$\text{Im}\{\chi_{A,B}^{(1)}(\omega_1)\} = \frac{1}{2\hbar} (1 - e^{-\beta \omega_1}) \hat{C}_{A,B}(\omega_1). \quad (41)$$

This represents the standard FDT at the first order in the perturbation, and, as was anticipated in section 2, it features a relation between the imaginary part of the Green function and the spectral density $\hat{C}_{A,B}(\omega_1)$. On the other hand, if $S_{A,B}(t_1)$ is even under time reversal, it follows that $\hat{S}_{A,B}^{(1)}(\omega_1) = 2 \text{Re}\{\chi_{A,B}^{(1)}(\omega_1)\}$ (see figure 1).

Starting from the general expression for the response function given in (37), which captures the physics of the problem, the strategy employed at the linear order may be straightforwardly repeated at an arbitrary higher order, thus leading to a generalization of the FDT for deterministic systems. For practical matters, our expansion, including second or third order around equilibrium, is already new and relevant.

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5.2. Equilibrium correlation functions: second order

We now present the first extension of the FDT beyond the linear order, thus showing the explicit calculations for the second order quantities. We start by writing out explicitly the expression for the response function:

\[ S_{A,B}^{(2)}(-t_1, -t_2) = R_{A,B}^{(2)}(-t_1, -t_1 - t_2) = \frac{1}{(\hbar^2)} \langle [B(-t_1 - t_2), [B(-t_1), A(0)]] \rangle_0 \]

\[ = \frac{1}{(\hbar^2)} \langle [B(-t_1 - t_2)B(-t_1)A(0)] \rangle_0 - \langle B(-t_1 - t_2)A(0)B(-t_1) \rangle_0 \]

\[ - \langle B(-t_1)A(0)B(-t_1 - t_2) \rangle_0 + \langle A(0)B(-t_1)B(-t_1 - t_2) \rangle_0 \]

\[ = \frac{1}{(\hbar^2)} \left( C_{A,B}(-t_1, -t_1 - t_2) - C_{A,B}(-t_1 - \tau, -t_1 - t_2) - C_{A,B}(-t_1, -t_1 - t_2 - \tau) + C_{A,B}(-t_1 - \tau, -t_1 - t_2 - \tau) \right) \]

(42)

where we have defined the correlation function \( C_{A,B}(t_1, t_2) = \langle B(t_2)B(t_1)A(0) \rangle_0 \). Then, we may consider, again, the complex conjugate of the Fourier transform of the three-time correlation functions occurring in equation (42), and find:

\[ \hat{C}_{A,B}(\omega_1 - \omega_2, \omega_2) = \int_{-\infty}^{+\infty} dt_2 \int_{-\infty}^{+\infty} e^{-i(\omega_1 t_1 + \omega_2 t_2)} C_{A,B}(-t_1, -t_1 - t_2) dt_1 \]

\[ = \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} e^{i(\omega_1 - \omega_2)\xi_1} e^{i\omega_2 \xi_2} C_{A,B}(\xi_1, \xi_2) d\xi_1 d\xi_2, \]

with \( \xi_1 = -t_1 \) and \( \xi_2 = -t_1 - t_2 \). Thus, one obtains, from equation (42):

\[ \hat{S}_{A,B}^{(2)}(\omega_1, \omega_2) = \frac{1}{(\hbar^2)} (1 - e^{-\beta\omega_2}) (\hat{C}_{A,B}(\omega_1, \omega_2) - e^{-\beta(\omega_1 - \omega_2)} \hat{C}_{A,B}(\omega_2, \omega_1 - \omega_2)) \]

\[ = \frac{1}{(\hbar^2)} (1 - e^{-\beta\omega_2}) \hat{\xi}_{A,B}^{(2)}(\omega_1, \omega_2), \]

(43)

where we have defined the generalized spectral density:

\[ \hat{C}_{A,B}^{(2)}(\omega_1, \omega_2) := \hat{C}_{A,B}(\omega_1 - \omega_2, \omega_2) - e^{-\beta(\omega_1 - \omega_2)} \hat{C}_{A,B}(\omega_2, \omega_1 - \omega_2). \]

Let us now exemplify how we can use these result to reconstruct the response of the system starting from observing its fluctuations.

