

New Langevin and Gradient Thermostats for Rigid Body Dynamics

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We introduce two new thermostats, one of Langevin type and one of gradient (Brownian) type, for rigid body dynamics. We formulate rotation using the quaternion representation of angular coordinates; both thermostats preserve the unit length of quaternions. The Langevin thermostat also ensures that the conjugate angular momenta stay within the tangent space of the quaternion coordinates, as required by the Hamiltonian dynamics of rigid bodies. We have constructed three geometric numerical integrators for the Langevin thermostat and one for the gradient thermostat. The numerical integrators reflect key properties of the thermostats themselves. Namely, they all preserve the unit length of quaternions, automatically, without the need of a projection onto the unit sphere. The Langevin integrators also ensure that the angular momenta remain within the tangent space of the quaternion coordinates. The Langevin integrators are quasi-symplectic and of weak order two. The numerical method for the gradient thermostat is of weak order one. Its construction exploits ideas of Lie-group type integrators for differential equations on manifolds. We numerically compare the discretization errors of the Langevin integrators, as well as the efficiency of the gradient integrator compared to the Langevin ones when used in the simulation of rigid TIP4P water model with smoothly truncated electrostatic interactions. We observe that the gradient integrator is computationally less efficient than the Langevin integrators. We also compare the relative accuracy of the Langevin integrators in evaluating various static quantities and give recommendations as to the choice of an appropriate integrator.

Keywords. stochastic differential equations, weak approximation, ergodic limits, stochastic geometric integrators, Langevin equations

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I. INTRODUCTION

In most molecular simulations it is desirable to specify and keep constant the temperature of the simulated system. This is typically achieved by designing a system evolution which samples from the NVT ensemble (Gibbs measure). Within Monte Carlo methods, this is done by acceptance/rejection of trial moves (random displacements of particle positions) according to the Metropolis criterion (see, for example, Refs. 1 and 2 and references therein). In molecular dynamics (MD) simulations, the thermostating is achieved either deterministically (e.g. Nosé-Hoover thermostats), through coupling the system to additional degrees of freedom representing a thermal bath^{1,3}, or by a combination of damping and random perturbation of the motion formulated as a stochastic Langevin equation^{2,4-6}. A combination of the deterministic and stochastic approaches is also possible⁷⁻⁹.

A particular advantage of the Langevin approach is that each degree of freedom of the sys-

tem can be thermostated independently, without having to rely on the efficient energy exchange between different degrees of freedom, which is necessary when using dynamic thermostating. Good energy exchange is particularly hard to achieve between components of the system which evolve on different time scales (i.e., fast-slow separation of degrees of freedom). For Langevin equations, it is easier to ensure and to prove ergodicity (with the Gibbsian invariant measure) of the thermostat.

Langevin thermostats are also useful for models of dilute molecules in which the solvent is treated implicitly⁴. In the absence of thermostating, isolated molecules would move ballistically and the energy of the solute would be conserved. Augmenting the Hamiltonian dynamics of the solute with damping and noise leads to diffusive motion and couples the simulated molecules to a thermal reservoir, mimicking some of the effects of a solvent.

In systems which contain rigid bodies, Langevin or gradient approaches need to be developed for thermostating rotational degrees of freedom. In our previous work⁵, Langevin dynamics were proposed for rotational degrees of freedom based on the quaternion representation of rotational dynamics of Miller III *et al.*¹⁰ Using the operator splitting approach, two different weak 2nd-order (i.e., with

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2nd-order convergence of approximate averages to the exact ones; see further details on stochastic numerics, for example, in Refs. 6 and 11) methods were presented and tested. They were combined with either Langevin or gradient dynamics for the translational degrees of freedom. The resulting numerical methods were tested on a variant of the popular TIP4P rigid model of water. Subsequently, this method was applied to simulate a coarse-grained, implicit-solvent model of DNA in a range of contexts.^{12–15}

In this work we first revise the Langevin thermostat for rigid body dynamics proposed in Ref. 5. The thermostat from Ref. 5 automatically preserves the unit length of quaternions but does not keep the angular momenta conjugate to the quaternion coordinates on the tangent space, as required by the Hamiltonian dynamics of rigid bodies. As we show here, this non-physical behaviour of the thermostat does not affect evaluation of quantities of physical interest; it can, however, introduce rounding errors in numerical integration. The new Langevin thermostat proposed in this paper does not have this deficiency. For this new thermostat, we construct three geometric integrators (Langevin A, B and C) of weak order two. Langevin A and B are related to Langevin A and B proposed in Ref. 5. We also introduce a new Langevin C integrator, whose performance is similar to Langevin A with respect to the size of the leading terms in the discretization errors but, like Langevin B, it can be used with large values of the friction parameters (i.e. approaching the overdamped limit). Our new approach also highlights several simplifications in construction of integrators, eliminating the need for explicit matrix exponentials and Cholesky decompositions, which were required in Ref. 5. Further, we propose a new gradient (Brownian) thermostat for rigid body dynamics and construct a 1st-order geometric integrator for it. Both the gradient thermostat and the numerical scheme for it preserve the unit length of quaternions. We perform numerical comparison of the proposed Langevin and gradient thermostats and of the derived numerical integrators. The numerical tests demonstrate that the Langevin thermostat and its numerical integration by Langevin A or Langevin C constitute a powerful numerical technique for computing NVT ensemble averages for systems which contain rigid bodies.

The rest of the paper is organised as follows. In Section II we explicitly formulate the model of a molecular system with rotational degrees of freedom in quaternion representation, recalling and clarifying previous results from Ref. 5. A revised Langevin thermostat for rigid body dynamics is introduced in Section III and a new gradient (Brownian) thermostat is introduced in Section IV. In Section V we derive numerical methods

for the thermostats of Sections III and IV: revised Langevin A and B integrators, new Langevin C, and a numerical method for the gradient thermostat. In Section VI we present results of numerical experiments with the proposed numerical integrators applied to the system of rigid water molecules described by a screened TIP4P model interaction potential. Comparative performance of the thermostats and numerical methods for them is discussed in Section VII.

II. PRELIMINARIES

We consider a system of n rigid three-dimensional molecules described by the center-of-mass coordinates $\mathbf{r} = (r^{1\top}, \dots, r^{n\top})^\top \in \mathbb{R}^{3n}$, $r^j = (r_1^j, r_2^j, r_3^j)^\top \in \mathbb{R}^3$, and the rotational coordinates in the quaternion representation $\mathbf{q} = (q^{1\top}, \dots, q^{n\top})^\top$, $q^j = (q_0^j, q_1^j, q_2^j, q_3^j)^\top$, such that $|q^j| = 1$, i.e., $q^j \in \mathbb{S}^3$, which is the three-dimensional unit sphere with center at the origin. We use standard matrix notations, and “ \top ” denotes transpose. For further background on the quaternion representation of rigid body dynamics, see, for example, Refs. 16–18.

Following Ref. 10, we write the system Hamiltonian in the form

$$H(\mathbf{r}, \mathbf{p}, \mathbf{q}, \boldsymbol{\pi}) = \frac{\mathbf{p}^\top \mathbf{p}}{2m} + \sum_{j=1}^n \sum_{l=1}^3 V_l(q^j, \pi^j) + U(\mathbf{r}, \mathbf{q}), \quad (1)$$

where $\mathbf{p} = (p^{1\top}, \dots, p^{n\top})^\top \in \mathbb{R}^{3n}$, $p^j = (p_1^j, p_2^j, p_3^j)^\top \in \mathbb{R}^3$, are the center-of-mass momenta conjugate to \mathbf{r} ; $\boldsymbol{\pi} = (\pi^{1\top}, \dots, \pi^{n\top})^\top$, $\pi^j = (\pi_0^j, \pi_1^j, \pi_2^j, \pi_3^j)^\top$ are the angular momenta conjugate to \mathbf{q} such that $q^{j\top} \pi^j = 0$, i.e., $\pi^j \in T_{q^j} \mathbb{S}^3$, which is the tangent space of \mathbb{S}^3 at q^j ; and $U(\mathbf{r}, \mathbf{q})$ is the potential interaction energy. The second term in (1) represents the rotational kinetic energy of the system with

$$V_l(q, \pi) = \frac{1}{8I_l} [\pi^\top S_l q]^2, \quad l = 1, 2, 3, \quad (2)$$

where the three constant 4-by-4 matrices S_l are

$$S_1 = \begin{bmatrix} 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 \end{bmatrix}, \quad S_2 = \begin{bmatrix} 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix},$$

$$S_3 = \begin{bmatrix} 0 & 0 & 0 & -1 \\ 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix},$$

and I_l are the principal moments of inertia of the rigid molecule. We also introduce $S_0 = \text{diag}(1, 1, 1, 1)$, the diagonal matrix $D =$

diag(0, 1/I₁, 1/I₂, 1/I₃), and the orthogonal matrix:

$$S(q) = [S_0q, S_1q, S_2q, S_3q] \\ = \begin{bmatrix} q_0 & -q_1 & -q_2 & -q_3 \\ q_1 & q_0 & -q_3 & q_2 \\ q_2 & q_3 & q_0 & -q_1 \\ q_3 & -q_2 & q_1 & q_0 \end{bmatrix}. \quad (3)$$

Note that $q^\top S(q) = (1, 0, 0, 0)$ and $q^\top S(q)D = (0, 0, 0, 0)$. The rotational kinetic energy of a molecule can be expressed in terms of the matrices D and S as follows:

$$\sum_{l=1}^3 V_l(q, \pi) = \frac{1}{8} \pi^\top S(q)DS^\top(q)\pi.$$

We assume that $U(\mathbf{r}, \mathbf{q})$ is a sufficiently smooth function. Let $f^j(\mathbf{r}, \mathbf{q}) = -\nabla_{\mathbf{r},j}U(\mathbf{r}, \mathbf{q}) \in \mathbb{R}^3$, which is the translational force acting on the centre of mass of molecule j , and $F^j(\mathbf{r}, \mathbf{q}) = -\tilde{\nabla}_{q^j}U(\mathbf{r}, \mathbf{q}) \in T_{q^j}\mathbb{S}^3$, which is the rotational force. Note that, while $\nabla_{\mathbf{r},j}$ is the gradient in the Cartesian coordinates in \mathbb{R}^3 , $\tilde{\nabla}_{q^j}$ is the directional derivative¹⁹ tangent to the three dimensional sphere \mathbb{S}^3 implying that

$$\mathbf{q}^\top \tilde{\nabla}_{q^j}U(\mathbf{r}, \mathbf{q}) = 0. \quad (4)$$

For a discussion of the evaluation of $\tilde{\nabla}_{q^j}$, which can also be calculated via Cartesian torques, see Appendix A.