- We start by considering the observable \( B(-t_1 - t_2)B(-t_1)A(0) \) and derive its expectation value \( C_{A,B}(-t_1, -t_1 - t_2) = \text{Tr} \{ B(-t_1 - t_2)B(-t_1)A(0)\rho^{(0)} \} \).
- We then compute the complex conjugate of the two-dimensional Fourier transform of \( C_{A,B}(t_1, t_2) \) and obtain \( \hat{C}_{A,B}(\omega_1 - \omega_2, \omega_2) \).
- Using equation (44), we construct \( \hat{\xi}_{A,B}^{(2)}(\omega_1, \omega_2) \) and, eventually, using equation (43), we obtain \( S_{A,B}^{(2)}(\omega_1, \omega_2) \).
- Furthermore, we plug \( \hat{\xi}_{A,B}^{(2)}(\omega_1, \omega_2) \) into equation (23) and derive, via a double convolution integral, the quantity \( \Delta_{A,B}^{(2)}(\omega_1, \omega_2) \).
- Finally, using the definition given in equation (22), we eventually obtain \( \chi_{A,B}^{(2)}(\omega_1, \omega_2) \), which contains the complete information on the second order response of the system.
Therefore, linking the statistical properties of the fluctuations of the system to its response to external perturbations requires linear changes of variables, simple algebraic sums and multiplications, and a multiple convolution integral. These operations, albeit cumbersome, can be easily implemented numerically.

5.3. Equilibrium correlation functions: third order

We hereby present the explicit calculations for the third order quantities. As easily seen, the number of terms becomes almost unmanageable, but in section 5.4 we propose a general formula. We have:

\[
S_{A,B}^{(3)}(-t_1, -t_2, -t_3) = R_{A,B}^{(3)}(-t_1, -t_1 - t_2, -t_1 - t_2 - t_3) \\
= -\frac{1}{(i\hbar)^3} \langle B(-t_1 - t_2 - t_3), [B(-t_1 - t_2), [B(-t_1), A(0)]] \rangle_0 \\
= -\frac{1}{(i\hbar)^3} (C_{A,B}(-t_1, -t_1 - t_2, -t_1 - t_2 - t_3) \\
- C_{A,B}(-t_1 - t_2, -t_1 - t_2 - t_3, -t_1 - \tau) \\
- C_{A,B}(-t_1, -t_1 - t_2 - t_3, -t_1 - t_2 - \tau) \\
+ C_{A,B}(-t_1 - t_2 - t_3, -t_1 - t_2 - \tau, -t_1 - \tau) \\
- C_{A,B}(-t_1, -t_1 - t_2 - t_3 - \tau, -t_1 - t_2 - \tau) \\
- C_{A,B}(-t_1 - t_1 - t_2 - t_3 - \tau, -t_1 - t_2 - \tau, -t_1 - \tau))
\]

(45)

where we have defined the four-time correlation function \(C_{A,B}(t_1, t_2, t_3) = \langle B(t_3)B(t_2)B(t_1)A(0) \rangle_0\). Similarly to what was obtained for the second order terms, we have that:

\[
\mathcal{C}_{A,B}(\omega_1 - \omega_2, \omega_2 - \omega_3, \omega_3) = \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} e^{-i(\omega_1 t_1 + \omega_2 t_2)} \\
\times C_{A,B}(-t_1 - t_1 - t_2 - t_1 - t_2 - t_3) \, dt_1 \, dt_2 \, dt_3
\]

(46)

Thus, from equation (45) one finally obtains:

\[
\tilde{S}_{A,B}^{(3)}(\omega_1, \omega_2, \omega_3) = -\frac{e^3}{(i\hbar)^3} (1 - e^{-\beta \omega_3}) (\hat{C}_{A,B}(\omega_1 - \omega_2, \omega_2 - \omega_3, \omega_3) \\
- e^{-\beta(\omega_1 - \omega_2)} \hat{C}_{A,B}(\omega_2 - \omega_3, \omega_3, \omega_1 - \omega_2) \\
- e^{-\beta(\omega_2 - \omega_3)} \hat{C}_{A,B}(\omega_1 - \omega_2, \omega_3, \omega_2 - \omega_3) \\
+ e^{-\beta(\omega_1 - \omega_2)} e^{-\beta(\omega_2 - \omega_3)} \hat{C}_{A,B}(\omega_3, \omega_2 - \omega_3, \omega_1 - \omega_2))
\]

\[
= -\frac{1}{(i\hbar)^3} (1 - e^{\beta \omega_3}) \hat{C}_{A,B}^{(3)}(\omega_1, \omega_2, \omega_3)
\]

(47)

where we have defined the function

\[
\hat{C}_{A,B}^{(3)}(\omega_1, \omega_2, \omega_3) := \hat{C}_{A,B}(\omega_1 - \omega_2, \omega_2 - \omega_3, \omega_3) - e^{-\beta(\omega_1 - \omega_2)} \hat{C}_{A,B}(\omega_2 - \omega_3, \omega_3, \omega_1 - \omega_2) \\
- e^{-\beta(\omega_2 - \omega_3)} \hat{C}_{A,B}(\omega_1 - \omega_2, \omega_3, \omega_2 - \omega_3) + e^{-\beta(\omega_1 - \omega_2)} \\
\times e^{-\beta(\omega_2 - \omega_3)} \hat{C}_{A,B}(\omega_3, \omega_2 - \omega_3, \omega_1 - \omega_2).
\]

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5.4. Equilibrium correlation functions: general formula

The results obtained at the lower orders of the expansion pave the way for a generalization of the explicit formulas detailed above. To this aim, let us define the $n$-time correlation function $C_{A,B}(t_1, t_2, \ldots, t_n) = \langle B(t_n) \cdots B(t_2) B(t_1) A(0) \rangle_0$. Then, for a given $n$, the function $\hat{C}_{A,B}(\omega_1, \cdots, \omega_n)$ attains the structure:

$$\hat{C}_{A,B}(\omega_1, \cdots, \omega_n) = \sum_{m=0}^{n-1} (-1)^m e^{-\beta \hbar \sum_{k=1}^{m} \omega_k} \times \sum_{j_m=m}^{n-1} \sum_{j_{m-1}=1}^{j_m-1} \cdots \sum_{j_1=1}^{j_2-1} \hat{C}_{A,B}(\tilde{\omega}_1, \cdots, \tilde{\omega}_n, \tilde{\omega}_{j_m}, \cdots, \tilde{\omega}_{j_1}),$$

with

$$\tilde{\omega}_k = \begin{cases} \omega_k - \omega_{k+1}, & \text{for } k \in [1, n); \\ \omega_k, & \text{for } k = n. \end{cases}$$

For any $m \in [0, n-1]$, the sums on the right-hand side of equation (48) yield $(n-1)!/m!(n-m-1)!$ terms (corresponding to all possible combinations of time-ordered equilibrium correlation functions), and it is intended, in our notation, that the term corresponding to $m = 0$ yields $\hat{C}_{A,B}(\tilde{\omega}_1, \cdots, \tilde{\omega}_n)$. The various terms in the summation on the right hand side of equation (48) are obtained by permuting the $n$ arguments of the function $\hat{C}_{A,B}$. See equations (44) and (47) for the second and third order cases, respectively. The function $\hat{S}_{A,B}(\omega_1, \cdots, \omega_n)$ generalizes, to an arbitrary order, the spectral density $\hat{C}_{A,B}(\omega_1)$ appearing in equation (41). In fact, the function $\hat{S}_{A,B}(\omega_1, \cdots, \omega_n)$ is easily derived from equation (48) and reads:

$$\hat{S}_{A,B}(\omega_1, \cdots, \omega_n) = \left(\frac{-1}{i\hbar}\right)^n (1 - e^{-\beta \hbar \omega_n}) \hat{C}_{A,B}(\omega_1, \cdots, \omega_n).$$

As described in section 5.2, dedicated to the second order, it is possible to define an experimental procedure for deducing the response of the system from the spectral properties of the observable $C_{A,B}(t_1, t_2, \ldots, t_n)$ through a cumbersome, yet straightforward, set of operations.

6. Conclusions

The FDT represents a milestone in the endeavor towards a comprehensive theory aimed at connecting the internal fluctuations of a system to its response to external forcings. The seminal formulation proposed by Kubo [6] addressed linear deviations from equilibrium, and has found a vast range of applications in many fields of natural sciences. Recent investigations [16, 17, 25, 27] have tried to extend the FDT outside of the original domain by focusing on linear deviations from nonequilibrium steady states in the framework of Axiom A dynamical systems. It has been underlined that when the unperturbed invariant measure is singular with respect to Lebesgue, as usually the case in deterministic dissipative systems, a novel term arises, as shown by Ruelle [16], which seems to prevent an immediate extension of the FDT around a nonequilibrium steady state, although recent
works suggest the possibility of practically extending the range of validity of FDT for the majority of cases of interest in physics [27]. Nonetheless, a general response theory can be formulated also in this case [36, 16, 26], and can be successfully framed in terms of frequency-dependent susceptibilities at all orders of nonlinearity [20].