The derivatives of (1) with respect to coordinates and momenta determine the dynamics prior to incorporation of damping and noise. In particular, we note

$$\sum_{l=1}^3 \nabla_\pi V_l(q, \pi) = \frac{1}{4} \sum_{l=1}^3 \frac{1}{I_l} S_l q [S_l q]^\top \pi \quad (5) \\ = \frac{1}{4} S(q)DS^\top(q)\pi, \\ \sum_{l=1}^3 \nabla_q V_l(q, \pi) = -\frac{1}{4} \sum_{l=1}^3 \frac{1}{I_l} [\pi^\top S_l q] S_l \pi.$$

The following Langevin thermostat for rigid body dynamics, derived in Ref. 5, is written here

in a more explicit form:

$$dR^j = \frac{P^j}{m} dt, \quad R^j(0) = r^j, \quad (6)$$

$$dP^j = f^j(\mathbf{R}, \mathbf{Q}) dt \\ - \gamma P^j dt + \sqrt{\frac{2m\gamma}{\beta}} dw^j(t), \quad P^j(0) = p^j,$$

$$dQ^j = \frac{1}{4} S(Q^j)DS^\top(Q^j)\Pi^j dt, \quad Q^j(0) = q^j, \quad (7) \\ |q^j| = 1,$$

$$d\Pi^j = \frac{1}{4} \sum_{l=1}^3 \frac{1}{I_l} (\Pi^j{}^\top S_l Q^j) S_l \Pi^j dt + F^j(\mathbf{R}, \mathbf{Q}) dt \\ - \Gamma J(Q^j)\Pi^j dt + \sqrt{\frac{2M\Gamma}{\beta}} dW^j(t), \\ \Pi^j(0) = \pi^j, \quad j = 1, \dots, n,$$

where $(\mathbf{w}^\top, \mathbf{W}^\top)^\top = (w^{1\top}, \dots, w^{n\top}, W^{1\top}, \dots, W^{n\top})^\top$ is a $(3n+4n)$ -dimensional standard Wiener process with $w^j = (w_1^j, w_2^j, w_3^j)^\top$ and $W^j = (W_0^j, W_1^j, W_2^j, W_3^j)^\top$; $\gamma \geq 0$ and $\Gamma \geq 0$ are the friction coefficients for the translational and rotational motions, respectively, measured in units of inverse time, which control the strength of coupling of the system to the ‘‘heat bath’’ with the inverse temperature $\beta = 1/(k_B T) > 0$. In the above equations we also use

$$J(q) = \frac{M}{4} S(q)DS^\top(q), \quad M = \frac{4}{\sum_{l=1}^3 \frac{1}{I_l}}. \quad (8)$$

Note that $\text{Tr} J(q) = 1$.

It was shown in Ref. 5 that the solution of (6)-(7) preserves the quaternion length

$$|Q^j(t)| = 1, \quad j = 1, \dots, n, \quad \text{for all } t \geq 0, \quad (9)$$

i.e., there is no need to prescribe an additional algebraic constraint on (6)-(7). At the same time, the condition $q^j{}^\top \pi^j = 0$, which is satisfied by the deterministic Hamiltonian dynamics of a rigid body¹⁰, is not preserved by the solution of the stochastic thermostat (6)-(7) as explained below.

Let us introduce $\Omega^j(t) := \frac{1}{2}(Q^j(t))^\top \Pi^j(t)$. We see that $2\Omega^j(t)$ represents the component of the angular momenta $\Pi^j(t)$ parallel to the rotational coordinates $Q^j(t)$. Recall that $Q^j(t)$, being unit quaternions, are constrained to unit spheres; therefore, as in the deterministic case, the quantities $\Omega^j(t)$ should be zero from the physical point of view, i.e., $\Pi^j(t) \in T_{Q^j}\mathbb{S}^3$. However, the Langevin thermostat (6)-(7) does not keep $\Pi^j(t)$ on the tangent space $T_{Q^j}\mathbb{S}^3$. Indeed, by direct calculations we obtain

$$d\Omega^j = \frac{1}{2} \sqrt{2M\Gamma/\beta} Q^j{}^\top dW^j(t), \quad j = 1, \dots, n. \quad (10)$$

Consequently, if $\Omega^j(0) = 0$ then $E\Omega^j(t) = 0$ and $E[\Omega^j(t)]^2 = M\Gamma t/(2\beta)$. Nevertheless, the presence in (6)-(7) of the component of $\Pi^j(t)$ parallel to $Q^j(t)$ does not affect evaluation of quantities of physical interest (see Appendix B), and hence they are computed correctly using (6)-(7). At the same time, unbounded growth of the variance of this non-physical component with time can introduce rounding errors in numerical integration of this thermostat. The new thermostat (see Section III) does not have this deficiency.

III. NEW LANGEVIN THERMOSTAT FOR RIGID BODY DYNAMICS

As we discussed in the previous section, the Langevin thermostat in Ref. 5 has a non-zero value for the non-physical component in the angular momenta $\Pi^j(t)$ parallel to the rotational coordinates $Q^j(t)$, which can introduce rounding errors in numerical integration of this thermostat. Here we propose a new stochastic thermostat which preserves both the unit length of quaternions and the condition $(Q^j(t))^\top \Pi^j(t) = 0$, i.e., $\Pi^j(t) \in T_{Q^j} \mathbb{S}^3$. This thermostat takes the form

$$dR^j = \frac{P^j}{m} dt, \quad R^j(0) = r^j, \quad (11)$$

$$dP^j = f^j(\mathbf{R}, \mathbf{Q}) dt - \gamma P^j dt + \sqrt{\frac{2m\gamma}{\beta}} dw^j(t), \quad P^j(0) = p^j,$$

$$dQ^j = \frac{1}{4} S(Q^j) D S^\top(Q^j) \Pi^j dt, \quad Q^j(0) = q^j, \quad (12)$$

$$|q^j| = 1,$$

$$d\Pi^j = \frac{1}{4} \sum_{l=1}^3 \frac{1}{I_l} (\Pi^{j\top} S_l Q^j) S_l \Pi^j dt + F^j(\mathbf{R}, \mathbf{Q}) dt - \Gamma J(Q^j) \Pi^j dt + \sqrt{\frac{2M\Gamma}{\beta}} \sum_{l=1}^3 S_l Q^j dW_l^j(t),$$

$$\Pi^j(0) = \pi^j, \quad q^{j\top} \pi^j = 0, \quad j = 1, \dots, n,$$

where $(\mathbf{w}^\top, \mathbf{W}^\top)^\top = (w^1, \dots, w^n, W^1, \dots, W^n)^\top$ is a $(3n+3n)$ -dimensional standard Wiener process with $w^j = (w_1^j, w_2^j, w_3^j)^\top$ and $W^j = (W_1^j, W_2^j, W_3^j)^\top$; the rest of the notation is as in (6)-(7).

It is not difficult to show that the new thermostat (11)-(12) possesses the following properties:

- The Ito interpretation of the system of stochastic differential equations (SDEs) (11)-(12) coincides with its Stratonovich interpretation.
- As in the case of (6)-(7), the solution of (11)-(12) preserves the quaternion length (cf. (9)).

- The solution of (11)-(12) automatically preserves the following constraint:

$$\mathbf{Q}^\top(t) \mathbf{\Pi}(t) = 0, \quad \text{for all } t \geq 0. \quad (13)$$

- Assume that the solution $X(t) = (\mathbf{R}^\top(t), \mathbf{P}^\top(t), \mathbf{Q}^\top(t), \mathbf{\Pi}^\top(t))^\top$ of (11)-(12) is an ergodic process^{20,21} on

$$\mathbb{D} = \{x = (\mathbf{r}^\top, \mathbf{p}^\top, \mathbf{q}^\top, \boldsymbol{\pi}^\top)^\top \in \mathbb{R}^{14n} : |q^j| = 1, q^{j\top} \pi^j = 0, j = 1, \dots, n\}.$$

Then it can be shown that the invariant measure of $X(t)$ is Gibbsian with the density $\rho(\mathbf{r}, \mathbf{p}, \mathbf{q}, \boldsymbol{\pi})$ on \mathbb{D} :

$$\rho(\mathbf{r}, \mathbf{p}, \mathbf{q}, \boldsymbol{\pi}) \propto \exp(-\beta H(\mathbf{r}, \mathbf{p}, \mathbf{q}, \boldsymbol{\pi})), \quad (14)$$

which corresponds to the *NVT* ensemble of rigid bodies, as required.

We note that the old thermostat (6)-(7) required a $7n$ -dimensional Wiener process while the new thermostat (11)-(12) requires a $6n$ -dimensional Wiener process, which is consistent with the number of degrees of freedom in the system.

IV. GRADIENT THERMOSTAT FOR RIGID BODY DYNAMICS

Gradient systems are popular in molecular dynamics for thermostating translational degrees of freedom^{2,6,22} (see also references therein). In Ref. 5 a mixture of a gradient system for the translational dynamics and a Langevin-type equation for the rotational dynamics was suggested. In this Section we propose Brownian dynamics for thermostating rigid body dynamics, i.e., a gradient system for the center-of-mass coordinates and the rotational coordinates in the quaternion representation.

It is easy to verify that

$$\int_{\mathbb{D}_{\text{mom}}} \exp(-\beta H(\mathbf{r}, \mathbf{p}, \mathbf{q}, \boldsymbol{\pi})) d\mathbf{p} d\boldsymbol{\pi} \propto \exp(-\beta U(\mathbf{r}, \mathbf{q})) =: \tilde{\rho}(\mathbf{r}, \mathbf{q}), \quad (15)$$

where $(\mathbf{r}^\top, \mathbf{q}^\top)^\top \in \mathbb{D}' = \{(\mathbf{r}^\top, \mathbf{q}^\top)^\top \in \mathbb{R}^{7n} : |q^j| = 1\}$ and the domain of conjugate momenta $\mathbb{D}_{\text{mom}} = \{(\mathbf{p}^\top, \boldsymbol{\pi}^\top)^\top \in \mathbb{R}^{7n} : \mathbf{q}^\top \boldsymbol{\pi} = 0\}$.

We introduce the gradient system in the form of Stratonovich SDEs:

$$d\mathbf{R} = \frac{v}{m} \mathbf{f}(\mathbf{R}, \mathbf{Q}) dt + \sqrt{\frac{2v}{m\beta}} d\mathbf{w}(t), \quad \mathbf{R}(0) = \mathbf{r}, \quad (16)$$

$$dQ^j = \frac{\Upsilon}{M} F^j(\mathbf{R}, \mathbf{Q}) dt + \sqrt{\frac{2\Upsilon}{M\beta}} \sum_{l=1}^3 S_l Q^j \star dW_l^j(t), \quad (17)$$

$$Q^j(0) = q^j, \quad |q^j| = 1, \quad j = 1, \dots, n,$$

where “ \star ” indicates the Stratonovich form of the SDEs, parameters $\nu > 0$ and $\Upsilon > 0$ control the speed of evolution of the gradient system (16)-(17), $\mathbf{f} = (f^1{}^\top, \dots, f^n{}^\top)^\top$ and the rest of the notation is as in (11)-(12). Note that, unlike in the case of (11)-(12), the Stratonovich and Ito interpretations of the SDEs (16)-(17) do not coincide.

This new gradient thermostat possesses the following properties.

- As in the case of (6)-(7) and (11)-(12), the solution of (16)-(17) preserves the quaternion length (cf. (9)).
- Assume that the solution $X(t) = (\mathbf{R}^\top(t), \mathbf{Q}^\top(t))^\top \in \mathbb{D}'$ of (16)-(17) is an ergodic process²⁰. Then, by the usual means of the stationary Fokker-Planck equation (see Appendix C), one can show that its invariant measure is Gibbsian with the density $\tilde{\rho}(\mathbf{r}, \mathbf{q})$ from (15).

When a thermostat is used only to control the temperature of a simulated system, and not also to mimic the dynamical effects of an implicit solvent, the Langevin thermostat (11)-(12) is suitable for computing both dynamical and static quantities (provided the friction coefficients are relatively small), whereas the gradient thermostat (16)-(17) can be used to compute only static quantities^{2,6} in such systems.

V. NUMERICAL METHODS

In this section we construct geometric integrators for the new Langevin thermostat (11)-(12) (Sections VA-VC) and for the new gradient thermostat (16)-(17) (Section VD). The numerical methods for the Langevin thermostat are based on the splitting technique. It was observed in Ref. 23 that numerical schemes based on different splittings might have considerably different properties. Roughly speaking, Langevin thermostat SDEs (11)-(12) consist of three components: Hamiltonian + damping + noise. The integrator Langevin A is based on the splitting of (11)-(12) into the stochastic Hamiltonian system (Hamiltonian + noise) and the deterministic system of linear differential equations corresponding to the Langevin damping. The other two schemes, Langevin B and C, are based on splitting of (11)-(12) into the deterministic Hamiltonian system and the Ornstein-Uhlenbeck process (damping + noise) using their different concatenations. All three schemes are of weak order 2 and use one evaluation of forces per step. The numerical method for the gradient thermostat (16)-(17) also uses one force evaluation per step, but it is of weak order 1. To preserve the length of quaternions in the

case of numerical integration of (16)-(17), we use ideas of Lie-group type integrators for differential equations on manifolds (see, for example, Ref. 24).

In what follows we assume that (11)-(12) and (16)-(17) have to be solved on a time interval $[0, T]$ and, for simplicity, we use a uniform time discretization with the step $h = T/N$.

In Sections VA-VC we use the mapping $\Psi_{t,l}(q, \pi) : (q, \pi) \mapsto (\mathcal{Q}, \Pi)$ defined by (see, e.g. Refs. 5 and 10):

$$\begin{aligned}\mathcal{Q} &= \cos(\chi_l t)q + \sin(\chi_l t)S_l q, \\ \Pi &= \cos(\chi_l t)\pi + \sin(\chi_l t)S_l \pi,\end{aligned}\tag{18}$$

where

$$\chi_l = \frac{1}{4I_l}\pi^\top S_l q.$$

We also introduce a composite map

$$\Psi_t = \Psi_{t/2,3} \circ \Psi_{t/2,2} \circ \Psi_{t,1} \circ \Psi_{t/2,2} \circ \Psi_{t/2,3}, \tag{19}$$

where “ \circ ” denotes function composition, i.e., $(g \circ f)(x) = g(f(x))$.

A. Geometric integrator Langevin A: revisited

The geometric integrator of this section for solving the new Langevin thermostat (11)-(12) is similar to the proposed in Ref. 5 Langevin A for (6)-(7). It is based on splitting the Langevin system (11)-(12) into the stochastic Hamiltonian system (i.e., (11)-(12) without the damping terms) and the deterministic system of linear differential equations

$$\begin{aligned}\dot{\mathbf{p}} &= -\gamma \mathbf{p} \\ \dot{\pi}^j &= -\Gamma J(q^j)\pi^j, \quad j = 1, \dots, n.\end{aligned}\tag{20}$$

We construct a weak 2nd-order quasi-symplectic integrator for the stochastic Hamiltonian system^{11,25} and appropriately concatenate^{11,26} it with the exact solution of (20). The resulting numerical method has the form:

$$\begin{aligned}\mathbf{P}_0 &= \mathbf{p}, \quad \mathbf{R}_0 = \mathbf{r}, \\ \mathbf{Q}_0 &= \mathbf{q} \text{ with } |q^j| = 1, \quad j = 1, \dots, n, \\ \mathbf{\Pi}_0 &= \pi \text{ with } \mathbf{q}^\top \pi = \mathbf{0}, \\ \mathcal{P}_{1,k} &= e^{-\gamma \frac{h}{2}} \mathbf{P}_k, \\ \Pi_{1,k}^j &= e^{-\Gamma J(Q_k^j) \frac{h}{2}} \Pi_k^j, \quad j = 1, \dots, n,\end{aligned}\tag{21}$$

$$\begin{aligned}
\mathcal{P}_{2,k} &= \mathcal{P}_{1,k} + \frac{h}{2} \mathbf{f}(\mathbf{R}_k, \mathbf{Q}_k) + \frac{\sqrt{h}}{2} \sqrt{\frac{2m\gamma}{\beta}} \xi_k \\
\Pi_{2,k}^j &= \Pi_{1,k}^j + \frac{h}{2} F^j(\mathbf{R}_k, \mathbf{Q}_k) \\
&\quad + \frac{\sqrt{h}}{2} \sqrt{\frac{2M\Gamma}{\beta}} \sum_{l=1}^3 S_l \mathbf{Q}_k \eta_k^{j,l}, \\
j &= 1, \dots, n, \\
\mathbf{R}_{k+1} &= \mathbf{R}_k + \frac{h}{m} \mathcal{P}_{2,k},
\end{aligned}$$

$$(Q_{k+1}^j, \Pi_{3,k}^j) = \Psi_h(Q_k^j, \Pi_{2,k}^j), \quad j = 1, \dots, n,$$

$$\begin{aligned}
\Pi_{4,k}^j &= \Pi_{3,k}^j + \frac{h}{2} F^j(\mathbf{R}_{k+1}, \mathbf{Q}_{k+1}) \\
&\quad + \frac{\sqrt{h}}{2} \sqrt{\frac{2M\Gamma}{\beta}} \sum_{l=1}^3 S_l \mathbf{Q}_{k+1} \eta_k^{j,l}, \quad j = 1, \dots, n,
\end{aligned}$$

$$\mathcal{P}_{3,k} = \mathcal{P}_{2,k} + \frac{h}{2} \mathbf{f}(\mathbf{R}_{k+1}, \mathbf{Q}_{k+1}) + \frac{\sqrt{h}}{2} \sqrt{\frac{2m\gamma}{\beta}} \xi_k,$$

$$\begin{aligned}
\mathbf{P}_{k+1} &= e^{-\gamma \frac{h}{2}} \mathcal{P}_{3,k}, \\
\Pi_{k+1}^j &= e^{-\Gamma J(Q_{k+1}^j) \frac{h}{2}} \Pi_{4,k}^j, \quad j = 1, \dots, n, \\
k &= 0, \dots, N-1,
\end{aligned}$$

where $\xi_k = (\xi_{1,k}, \dots, \xi_{3n,k})^\top$ and $\eta_k^{j,l}$, $l = 1, 2, 3$, $j = 1, \dots, n$, with their components being i.i.d. (independent and identically distributed) with the same probability distribution

$$P(\theta = 0) = 2/3, \quad P(\theta = \pm\sqrt{3}) = 1/6. \quad (22)$$

We proved (the proof is not presented here) that the geometric integrator (21)-(22) possesses properties stated in the next proposition. The concept of quasi-symplectic methods is described in Refs. 11 and 26 and also Refs. 5 and 6. The proof of weak convergence order is done by standard arguments based on the general convergence theorem (see p. 100 in Ref. 11).

Proposition V.1 *The numerical scheme (21)-(22) for (11)-(12) is quasi-symplectic, it preserves the structural properties (9) and (13) and it is of weak order two.*

We note that one can choose ξ_k and $\eta_k^{j,l}$, $l = 1, 2, 3$, $j = 1, \dots, n$, so that their components are i.i.d. Gaussian random variables with zero mean and unit variance. In this case the weak order of the scheme remains second as when we use the simple discrete distribution (22). Let us remark in passing that in the case of Gaussian random variables the above scheme also converges in the

mean-square (also called strong) sense¹¹ with order one.

Finally, writing $J(q)$ explicitly in terms of $S(q)$ and D , see (8), reveals that the exponent appearing in (21) is easier to compute than originally suggested in Ref. 5. In particular, explicit evaluation of a matrix exponent is not required:

$$\begin{aligned}
e^{-\Gamma J(q) \frac{h}{2}} &= S(q) e^{-\frac{\Gamma M h}{8} D} S^\top(q) \\
&= \sum_{l=1}^3 e^{-\frac{\Gamma M h}{8 I_l}} S_l q [S_l q]^\top. \quad (23)
\end{aligned}$$

B. Geometric integrator Langevin B: revisited

The geometric integrator of this section for solving the new Langevin thermostat (11)-(12) is similar to the proposed in Ref. 5 Langevin B for (6)-(7). It is based on the following splitting:

$$\begin{aligned}
d\mathbf{P}_I &= -\gamma \mathbf{P}_I dt + \sqrt{\frac{2m\gamma}{\beta}} d\mathbf{w}(t), \\
d\Pi_I^j &= -\Gamma J(q) \Pi_I^j dt + \sqrt{\frac{2M\Gamma}{\beta}} \sum_{l=1}^3 S_l q dW_l^j(t); \quad (24)
\end{aligned}$$

$$\begin{aligned}
d\mathbf{R}_{II} &= \frac{\mathbf{P}_{II}}{m} dt \\
d\mathbf{P}_{II} &= \mathbf{f}(\mathbf{R}_{II}, \mathbf{Q}_{II}) dt, \\
dQ_{II}^j &= \frac{1}{4} S(Q_{II}^j) D S^\top(Q_{II}^j) \Pi_{II}^j dt, \\
d\Pi_{II}^j &= F^j(\mathbf{R}_{II}, \mathbf{Q}_{II}) dt \\
&\quad + \frac{1}{4} \sum_{l=1}^3 \frac{1}{I_l} \left[(\Pi_{II}^j)^\top S_l Q_{II}^j \right] S_l \Pi_{II}^j dt, \\
j &= 1, \dots, n.
\end{aligned} \quad (25)$$

The SDEs (24) have the exact solution:

$$\begin{aligned}
\mathbf{P}_I(t) &= \mathbf{P}_I(0) e^{-\gamma t} + \sqrt{\frac{2m\gamma}{\beta}} \int_0^t e^{-\gamma(t-s)} d\mathbf{w}(s), \\
\Pi_I^j(t) &= e^{-\Gamma J(q)t} \Pi_I^j(0) \\
&\quad + \sqrt{\frac{2M\Gamma}{\beta}} \sum_{l=1}^3 \int_0^t e^{-\Gamma J(q)(t-s)} S_l q dW_l^j(s). \quad (26)
\end{aligned}$$

To construct a method based on the splitting (24)-(25), we take half a step of (24) using (26), one step of the symplectic method for (25) from Ref. 10, and again half a step of (24).