In this work, instead, we have partly pursued a different approach, with the goal of highlighting the strong link between causality and the possibility of connecting fluctuations and response, both at the linear and nonlinear level. We have first shown, in a rather general setting, how the formalism of the Ruelle response theory can be used to derive in a novel way Kramers–Kronig relations connecting the real and imaginary part of the Fourier transforms of the $n$th order Green function, i.e. the susceptibility $\chi^{(n)}(\omega_1, \ldots, \omega_n)$. Moreover, we have extended the Kramers–Kronig theory by showing that the application of multiple convolution integrals allows one to derive the susceptibility from the Fourier transform of corresponding response function $\hat{S}^{(n)}(\omega_1, \ldots, \omega_n)$ (see section 3). In this derivation, we shed light on the role of the causality principle (embodied in the $\Theta$ functions forming the definition of the Green function, see equation (18)) and of the time symmetries of the response function. Thus, equations (21) and (23) represent a first, very general, result.

Moreover, in the second part of the work, we have focused on systems whose invariant measure is absolutely continuous with respect to Lebesgue and have written a formal extension of the FDT to all orders of nonlinearity. We have eventually discussed in detail the case of a (classical or quantum) Hamiltonian system perturbed by an external field, described by the operator $B(t)$, from its equilibrium state, given in terms of the statistical density operator $\rho^{(0)}$. The idea underlying our approach was preliminarily proposed in [39] in the context of classical Hamiltonian systems. Then, by resorting to a compact general expression available for the nonlinear Green function, we have derived a link between the statistical properties of the equilibrium fluctuations, incorporated in the generalized spectral density $\hat{C}^{(n)}_{A,B}(\omega_1, \ldots, \omega_n)$, and the response, related to the function $\chi^{(n)}(\omega_1, \ldots, \omega_n)$ at an arbitrary order of nonlinearity. In particular, we have provided an exact expression for the generalized spectral density, equation (48), which, supplemented with equations (21) and (23), allows one to establish a suitable extension of the FDT for nonlinear processes. In the appendix we provide some details on how one can connect the response of a system perturbed from the canonical ensemble to dissipation, by showing that the imaginary part of the susceptibility at all orders of nonlinearity is related to the power dissipated in the system if we select as observable the physical quantity conjugated to the external field.

Moreover, we note that our method resembles the approach discussed in [40], where a compact stochastic version of a generalized FDT is accomplished by means of a perturbation theory around a reference equilibrium state, equipped with detailed balance dynamics. Further connections between the two perturbation theories, employed, respectively, in the deterministic and in the stochastic settings, would be worth investigating.

While the FDT has an especially compact structure in the linear case, in the nonlinear case the derivation of the susceptibility of the system from the observation of suitably defined correlations requires linear changes of variables, simple algebraic sums and multiplications, and a multiple convolution integral. These operations are lengthy but overall trivial and, in principle, of easy implementation. The results presented in
Beyond the linear fluctuation-dissipation theorem: the role of causality

this paper constitute a general theoretical embedding for the analysis of the linear and nonlinear response to perturbations of a physical system close to equilibrium, and extends some results of the optical literature to a much more general setting. At this stage, it is not clear whether the nonlinear extension of the FDT presented here could have relevant practical consequences at the theoretical, experimental, or modeling level, but this might well be the case. This is analogous to what was experienced in the case of optics, where the rather intricate expressions of the nonlinear optical susceptibilities later became fundamental tools for understanding a vast set of nonlinear optical phenomena [8, 9], and where the rather abstract Kramers–Kronig relations have proved to be crucial instruments for reconstructing and interpreting spectroscopic results [11]. In order to assess this, one should perform detailed calculations on specific physical models and test how useful, in any sense, are the consistency relations derived here for understanding the statistical properties of the investigated model. This task is beyond the scope of the present paper, where we want to show the feasibility of extending the FDT to nonlinear phenomena, and will be the object of future investigations.