The vector $\int_0^t e^{-\Gamma J(q)(t-s)} S_l q dW_l^j(s)$ in (26) is Gaussian with zero mean and covariance

$$C_l(t; q) = \int_0^t e^{-\Gamma J(q)(t-s)} S_l q (S_l q)^\top e^{-\Gamma J(q)(t-s)} ds.$$

One can show that the covariance matrix $C(t; q)$ of the sum $\sum_{l=1}^3 \int_0^t e^{-\Gamma J(q)(t-s)} S_l q dW_l^j(s)$ is equal to

$$C(t; q) = \frac{2}{M\Gamma} S(q) \Lambda_C(t; \Gamma) S^\top(q),$$

where

$$\begin{aligned} \Lambda_C(t; \Gamma) = & \text{diag}(0, I_1(1 - \exp(-M\Gamma t/(2I_1))), \\ & I_2(1 - \exp(-M\Gamma t/(2I_2))), \\ & I_3(1 - \exp(-M\Gamma t/(2I_3))). \end{aligned}$$

If we introduce a 4×3 -dimensional matrix $\sigma(t, q)$ such that

$$\sigma(t; q) \sigma^\top(t; q) = C(t; q), \quad (27)$$

e.g., $\sigma(t; q)$ with the columns

$$\sigma_l(t; q) = \sqrt{\frac{2}{M\Gamma}} I_l \left(1 - e^{-\frac{M\Gamma t}{2I_l}}\right) S_l q,$$

$l = 1, 2, 3$, then the expression for $\Pi_l^j(t)$ in (26) can be written as

$$\Pi_l^j(t) = e^{-\Gamma J(q)t} \Pi_l^j(0) + \sqrt{\frac{2M\Gamma}{\beta}} \sum_{l=1}^3 \sigma_l(t; q) \chi_l^j,$$

where χ_l^j are independent Gaussian random variables with zero mean and unit variance. We point out a substantial simplification in the calculation of σ relative to the equivalent stage of Langevin B in Ref. 5, which is made evident by the explicit use of the matrix $S(q)$.

Using the above calculations, and simpler (but analogous) procedures for the linear momenta, we obtain the following quasi-symplectic scheme for (11)-(12):

$$\mathbf{P}_0 = \mathbf{p}, \quad \mathbf{R}_0 = \mathbf{r}, \quad \mathbf{Q}_0 = \mathbf{q}, \quad |q^j| = 1, \quad j = 1, \dots, n$$

$$\mathbf{\Pi}_0 = \pi, \quad \mathbf{q}^\top \pi = 0$$

$$\mathcal{P}_{1,k} = \mathbf{P}_k e^{-\gamma h/2} + \sqrt{\frac{m}{\beta}} (1 - e^{-\gamma h}) \xi_k$$

$$\Pi_{1,k}^j = e^{-\Gamma J(Q_k^j) \frac{h}{2}} \Pi_k^j$$

$$+ \sqrt{\frac{4}{\beta}} \sum_{l=1}^3 \sqrt{I_l} \left(1 - e^{-\frac{M\Gamma h}{4I_l}}\right) S_l Q_k^j \eta_k^{j,l}, \quad j = 1, \dots, n, \quad (28)$$

$$\mathcal{P}_{2,k} = \mathcal{P}_{1,k} + \frac{h}{2} \mathbf{f}(\mathbf{R}_k, \mathbf{Q}_k),$$

$$\Pi_{2,k}^j = \Pi_{1,k}^j + \frac{h}{2} F^j(\mathbf{R}_k, \mathbf{Q}_k), \quad j = 1, \dots, n,$$

$$\mathbf{R}_{k+1} = \mathbf{R}_k + \frac{h}{m} \mathcal{P}_{2,k},$$

$$(Q_{k+1}^j, \Pi_{3,k}^j) = \Psi_h(Q_k^j, \Pi_{2,k}^j), \quad j = 1, \dots, n,$$

$$\Pi_{4,k}^j = \Pi_{3,k}^j + \frac{h}{2} F^j(\mathbf{R}_{k+1}, \mathbf{Q}_{k+1}), \quad j = 1, \dots, n,$$

$$\mathcal{P}_{3,k} = \mathcal{P}_{2,k} + \frac{h}{2} \mathbf{f}(\mathbf{R}_{k+1}, \mathbf{Q}_{k+1}),$$

$$\mathbf{P}_{k+1} = \mathcal{P}_{3,k} e^{-\gamma h/2} + \sqrt{\frac{m}{\beta}} (1 - e^{-\gamma h}) \zeta_k,$$

$$\begin{aligned} \Pi_{k+1}^j = & e^{-\Gamma J(Q_{k+1}^j) \frac{h}{2}} \Pi_{4,k}^j \\ & + \sqrt{\frac{4}{\beta}} \sum_{l=1}^3 \sqrt{I_l} \left(1 - e^{-\frac{M\Gamma h}{4I_l}}\right) S_l Q_{k+1}^j \varsigma_k^{j,l}, \end{aligned}$$

$$j = 1, \dots, n,$$

$$k = 0, \dots, N-1,$$

where $\xi_k = (\xi_{1,k}, \dots, \xi_{3n,k})^\top$, $\zeta_k = (\zeta_{1,k}, \dots, \zeta_{3n,k})^\top$ and $\eta_k^j = (\eta_{1,k}^j, \dots, \eta_{3,k}^j)^\top$, $\varsigma_k^j = (\varsigma_{1,k}^j, \dots, \varsigma_{3,k}^j)^\top$, $j = 1, \dots, n$, with their components being i.i.d. random variables with the same law (22).

Properties of the integrator (28), (22) are summarized in the next proposition; proofs, obtainable by standard methods as for Langevin A, are omitted here.

Proposition V.2 *The numerical scheme (28), (22) for (11)-(12) is quasi-symplectic, it preserves (9) and (13) and it is of weak order two.*

We note that in the case of translational degrees of freedom Langevin B coincides with the scheme called ‘OBABO’ in Ref. 23.

C. Geometric integrator: Langevin C

This integrator is based on the same splitting (24)-(25) as Langevin B but using a different concatenation: we take half a step of a symplectic method for (25), one step of (24) using (26), and again half a step of (25). The resulting method

takes the form

$$\begin{aligned}
\mathbf{P}_0 &= \mathbf{p}, \quad \mathbf{R}_0 = \mathbf{r}, \quad \mathbf{Q}_0 = \mathbf{q}, \\
|q^j| &= 1, \quad j = 1, \dots, n, \\
\mathbf{\Pi}_0 &= \pi, \quad \mathbf{q}^\top \pi = 0, \\
\mathcal{P}_{1,k} &= \mathbf{P}_k + \frac{h}{2} \mathbf{f}(\mathbf{R}_k, \mathbf{Q}_k), \\
\Pi_{1,k}^j &= \Pi_k^j + \frac{h}{2} F^j(\mathbf{R}_k, \mathbf{Q}_k), \quad j = 1, \dots, n, \\
R_{1,k} &= \mathbf{R}_k + \frac{h}{2m} \mathcal{P}_{1,k}, \\
(\mathcal{Q}_{1,k}^j, \Pi_{2,k}^j) &= \Psi_{h/2}(\mathcal{Q}_k^j, \Pi_{1,k}^j), \quad j = 1, \dots, n, \\
\mathcal{P}_{2,k} &= \mathcal{P}_{1,k} e^{-\gamma h} + \sqrt{\frac{m}{\beta}} (1 - e^{-2\gamma h}) \xi_k \\
\Pi_{3,k}^j &= e^{-\Gamma J(\mathcal{Q}_{1,k}^j)h} \Pi_{2,k}^j \\
&\quad + \sqrt{\frac{4}{\beta}} \sum_{l=1}^3 \sqrt{I_l} \left(1 - e^{-\frac{M\Gamma h}{2I_l}}\right) S_l \mathcal{Q}_{1,k}^j \eta_k^{j,l}, \\
&\quad j = 1, \dots, n,
\end{aligned} \tag{29}$$

$$\begin{aligned}
\mathbf{R}_{k+1} &= R_{1,k} + \frac{h}{2m} \mathcal{P}_{2,k}, \\
(\mathcal{Q}_{k+1}^j, \Pi_{4,k}^j) &= \Psi_{h/2}(\mathcal{Q}_{1,k}^j, \Pi_{3,k}^j), \quad j = 1, \dots, n,
\end{aligned}$$

$$\begin{aligned}
\mathbf{P}_{k+1} &= \mathcal{P}_{2,k} + \frac{h}{2} \mathbf{f}(\mathbf{R}_{k+1}, \mathbf{Q}_{k+1}), \\
\Pi_{k+1}^j &= \Pi_{4,k}^j + \frac{h}{2} F^j(\mathbf{R}_{k+1}, \mathbf{Q}_{k+1}), \quad j = 1, \dots, n,
\end{aligned}$$

where $\xi_k = (\xi_{1,k}, \dots, \xi_{3n,k})^\top$ and $\eta_k^j = (\eta_{1,k}^j, \dots, \eta_{3,k}^j)^\top$, $j = 1, \dots, n$, with their components being i.i.d. random variables with the same law (22).

Properties of the integrator (29) are summarized in the next proposition (its proof is omitted here).

Proposition V.3 *The numerical scheme (29) for (11)-(12) is quasi-symplectic, it preserves (9) and (13) and it is of weak order two.*

We note that in the case of translational degrees of freedom Langevin C coincides with the scheme called ‘BAOAB’ in Ref. 23, which was shown there to be the most efficient scheme among various types of splittings of translational Langevin equations for systems without rotational degrees of freedom.

D. Numerical scheme for the gradient thermostat

To preserve the length of quaternions in the case of numerical integration of the gradient sys-

tem (16)-(17), we use ideas of Lie-group type integrators for deterministic ordinary differential equations on manifolds (see, e.g., Ref. 24 and the references therein and also Ref. 27 were such ideas where used for constructing mean-square approximations for Stratonovich SDEs). The main idea is to rewrite the components Q^j of the solution to (16)-(17) in the form $Q^j(t) = \exp(Y^j(t))Q^j(0)$ and then solve numerically the SDEs for the 4×4 -matrices $Y^j(t)$. To this end, we introduce the 4×4 skew-symmetric matrices:

$$\begin{aligned}
\mathbb{F}_j(\mathbf{r}, \mathbf{q}) &= F^j(\mathbf{r}, \mathbf{q})q^{j\top} - q^j(F^j(\mathbf{r}, \mathbf{q}))^\top, \\
&\quad j = 1, \dots, n.
\end{aligned}$$

Note that $\mathbb{F}_j(\mathbf{r}, \mathbf{q})q^j = F^j(\mathbf{r}, \mathbf{q})$ under $|q^j| = 1$ and the equations (17) can be written as

$$\begin{aligned}
dQ^j &= \frac{\Upsilon}{M} \mathbb{F}_j(\mathbf{R}, \mathbf{Q})Q^j dt \\
&\quad + \sqrt{\frac{2\Upsilon}{M\beta}} \sum_{l=1}^3 S_l Q^j \star dW_l^j(t), \\
Q^j(0) &= q^j, \quad |q^j| = 1.
\end{aligned} \tag{30}$$

We also remark that if $\mathbb{F}_j(\mathbf{r}, \mathbf{q}) = 0$, Q^j are Wiener processes on the three-dimensional sphere²⁸⁻³¹. One can show that

$$\begin{aligned}
Y^j(t+h) &= h \frac{\Upsilon}{M} \mathbb{F}_j(\mathbf{R}(t), \mathbf{Q}(t)) \\
&\quad + \sqrt{\frac{2\Upsilon}{M\beta}} \sum_{l=1}^3 (W_l^j(t+h) - W_l^j(t)) S_l \\
&\quad + \text{terms of higher order.}
\end{aligned}$$

Consequently, we derived the following numerical method for (16)-(17):

$$\begin{aligned}
\mathbf{R}_0 &= \mathbf{r}, \quad \mathbf{Q}_0 = \mathbf{q}, \quad |q^j| = 1, \quad j = 1, \dots, n, \tag{31} \\
\mathbf{R}_{k+1} &= \mathbf{R}_k + h \frac{v}{m} \mathbf{f}(\mathbf{R}_k, \mathbf{Q}_k) + \sqrt{h} \sqrt{\frac{2v}{m\beta}} \xi_k, \\
Y_k^j &= h \frac{\Upsilon}{M} \mathbb{F}_j(\mathbf{R}_k, \mathbf{Q}_k) + \sqrt{h} \sqrt{\frac{2\Upsilon}{M\beta}} \sum_{l=1}^3 \eta_k^{j,l} S_l, \\
\mathbf{Q}_{k+1}^j &= \exp(Y_k^j) \mathbf{Q}_k^j, \quad j = 1, \dots, n,
\end{aligned}$$

where $\xi_k = (\xi_{1,k}, \dots, \xi_{3n,k})^\top$ and $\xi_{i,k}$, $i = 1, \dots, 3n$, $\eta_k^{j,l}$, $l = 1, 2, 3$, $j = 1, \dots, n$, are i.i.d. random variables with the same law

$$P(\theta = \pm 1) = 1/2. \tag{32}$$

Since the matrix Y_k^j is skew symmetric, the exponent $\exp(Y_k^j)$ can be effectively computed using the Rodrigues formula (see Appendix D).

Note that it is sufficient here to use the simpler distribution (32) than (22) used in the Langevin integrators since the scheme (31) is of weak order

one, while the Langevin integrators from the previous sections are of weak order two (for further reading see, e.g. Ref. 11). We proved (the proof is not included here) that the geometric integrator (31) possesses properties stated in the following proposition.

Proposition V.4 *The numerical scheme (31) for (16)-(17) preserves the length of quaternions, i.e., $|Q_k^j| = 1$, $j = 1, \dots, n$, for all k , and it is of weak order one.*

We note that one can choose ξ_k and $\eta_k^{j,l}$, $l = 1, 2, 3$, $j = 1, \dots, n$, so that their components are i.i.d. Gaussian random variables with zero mean and unit variance. In this case the weak order of the scheme remains 1st as when we use the simple discrete distribution (32). Let us remark in passing that in the case of Gaussian random variables the above scheme also converges in the mean-square sense with order 1/2. It is not difficult to derive a method of mean-square order one, which preserves the length of quaternions, but it is not of applicable interest in our context and hence omitted. As far as we know, this is the first time when a Lie-group type weak scheme is considered and applied in the context of stochastic thermostats.

VI. NUMERICAL EXPERIMENTS

We have implemented Langevin A, B, and C integrators and the weak 1-st order gradient integrator in the simulation of a rigid TIP4P water model with smoothly truncated electrostatic interactions³². The system with periodic boundary conditions contains 1728 molecules and density 989.85 kg/m³. All simulation runs start from the same initial state, which is a well-equilibrated liquid state at 300 K obtained in a long simulation with $h = 1$ fs. After a further 20 000 step equilibration run (which gives a sufficiently long equilibration time for all the considered time steps, taking into account that the initial state is already well equilibrated), the measurements are accumulated during the subsequent 200 000 steps.

During the simulations, we have monitored the preservation of the constraint $|q^j| = 1$ by all integrators and $q^{j\top}\pi^j = 0$ by the Langevin integrators, $j = 1, \dots, n$. At the beginning of the simulation $|q^j| = 1$ to within the machine precision of about 10^{-16} . The behavior of $\max_j |q^j| - 1$ and $\min_j |q^j| - 1$ as functions of the simulation time indicates that $|q^j|$ are conserved by the integrators to within the round-off error, which gradually accumulates with increasing number of steps, but independent of the step size h . After 200 000 steps the largest deviation is of order 10^{-13} . Similar behavior is observed for the maximum deviation of $q^{j\top}\pi^j$ from zero.

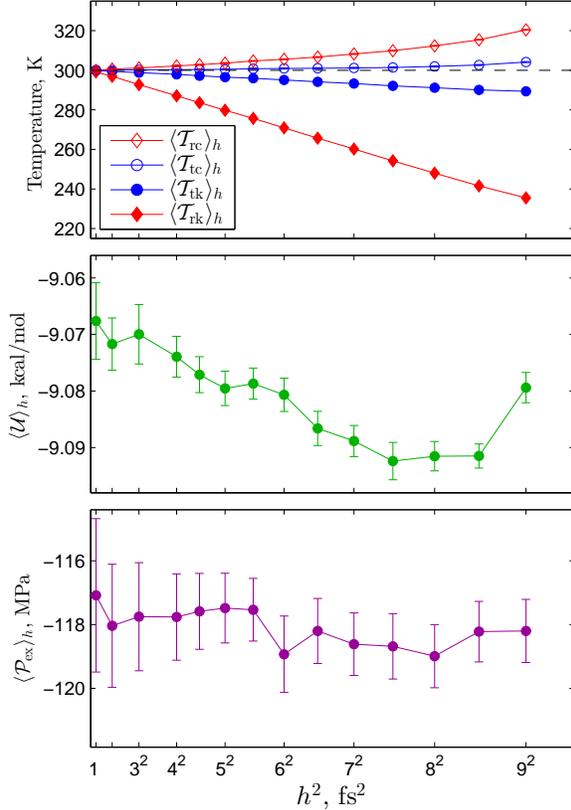


FIG. 1. Langevin A thermostat with $\gamma = 5 \text{ ps}^{-1}$ and $\Gamma = 10 \text{ ps}^{-1}$. Error bars denote estimated 95% confidence intervals in the measure quantities.

The following quantities are measured during simulation runs:

- Translational kinetic temperature

$$\langle \mathcal{T}_{tk} \rangle_h = \frac{\langle \mathbf{p}^\top \mathbf{p} \rangle_h}{3mk_B n};$$

- Rotational kinetic temperature

$$\langle \mathcal{T}_{rk} \rangle_h = \frac{2 \langle \sum_{j=1}^n \sum_{l=1}^3 V_l(q^j, \pi^j) \rangle_h}{3k_B n};$$

- Translational configurational temperature

$$\langle \mathcal{T}_{tc} \rangle_h = \frac{\langle \sum_{j=1}^n |\nabla_{r^j} U|^2 \rangle_h}{k_B \langle \sum_{j=1}^n \nabla_{r^j}^2 U \rangle_h};$$

- Rotational configurational temperature³³

$$\langle \mathcal{T}_{rc} \rangle_h = \frac{\langle \sum_{j=1}^n |\nabla_{\omega^j} U|^2 \rangle_h}{k_B \langle \sum_{j=1}^n \nabla_{\omega^j}^2 U \rangle_h},$$

where ∇_{ω^j} is the angular gradient operator for molecule j ;

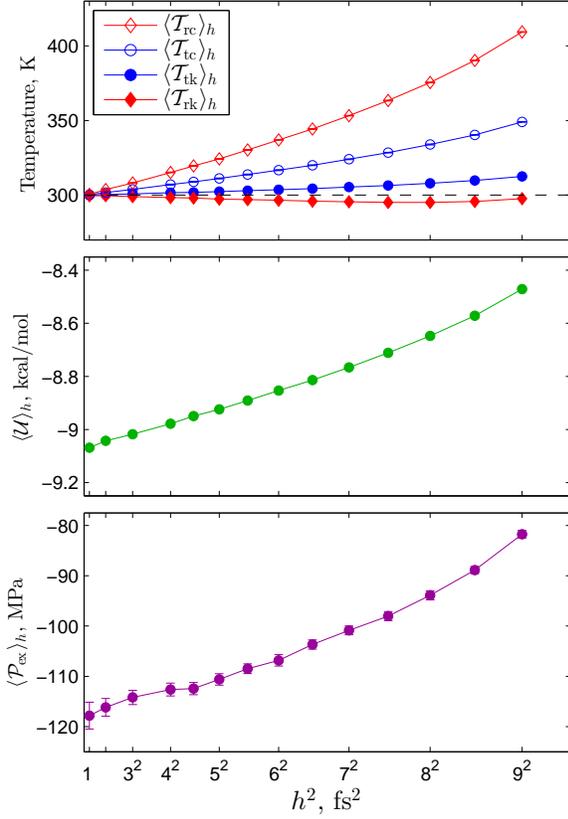


FIG. 2. Langevin B thermostat with $\gamma = 5 \text{ ps}^{-1}$ and $\Gamma = 10 \text{ ps}^{-1}$.

- Potential energy per molecule

$$\langle \mathcal{U} \rangle_h = \frac{1}{n} \langle U \rangle_h;$$

- Excess pressure

$$\langle \mathcal{P}_{ex} \rangle_h = -\frac{\left\langle \sum_{j=1}^n r^j \cdot f^j \right\rangle_h}{3V},$$

where V is the system volume.

Angle brackets with subscript h represent the average over a simulation run with time step h .

We run simulations with different time steps h ranging from 1 to 9 fs. Due to the discretization errors of the numerical methods, measured quantities exhibit the following dependence on h for small h ^{11,34}:

$$\langle A \rangle_h = \langle A \rangle_0 + E_A h^p + \mathcal{O}(h^{p+1}), \quad (33)$$

where p is the order of the integrator. Thus, $p = 2$ for the 2nd-order Langevin integrators, and $p = 1$ for the 1-st order gradient integrator. $\langle A \rangle_0$ denotes the value of the average in the limit $h \rightarrow 0$, and E_A characterises the size of the leading term of the discretization error for the measured quantity A .