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Appendix. Dissipation and susceptibility

It is possible to link the imaginary part of the susceptibility to the time-integrated value of a quantity, which, in the case of Hamiltonian systems in contact with a thermal bath and in the special context of linear processes, is related to the energy dissipation (and consequent entropy production) of the system as a result of the interaction with the perturbative field. Hereby, we wish to extend this result in a more general context. We follow the formalism presented by Reichl [35]. We then consider the quantity $P^{(n)}(t) = -\overline{T}(t) \cdot d/dt \rho_{_1}^{(n)}(A)$, where $P(t)$ is a generalized power absorption of the system associated with the interaction between the time-varying field $T(t)$ and the conjugated observable $A$. We can rewrite $P(t)$ as follows:

$$P^{(n)}(t) = -\frac{1}{(2\pi)^2} \int d\omega d\nu d\omega_1 \cdots d\omega_1 \hat{T}(\omega) \exp[-i\omega t]$$
$$\times \frac{d}{dt} \exp[-i\nu t] \chi^{(n)}(\omega_1, \ldots, \omega_n) \hat{T}(\omega_1) \cdots \hat{T}(\omega_n) \delta \left( \nu - \sum_{j=1}^{n} \omega_j \right)$$

(A.1)

$$P^{(n)}(t) = \frac{1}{(2\pi)^2} \int d\omega d\omega_1 \cdots d\omega_1 \hat{T}(\omega) \exp[-i\omega t] \left( i \sum_{j=1}^{n} \omega_j \right)$$
$$\times \exp \left[ -i \sum_{j=1}^{n} \omega_j t \right] \chi^{(n)}(\omega_1, \ldots, \omega_n) \hat{T}(\omega_1) \cdots \hat{T}(\omega_n).$$

(A.2)
We integrate $P^{(n)}(t)$ over all times:

$$\int_{-\infty}^{\infty} dt P^{(n)}(t) = \int d\omega_{1} \ldots d\omega_{1} \hat{T} \left( -\sum_{j=1}^{n} \omega_{j} \right) \left( i \sum_{j=1}^{n} \omega_{j} \right) \times \chi^{(n)}(\omega_{1}, \ldots, \omega_{n}) \hat{T}(\omega_{1}) \cdots \hat{T}(\omega_{n}),$$

(A.3)

and derive that the total power absorption at order $n$ comes from coupling the response at frequency $i \sum_{j=1}^{n} \omega_{j}$ with the incoming field at the opposite frequency. Therefore, the larger the band of the time modulation $T(t)$, the easier it will be to find matching conditions on the frequency. Since $T(t)$ is a real function, we have that $T(\omega) = (T(\omega))^*$. Therefore, since $P(t)$ is a real function, we derive that:

$$\int_{-\infty}^{\infty} dt P^{(n)}(t) = - \int d\omega_{1} \ldots d\omega_{1} \left( \sum_{j=1}^{n} \omega_{j} \right) \text{Im} \{ \chi^{(n)}(\omega_{1}, \ldots, \omega_{n}) \} \times \hat{T}(\omega_{1}) \cdots \hat{T}(\omega_{n}) \hat{T} \left( -\sum_{j=1}^{n} \omega_{j} \right),$$

(A.4)

which proves that at all orders of nonlinearity, the imaginary part of the susceptibility describes the power dissipation of the system as defined by $P^{(n)}(t) = -T(t) \cdot d/dt \rho^{(n)}(t)$. In the special case of impulsive perturbations, so that $T(t) = T_{0} \delta(t) \rightarrow \hat{T}(\omega) = T_{0}$, we have:

$$\int_{-\infty}^{\infty} dt P^{(n)}(t) = - \int d\omega_{1} \ldots d\omega_{1} \left( \sum_{j=1}^{n} \omega_{j} \right) \text{Im} \{ \chi^{(n)}(\omega_{1}, \ldots, \omega_{n}) \} T_{0}^{n+1}. \quad (A.5)$$

One must note that in the case of a non-continuum spectrum time modulation $T(t)$—e.g. when $T(t)$ is constituted by $2m$ frequency components (positive and negative)—contributions to the absorption at $n$th order will come only from the generated terms where the sum of $n$ frequencies chosen, possibly with repetition, among the $2m$ frequencies of $T(t)$ match one of the $2^{m}$ contributions to the absorption at $m$ frequencies of $T(t)$ itself. In particular, in the case of a monochromatic input $T(t)$, no absorption will take place, e.g., at all even orders of nonlinearity.

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