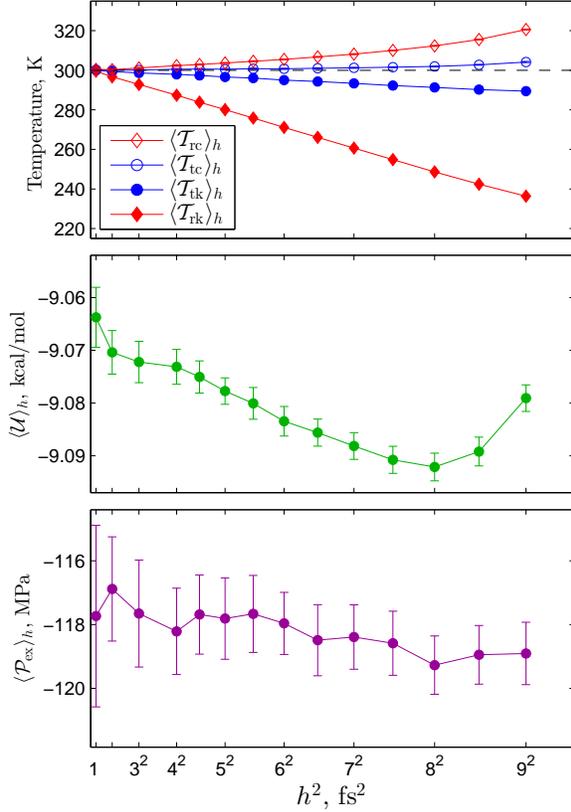


FIG. 3. Langevin C thermostat with $\gamma = 5 \text{ ps}^{-1}$ and $\Gamma = 10 \text{ ps}^{-1}$.

The results are presented in Figs. 1-4. Error bars represent 95% confidence intervals estimated using the block averaging approach³⁵. As expected, we observe at small h a linear dependence of average measured quantities $\langle A \rangle_h$ on h^2 for the Langevin thermostats and on h for the gradient thermostat. Using linear regression, we calculate the values of $\langle A \rangle_0$ and E_A for the measured quantities as defined in Eq. (33). The results are presented in Table I. We observe that for all numerical methods all four measures of the system temperature converge in the limit $h \rightarrow 0$ to the correct value of $T = 300 \text{ K}$ set by the thermostats. At the same time, the leading discretization error terms, characterised by E_A , are different for different measures of temperature and for different numerical methods. We also see that the estimated values of $\langle \mathcal{U} \rangle_0$ and $\langle \mathcal{P}_{ex} \rangle_0$ agree for all integrators, which is an indicator that all the integrators sample from the same ensemble.

While here we present only results for one set of thermostat parameters ($\gamma = 5 \text{ ps}^{-1}$ and $\Gamma = 10 \text{ ps}^{-1}$ for the Langevin thermostat and $v = 4 \text{ fs}$ and $\Upsilon = 1 \text{ fs}$ for the gradient thermostat), we have investigated the performance of the integrators in a wide range of parameter values. The results obtained with Langevin A and B integrators are iden-

TABLE I. Results for Langevin A, B, and C thermostats with $\gamma = 5 \text{ ps}^{-1}$ and $\Gamma = 10 \text{ ps}^{-1}$ and gradient thermostat with $v = 4 \text{ fs}$ and $\Upsilon = 1 \text{ fs}$. Values of $\langle A \rangle_0$ and E_A , defined in Eq. (33), were obtained by linear regression from $\langle A \rangle_h$ for $h \leq 6 \text{ fs}$ for Langevin integrators and for $h \leq 4 \text{ fs}$ for the gradient integrator. Quantities E_A are measured in the units of the corresponding quantity A per fs^p , where $p = 2$ for Langevin integrators and $p = 1$ for the gradient integrator. Numbers in parentheses indicate the statistical error in the last digit(s) shown with a 95% confidence level.

A (unit)	Langevin A		Langevin B		Langevin C		Gradient	
	$\langle A \rangle_0$	E_A	$\langle A \rangle_0$	E_A	$\langle A \rangle_0$	E_A	$\langle A \rangle_0$	E_A
\mathcal{T}_{tk} (K)	300.0(2)	-0.136(8)	299.9(2)	0.100(13)	300.0(2)	-0.135(7)	-	-
\mathcal{T}_{rk} (K)	299.9(2)	-0.808(8)	299.8(3)	-0.092(13)	300.1(2)	-0.803(8)	-	-
\mathcal{T}_{tc} (K)	300.1(3)	0.022(13)	299.9(4)	0.45(2)	300.1(3)	0.021(13)	299.6(1.0)	3.6(5)
\mathcal{T}_{rc} (K)	299.8(3)	0.158(11)	299.6(4)	0.99(2)	299.9(3)	0.152(11)	298.6(1.6)	9.9(4)
\mathcal{U} (kcal/mol)	-9.068(4)	-0.0004(2)	-9.071(4)	0.0059(2)	-9.066(3)	-0.0005(2)	-9.075(11)	0.033(4)
\mathcal{P}_{ex} (MPa)	-117.4(1.3)	-0.02(5)	-117.4(1.6)	0.27(9)	-117.5(1.4)	-0.01(5)	-118(11)	1.7(2.8)

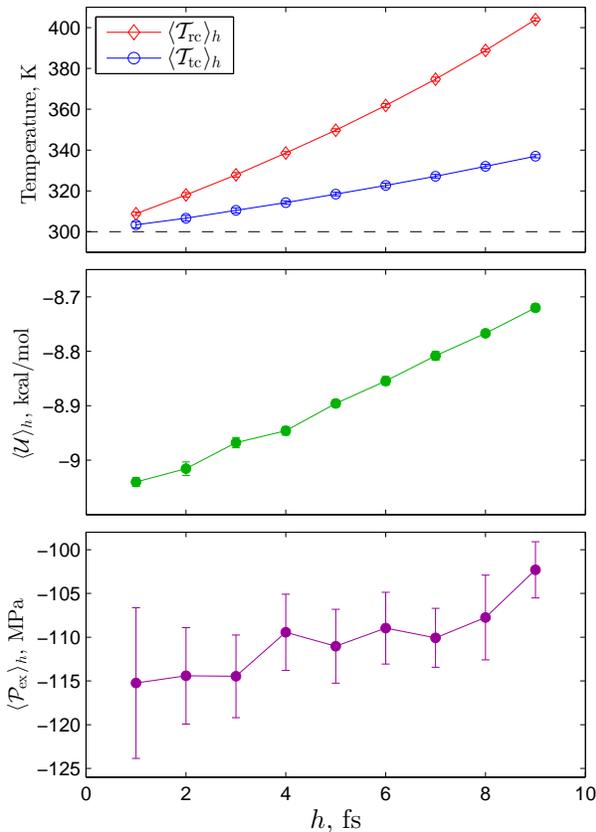


FIG. 4. Gradient thermostat with $v = 4 \text{ fs}$ and $\Upsilon = 1 \text{ fs}$.

tical within the sampling errors to those of the corresponding integrators in Refs. 5 and 32. This is expected since, as demonstrated in Appendix B, the components of π^j parallel to q^j do not influence the physical properties of the system.

Because of the exact treatment of the Ornstein-Uhlenbeck process, Langevin B and C integrators

can be used with arbitrarily large values of γ and Γ . On the other hand, Langevin A integrator breaks down for γ larger than about 100 ps^{-1} and for Γ larger than about 200 ps^{-1} (see also Fig. 9 in Ref. 5). We determine that optimal Langevin thermostat parameters for the sampling of this system are $\gamma = 3\text{-}6 \text{ ps}^{-1}$ and $\Gamma = 7\text{-}15 \text{ ps}^{-1}$. The ‘optimality’ is understood in the following sense. Larger values of γ and Γ lead to the slowing down of the system evolution, as indicated by the decreasing diffusion coefficient³², resulting in less efficient sampling, i.e. larger statistical errors in the measured quantities. With smaller values of γ and Γ the thermostat takes longer to reach the equilibrium state if the system is initially out of equilibrium. Of course, when the system is well equilibrated, it is reasonable to use smaller values of γ and Γ , especially if one wants to measure time-dependent properties, e.g., time autocorrelation functions. Also note that stronger coupling to the thermostat stabilizes the integrator: while it becomes unstable at around $h = 8 \text{ fs}$ for very small values of γ and Γ , it is stable up to about $h = 10 \text{ fs}$ when $\gamma + \Gamma$ is larger than about 8 ps^{-1} .

With the gradient system, scaling v and Υ together does not change the properties of the trajectories, only the speed at which these trajectories are traversed. This property is manifest in the integrator by the fact that thermostat parameters appear together with the time step h as $h v$ and $h \Upsilon$. As a consequence, it is always possible to use larger h with smaller v and Υ ; clearly, however, this does not represent better sampling. For simplicity of numerical experimentation, we use the same range of h values as with the Langevin integrators, while adjusting v and Υ to achieve optimal simulation efficiency. For a given h , it is obviously preferable to use larger values of v and Υ in order to make larger effective integration steps, thus faster exploring the system configuration space. However, we found that the gradient integrator becomes un-

stable when $h\nu$ exceeds approximately 150 fs^2 for small $h\Upsilon$ and $h\Upsilon$ exceeds approximately 70 fs^2 for small $h\nu$. Also, the linear dependence of the discretization errors on h in Eq. (33) extends only up to $h\nu \approx 20 \text{ fs}^2$ for small $h\Upsilon$ and up to $h\Upsilon \approx 5 \text{ fs}^2$ for small $h\nu$. In Fig. 4 we present results for the gradient integrator with $\nu = 4 \text{ fs}$ and $\Upsilon = 1 \text{ fs}$ and use simulation runs with $h \leq 4 \text{ fs}$ to obtain linear regression results presented in Table I.

VII. DISCUSSION AND CONCLUSIONS

When making measurements in molecular simulations, we are interested in accuracy and efficiency. By efficiency we mean obtaining results of desired precision using the least computational time. Efficiency of a thermostat + an integrator is usually measured in terms of force calculations because they dominate computational time in molecular dynamics simulations of large systems. Since all four integrators presented here use one force calculation per step, the computational times per step are essentially the same for all of them and hence we measure the efficiency in terms of the number of integration steps.

Accuracy is determined by the size of the errors. When computing stationary averages (ergodic limits), we usually encounter four types of errors: (1) system size error, i.e. error due a relatively small size of a simulated system representing a much larger real system (usually with the help of periodic boundary conditions); (2) equilibration error, i.e. error due to the distance from the stationary distribution caused by insufficient equilibration; (3) statistical error due to fluctuations of a measured quantity along a simulation trajectory; and (4) the numerical integration (discretization) error due to numerical approximation with finite time step h of the dynamical equations describing system evolution in time (see, for example, Refs. 6 and 36 and also Appendix B in Ref. 37).

The system size error is typically independent of the choice of the thermostat or numerical scheme and, therefore, is not relevant to the present discussion. The equilibration error can be made relatively insignificant by a preceding equilibration run, even though establishing the necessary duration of the equilibration run is not always straightforward. The statistical error is controlled by the length of integration time. When making measurements from a single long simulation run of N steps with step size h , the statistical error depends on the total simulation time $T = Nh$ as $O(\sqrt{t_c/T})$, where t_c characterises the time over which successive measurements become uncorrelated. As such, the statistical error can be reduced by increasing either the number of simulation steps N or the step size h , although increase of the latter is limited by

the size of the numerical integration error and ultimately by the stability of the integrator.

The numerical integration error can be reduced by decreasing the step size h , although smaller h results in a less efficient calculation for achieving a prescribed size of the statistical error (i.e. more steps are necessary). As we have seen in our numerical experiments, the size of the numerical error in the measurement of a quantity A is determined by the value of E_A [see Eq. (33)], which is influenced by the choice of a thermostat and its parameters, such as damping coefficients. Therefore, a better way to reduce the numerical error is to choose a thermostat and its parameters so that the magnitude of E_A is small for the quantity of interest A . In some cases it is possible to make $E_A = 0$, which means that for the measurement of A the numerical integrator behaves as a method of higher order^{23,32,38}. Since it is not always possible to make E_A small simultaneously for all A , when choosing the thermostat and its parameters we have to consider which quantity we need to determine most accurately.

Comparing the performance of the three Langevin integrators, we observe that Langevin B is better at controlling the kinetic temperatures, while Langevin A and C are better for more accurate measurements of the configurational temperatures, potential energy, and excess pressure. Since in most cases the quantities of interest are configurational (i.e. those that depend on particle positions), Langevin A and C should be the integrators of choice. In addition, while Langevin A cannot be used with very large values of the damping coefficients γ and Γ , Langevin C does not have such a restriction and can be used with arbitrarily large values of γ and Γ , which could be desirable if the thermostat is needed to also play the role of an implicit solvent.

It is interesting to note in passing that, despite the very different structure of Langevin A and C, their numerical errors for various measured quantities are surprisingly similar. We do not have an explanation for this ‘‘coincidence’’, and further analysis of the integrators is required to understand it.

From the comparison between the Langevin integrators and the gradient integrator we see that the statistical errors in the results (as measured by the estimated error bars on $\langle A \rangle_0$) of the gradient method are much larger, so the sampling efficiency of the gradient method is lower. This conclusion is reinforced by the observation that the mean-square displacement of molecules after the same number of integration steps is about 10 times larger for the Langevin integrators than for the gradient integrator with the same step size h and maximum possible values of ν and Υ . Thus the gradient integrator takes about 10 times more steps between successive

uncorrelated states. It is also clear that the sampling efficiency is limited by the stability of the gradient integrator, and so it cannot be substantially improved by designing higher order schemes. Besides, a weak 2nd-order gradient integrator would require at least two force evaluations per step.

In conclusion, we summarize our experimental observations as follows:

- Langevin A and C are the integrators of choice for the Langevin thermostat. Also, if Langevin thermostat needs to be used with relatively large values of the damping coefficients, then Langevin C should be used.
- The Langevin thermostat is better than the Brownian thermostat for sampling (i.e., the statistical error discussed at the start of this Section is smaller for the Langevin thermostat).

Even though we reached these conclusions based on the observations of a particular molecular system, we believe they are sufficiently generic. At the same time, there might be situations when the Brownian thermostat introduced in this paper is preferable to the Langevin one.

We also note that the Brownian thermostat integrator is of order one while the Langevin integrators are of order two. Further work in developing numerical methods for gradient systems is needed.

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Appendix A: Evaluation of the rotational force

To calculate the rotational force, $F^j(\mathbf{r}, \mathbf{q}) = -\tilde{\nabla}_{q^j} U(\mathbf{r}, \mathbf{q}) \in T_{q^j} \mathbb{S}^3$, it is necessary to evaluate a directional derivative of the potential tangent to the three dimensional sphere \mathbb{S}^3 , $\tilde{\nabla}_{q^j} U(\mathbf{r}, \mathbf{q})$. If the potential is expressed in quaternions, it is natural to calculate this derivative directly via

$$\tilde{\nabla}_{q^j} U(\mathbf{r}, \mathbf{q}) = \nabla_{q^j} U(\mathbf{r}, \mathbf{q}) - (q^j)^\top \nabla_{q^j} U(\mathbf{r}, \mathbf{q}) q^j,$$

where ∇_{q^j} is a conventional 4-component gradient.

Alternatively, the rotational force $F^j(\mathbf{r}, \mathbf{q})$ can be represented as $F^j(\mathbf{r}, \mathbf{q}) = 2S(q^j)(0, \tau^j)^\top$, where $\tau^j = (\tau_1^j, \tau_2^j, \tau_3^j)^\top \in \mathbb{R}^3$ is the torque acting on molecule j in the body-fixed reference frame¹⁰. To illustrate how $F^j(\mathbf{r}, \mathbf{q})$ can be computed, we consider a specific example – a system of rigid

molecules with pairwise interaction between interaction sites within molecules:

$$U(\mathbf{r}, \mathbf{q}) = \sum_j \sum_{m < j} \sum_{\alpha, \beta} u_{\alpha\beta} (|r^{j,\alpha} - r^{m,\beta}|), \quad (\text{A1})$$

where $r^{j,\alpha} = r^j + \mathbf{A}^\top(q^j)d^\alpha$ is the coordinate of the interaction site α within molecule j , with d^α being the site coordinate relative to the center of mass of a molecule in the body-fixed reference frame. Here

$$\mathbf{A}(q) = 2 \begin{bmatrix} q_0^2 + q_1^2 - \frac{1}{2} & q_1 q_2 + q_0 q_3 & q_1 q_3 - q_0 q_2 \\ q_1 q_2 - q_0 q_3 & q_0^2 + q_2^2 - \frac{1}{2} & q_2 q_3 + q_0 q_1 \\ q_1 q_3 + q_0 q_2 & q_2 q_3 - q_0 q_1 & q_0^2 + q_3^2 - \frac{1}{2} \end{bmatrix} \quad (\text{A2})$$

is the rotational matrix expressed in terms of quaternion coordinates. Force acting on the interaction site α of molecule j is given by

$$\begin{aligned} f^{j,\alpha} &= -\nabla_{r^{j,\alpha}} U(\mathbf{r}, \mathbf{q}) \\ &= -\sum_{m \neq j} \sum_{\beta} u'_{\alpha\beta} (|r^{j,\alpha} - r^{m,\beta}|) \frac{r^{j,\alpha} - r^{m,\beta}}{|r^{j,\alpha} - r^{m,\beta}|}. \end{aligned} \quad (\text{A3})$$

The total force acting on molecule j is $f^j = \sum_{\alpha} f^{j,\alpha}$. The torque acting on molecule j in the body-fixed reference frame is given by

$$\tau^j = \sum_{\alpha} d^\alpha \times (\mathbf{A}(q^j) f^{j,\alpha}). \quad (\text{A4})$$

Appendix B: Proof that the Langevin thermostat from Ref. 5 is correct for physical quantities

In this appendix we show that $\Omega^j(t)$ being non-zero has no consequences for the measurement of physical quantities. First, we modify the solution $X(t)$ of the SDEs (6)-(7) to turn it into an ergodic process. Let us introduce

$$\begin{aligned} \tilde{\Pi}^j(t) &:= \Pi^j(t) - (Q^j(t))^\top \Pi^j(t) Q^j(t) \\ &= \Pi^j(t) - Y^j(t) Q^j(t), \quad j = 1, \dots, n, \end{aligned}$$

which are the projections of $\Pi^j(t)$ on the tangent space $T_{Q^j} \mathbb{S}^3$, i.e., $\tilde{\Pi}^j$ are orthogonal to Q^j . By elementary calculations, we get

$$\begin{aligned} dQ^j &= \frac{1}{4} S(Q^j) D S^\top(Q^j) \tilde{\Pi}^j dt, \quad (\text{B1}) \\ Q^j(0) &= q^j, \quad |q^j| = 1, \\ d\tilde{\Pi}^j &= \frac{1}{4} \sum_{l=1}^3 \frac{1}{I_l} \left(\tilde{\Pi}^j{}^\top S_l Q^j \right) S_l \tilde{\Pi}^j dt \\ &\quad + F^j(\mathbf{R}, \mathbf{Q}) dt - \Gamma J(Q^j) \tilde{\Pi}^j dt \\ &\quad + \sqrt{\frac{2M\Gamma}{\beta}} (I - Q^j Q^j{}^\top) dW^j(t), \\ \tilde{\Pi}^j(0) &= \pi^j, \quad q^j{}^\top \pi^j = 0, \quad j = 1, \dots, n. \end{aligned}$$

We note the fact that the solution to (6), (B1) preserves the constraint $(Q^j(t))^T \tilde{\Pi}^j(t) = 0$ in addition to the constraint (9), i.e., unlike $\Pi^j(t)$, $\tilde{\Pi}^j(t)$ have an appropriately constrained dynamics from the physical point of view.

Let $\varphi(x) : \mathbb{D} \rightarrow \mathbb{R}$ be a function with polynomial growth at infinity. Recall that

$$\mathbb{D} = \{x = (\mathbf{r}^T, \mathbf{p}^T, \mathbf{q}^T, \boldsymbol{\pi}^T)^T \in \mathbb{R}^{14n} : |q^j| = 1, (q^j)^T \boldsymbol{\pi}^j = 0, j = 1, \dots, n\}.$$

Assume that the process $\tilde{X}(t) := (\mathbf{R}^T(t), \mathbf{P}^T(t), \mathbf{Q}^T(t), \tilde{\boldsymbol{\Pi}}^T(t))^T$ with $\tilde{\boldsymbol{\Pi}} = (\tilde{\Pi}^1, \dots, \tilde{\Pi}^n)^T$ is ergodic, i.e., there exists a unique invariant measure μ of \tilde{X} and independently of $x \in \mathbb{D}$ there exists the limit (see, for example, Refs. 20 and 21 and references therein):

$$\lim_{t \rightarrow \infty} E\varphi(\tilde{X}(t; x_0)) = \int_{\mathbb{D}} \varphi(x) d\mu(x) := \varphi^{erg}, \quad (\text{B2})$$

where $\tilde{X}(t; x_0)$ is attributed to the solution $\tilde{X}(t)$ of (6), (B1) with the initial condition $\tilde{X}(0) =$

$\tilde{X}(0; x_0) = x_0 \in \mathbb{D}$. Using the stationary Fokker-Planck equation, it is not difficult to check that μ is the Gibbsian (canonical ensemble) measure on \mathbb{D} possessing the density $\rho(\mathbf{r}, \mathbf{p}, \mathbf{q}, \boldsymbol{\pi})$ from (14).

Now we will show that $E\varphi(\tilde{X}(t; x_0)) = E\varphi(X(t; x_0))$ for φ which has physical meaning. To this end, introduce $\hat{\boldsymbol{\omega}} = (\hat{\omega}^1, \dots, \hat{\omega}^n)^T \in \mathbb{R}^{4n}$, $\hat{\omega}^j = (\omega_0^j, \omega_1^j, \omega_2^j, \omega_3^j)^T \in \mathbb{R}^4$ and $\boldsymbol{\omega} = (\omega^1, \dots, \omega^n)^T \in \mathbb{R}^{3n}$, $\omega^j = (\omega_1^j, \omega_2^j, \omega_3^j)^T \in \mathbb{R}^3$ so that $\hat{\omega}^j = \frac{1}{2} S^T(q^j) \boldsymbol{\pi}^j$, $j = 1, \dots, n$. We see that $\omega_1^j, \omega_2^j, \omega_3^j$ are the (conventional) angular momenta about the axes in the body-centred frame of molecule j , while the components ω_0^j are of an axillary nature. Let $\check{\mathbb{D}} = \{x = (\mathbf{r}^T, \mathbf{p}^T, \mathbf{q}^T, \boldsymbol{\pi}^T)^T \in \mathbb{R}^{14n} : |q^j| = 1, j = 1, \dots, n\} = \{x = (\mathbf{r}^T, \mathbf{p}^T, \mathbf{q}^T, \hat{\boldsymbol{\omega}}^T)^T \in \mathbb{R}^{14n} : |q^j| = 1, j = 1, \dots, n\}$. Note that $\mathbb{D} = \{x = (\mathbf{r}^T, \mathbf{p}^T, \mathbf{q}^T, \boldsymbol{\omega}^T)^T \in \mathbb{R}^{14n} : |q^j| = 1, \omega_0^j = 0, j = 1, \dots, n\}$. Assume that $\varphi(x) : \check{\mathbb{D}} \rightarrow \mathbb{R}$ is a function with polynomial growth at infinity which does not depend on the non-physical variable $\boldsymbol{\omega}_0 = (\omega_0^1, \dots, \omega_0^n)^T$. It is not difficult to see that

$$\begin{aligned} \varphi(x) &= \varphi(\mathbf{r}^T, \mathbf{p}^T, \mathbf{q}^T, \boldsymbol{\pi}^T) = \varphi(\mathbf{r}^T, \mathbf{p}^T, \mathbf{q}^T, 2\hat{\omega}^1 S^T(q^1), \dots, 2\hat{\omega}^n S^T(q^n)) \\ &= \varphi(\mathbf{r}^T, \mathbf{p}^T, \mathbf{q}^T, 2(\omega_0^1, \omega_1^1, \omega_2^1, \omega_3^1) S^T(q^1), \dots, 2(\omega_0^n, \omega_1^n, \omega_2^n, \omega_3^n) S^T(q^n)) \\ &= \varphi(\mathbf{r}^T, \mathbf{p}^T, \mathbf{q}^T, 2(0, \omega_1^1, \omega_2^1, \omega_3^1) S^T(q^1), \dots, 2(0, \omega_1^n, \omega_2^n, \omega_3^n) S^T(q^n)) \\ &= \varphi(\mathbf{r}^T, \mathbf{p}^T, \mathbf{q}^T, (\boldsymbol{\pi}^1 - q^1 \boldsymbol{\pi}^1 q^1)^T, \dots, (\boldsymbol{\pi}^n - q^n \boldsymbol{\pi}^n q^n)^T). \end{aligned} \quad (\text{B3})$$

In (B3), we may put $\boldsymbol{\omega}_0 = 0$ since $\varphi(x)$ does not depend on the non-physical quantity $\boldsymbol{\omega}_0$ and any value can be assigned to $\boldsymbol{\omega}_0$ without changing the value of φ . Further, (B3) implies that

$$\begin{aligned} &E\varphi(\mathbf{R}^T, \mathbf{P}^T, \mathbf{Q}^T, \boldsymbol{\Pi}^T)|_{(6)-(7)} \\ &= E\varphi(\mathbf{R}^T, \mathbf{P}^T, \mathbf{Q}^T, \tilde{\boldsymbol{\Pi}}^T(t))|_{(6),(B1)}, \end{aligned}$$

where expectation on the left is computed with respect to the system (6)-(7) and on the right with respect to (6), (B1). This explains why (6)-(7) can be used for calculating ergodic limits φ^{erg} for functions $\varphi(x)$ of physical interest (i.e., independent of $q^j \boldsymbol{\pi}^j$) despite (6)-(7) being not ergodic (cf. (10)).

In essence, the evolution of the physical degrees of freedom is unaffected by the non-physical component $\Omega^j(t)$, and the physical degrees of freedom sample from the Gibbs measure as desired. Further, no quantity of interest depends on the non-physical component of Π , and so averages obtained using the old Langevin thermostat (6)-(7) are correct.

Appendix C: The stationary Fokker-Planck equation for the gradient thermostat

Recall that in (16), (30)

$$\begin{aligned} f^j(\mathbf{r}, \mathbf{q}) &= -\nabla_{r^j} U(\mathbf{r}, \mathbf{q}), \\ \mathbb{F}_j(\mathbf{r}, \mathbf{q}) &= F^j(\mathbf{r}, \mathbf{q}) q^j - q^j (F^j(\mathbf{r}, \mathbf{q}))^T, \\ F^j(\mathbf{r}, \mathbf{q}) &= -\nabla_{q^j} U(\mathbf{r}, \mathbf{q}) + q^j \nabla_{q^j} U(\mathbf{r}, \mathbf{q}) q^j, \end{aligned}$$

and hence

$$\mathbb{F}_j(\mathbf{r}, \mathbf{q}) q^j = -\nabla_{q^j} U(\mathbf{r}, \mathbf{q}) q^j + q^j \nabla_{q^j} U(\mathbf{r}, \mathbf{q}) q^j,$$

where the gradients ∇_{r^j} and ∇_{q^j} are in the Cartesian coordinates in \mathbb{R}^3 and \mathbb{R}^4 , respectively. The stationary Fokker-Planck equation corresponding to (16), (30) has the form (see, for example, Refs. 20, 21, and 31):

$$L^* \rho = 0, \quad (\text{C1})$$

where

$$L^* \rho = \sum_{j=1}^n \left[\frac{v}{m\beta} \sum_{i=1}^3 \frac{\partial^2}{(\partial r_i^j)^2} \rho + \frac{\Upsilon}{M\beta} \sum_{i,k,l=0}^3 \frac{\partial}{\partial q_i^j} \left\{ (S_l q^j)_i \frac{\partial}{\partial q_k^j} ((S_l q^j)_{k\rho}) \right\} \right. \\ \left. + \frac{v}{m} \sum_{i=1}^3 \frac{\partial}{\partial r_i^j} \left(\frac{\partial U(\mathbf{r}, \mathbf{q})}{\partial r_i^j} \rho \right) + \frac{\Upsilon}{M} \sum_{i=0}^3 \frac{\partial}{\partial q_i^j} \left\{ \left(\frac{\partial U(\mathbf{r}, \mathbf{q})}{\partial q_i^j} q^j \top q^j - q^j \top \nabla_{q^j} U(\mathbf{r}, \mathbf{q}) q_i^j \right) \rho \right\} \right].$$

By direct calculations one can verify that the Gibbsian density $\tilde{\rho}(\mathbf{r}, \mathbf{q})$ from (15) satisfies (C1). We note that (C1) is written for $(\mathbf{r}, \mathbf{q}) \in \mathbb{R}^{7n}$ using the fact that (16), (30) is defined in \mathbb{R}^{7n} , i.e., we do not work here with the manifold \mathbb{S}^3 on which $Q^j(t)$ from (30) naturally live. Instead we work with \mathbb{R}^4 in which \mathbb{S}^3 is embedded. As the dynamics of our thermostat and integrator have the property that trajectories initially on the manifold do not leave it, the observation that the Gibbsian density is stationary over \mathbb{R}^{7n} means that it is also an invariant probability measure on the manifold of relevance to our modelling and simulations.

Appendix D: Computing the exponent of a real skew-symmetric matrix of order 4

The exponent of a skew-symmetric matrix

$$A = \begin{pmatrix} 0 & u_6 & u_5 & u_3 \\ -u_6 & 0 & u_4 & u_2 \\ -u_5 & -u_4 & 0 & u_1 \\ -u_3 & -u_2 & -u_1 & 0 \end{pmatrix},$$

is calculated according to the Rodrigues formula

$$e^A = \cos \mu I + \frac{\sin \mu}{\mu} A + (aA + bI)(A^2 + \mu^2 I),$$

where

$$a = \frac{\sin \alpha / \alpha - \sin \mu / \mu}{\delta}, \quad b = \frac{\cos \alpha - \cos \mu}{\delta}$$

and

$$\alpha = \sqrt{\frac{1}{2}(a_2 - \delta)}, \quad \mu = \sqrt{\frac{1}{2}(a_2 + \delta)},$$

$$\delta = \sqrt{a_2^2 - 4a_0},$$

$$a_0 = (u_1 u_6 + u_3 u_4 - u_2 u_5)^2, \quad a_2 = \sum_{i=1}^6 u_i^2.$$

This Rodrigues formula was considered in [T. Politi. A formula for the exponential of a real skew-symmetric matrix of order 4. *BIT Numer. Math.* 41 (2001), 842–845] but the expression given there contains misprints, namely signs in the denominator of a and in c are incorrect in Eq. (2.5) of Politi's paper.

Note that $a_0, a_2 \geq 0$ and $a_2^2 \geq 4a_0$, and so $\mu \geq \alpha$. When α and/or μ , or $\mu - \alpha$ are close to zero, the evaluation of the above expressions needs to be done with care to avoid subtractive cancellation or division by zero. In particular, if $\alpha < 10^{-4}$, then replace $\sin \alpha / \alpha$ with $(\alpha^2 / 20 - 1)\alpha^2 / 6 + 1$. Also replace $\sin \mu / \mu$ with $(\mu^2 / 20 - 1)\mu^2 / 6 + 1$ when $a_2 < 10^{-8}$.

When $\mu = \alpha$ (i.e. in the limit $\delta \rightarrow 0$), the eigenvalues of A are degenerate. In this case the expressions for a , and b can be approximated as follows:

$$a = \frac{\sin \gamma / \gamma - \cos \gamma}{a_2} + O(\delta^2), \quad b = \frac{\sin \gamma}{2\gamma} + O(\delta^2),$$

where $\gamma = \sqrt{a_2 / 2}$. We use this expression when $\delta < 10^{-8}$.

If the matrix A is close to zero, i.e., when a_2 is small, then the approximations which can be used for a and b are of the form

$$a = \frac{1}{6} - \frac{1}{120} a_2 + O(a_2^2), \quad b = \frac{1}{2} - \frac{1}{24} a_2 + O(a_2^2).$$

We use these expressions when $a_2 < 10^{-8}$.

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