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Hypercontractivity and Applications for Stochastic Hamiltonian Systems

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Abstract

The hypercontractivity is proved for the Markov semigroup associated with a class of stochastic Hamiltonian systems on Hilbert spaces. Consequently, the Markov semigroup converges exponentially to the invariant probability measure in entropy and is compact for large time. These strengthen the hypocoercivity results derived in the literature. Since the log-Sobolev inequality is invalid, we introduce a new argument to prove the hypercontractivity using coupling and dimension-free Harnack inequality. The main results are illustrated by concrete examples of the kinetic Fokker-Planck equation and highly degenerate diffusion processes.

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1 Introduction

To motivate the present study, we first recall the famous hypocoercivity result of C. Villani [14]. Consider the following degenerate SDE (stochastic differential equation) for \((X_t, Y_t)\) on \(\mathbb{R}^d \times \mathbb{R}^d\):

\[
\begin{aligned}
dX_t &= Y_t \, dt, \\
dY_t &= \{\nabla V(X_t) - Y_t\} \, dt + \sqrt{2} \, dW_t,
\end{aligned}
\]

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where $V \in C^2(\mathbb{R}^d)$ such that
\[
\mu(dx, dy) := e^{V(x) - \frac{1}{2} |y|^2} 
\]
is a probability measure on $\mathbb{R}^d \times \mathbb{R}^d$, and $W_t$ is the $d$-dimensional Brownian motion. This type degenerate SDE is known as “Stochastic Hamiltonian System (Abbrev. SHS)” in probability theory (see [22]), and the distribution density of the solution solves the kinetic Fokker-Planck equation (see [14]). Let $P_t$ be the Markov semigroup for the solution of (1.1). According to [14, Theorem 35], if there exists a constant $C > 0$ such that
\[
|\nabla^2 V| \leq C(1 + |\nabla V|)
\]
and the following Poincaré inequality holds for $\mu_1(dx) := \mu(dx \times \mathbb{R}^d)$:
\[
\mu_1(f^2) \leq C \mu_1(|\nabla f|^2), \quad f \in C^1_b(\mathbb{R}^d), \mu_1(f) = 0,
\]
then for some constants $c, \lambda > 0$ one has
\[
(1.2) \quad \mu(|\nabla P_t f|^2 + (P_t f)^2) \leq ce^{-\lambda t} \mu(|\nabla f|^2 + f^2), \quad f \in C^1_b(\mathbb{R}^2d), \mu(f) = 0, \quad t \geq 0.
\]

See [6, 7, 8, 10] and references within for $L^2$-exponential convergence of the same type degenerate diffusion semigroups. The methodology used in these papers relies heavily on the explicit formulation of the invariant probability measure $\mu$. In this paper, we investigate the hypercontractivity, a stronger property than the $L^2$-exponential convergence, for more general degenerate diffusion processes with inexplicit invariant probability measures.

The model we investigate here is the following SHS on $\mathbb{H} := \mathbb{H}_1 \times \mathbb{H}_2$, where $\mathbb{H}_1$ and $\mathbb{H}_2$ are two separable Hilbert spaces:
\[
\begin{cases}
  dX_t = (AX_t + BY_t) dt, \\
  dY_t = Z(X_t, Y_t) dt + \sigma dW_t,
\end{cases}
\]
where
- $A$ is a densely defined (possibly unbounded) linear operator on $\mathbb{H}_1$;
- $B$ is a bounded linear operator from $\mathbb{H}_2$ to $\mathbb{H}_1$;
- $Z$ is a densely defined map from $\mathbb{H}$ to $\mathbb{H}_2$;
- $\sigma$ is a linear operator on $\mathbb{H}_2$;
- $W_t$ is the cylindrical Brownian motion on $\mathbb{H}_2$, i.e.
\[
W_t = \sum_{i \geq 1} B^i t e_i
\]
for independent one-dimensional Brownian motions $\{B^i_t\}_{i \geq 1}$ and orthonormal basis $\{e_i\}_{i \geq 1}$ of $\mathbb{H}_2$. 


See [11, 20, 21] for results on the existence and uniqueness of (mild) solutions, as well as Harnack inequality and gradient estimate of the associated Markov semigroup $P_t$. We intend to find out explicit conditions ensuring the existence and uniqueness of the invariant probability measure $\mu$ (whose formulation is in general unknown) and, furthermore, the hypercontractivity of $P_t$.

According to Nelson [12], $P_t$ is called hypercontractive if it has an invariant probability measure $\mu$ such that

$$\|P_t\|_{L^2(\mu)\to L^4(\mu)} = \sup\{\|P_tf\|_{L^4(\mu)} : \mu(f^2) \leq 1\} = 1$$

for some $t > 0$.

By the semigroup property and the interpolation theorem, the norm $\|\cdot\|_{L^2(\mu)\to L^4(\mu)}$ can be replaced by $\|\cdot\|_{L^p(\mu)\to L^q(\mu)}$ for any $(p, q) \in (1, \infty)$ with $q > p$. As applications of the hypercontractivity, we will prove the compactness of $P_t$ for large $t > 0$ and the exponential convergence in entropy.

Due to L. Gross (see e.g. [9]), the hypercontractivity of $P_t$ follows from the log-Sobolev inequality

$$\mu(f^2 \log f^2) - \mu(f^2) \log \mu(f^2) \leq C\mathcal{E}(f, f), \quad f \in \mathcal{D}(\mathcal{E})$$

for some constant $C > 0$, where $(\mathcal{E}, \mathcal{D}(\mathcal{E}))$ is the associated energy form. Because of this result, the log-Sobolev inequality has been intensively investigated for forty years. However, since the energy form $\mathcal{E}$ associated with (1.3) satisfies

$$\mathcal{E}(f, f) = \mu(|\sigma^* \nabla_y f|^2) = 0$$

for $f \in C^1_b(\mathbb{R})$ with $f(x, y)$ depending only on $x$, the log-Sobolev inequality is invalid. So, to prove the hypercontractivity we need to develop a new argument.

The remainder of the paper is organized as follows. In Section 2, we introduce a general result on the hypercontractivity using coupling and dimension-free Harnack inequality initiated from [15]. This result is then applied in Sections 3 and 4 to finite- and infinite-dimensional SHS respectively. Finally, concrete examples are presented in Section 5 to illustrate our main results.

\section{Hypercontractivity using Harnack inequality}

In this section, we introduce a general result on the hypercontractivity using Harnack inequality. The basic idea of the study goes back to [15] for elliptic diffusion semigroups on manifolds, see also [2] for a recent study of functional SDEs.

For a probability space $(E, \mathcal{B}, \mu)$, let $P_t$ be a Markov semigroup on $\mathcal{B}_b(E)$ such that $\mu$ is $P_t$-invariant, i.e. $\mu(P_tf) = \mu(f)$ for $f \in L^1(\mu)$ and $t \geq 0$. Recall that a process $(X_t, Y_t)$ on $E \times E$ is called a coupling of the Markov process with semigroup $P_t$, if

$$(P_t f)(X_0) = \mathbb{E}(f(X_t)|X_0), \quad (P_t f)(Y_0) = \mathbb{E}(f(Y_t)|Y_0), \quad f \in \mathcal{B}_b(E), t \geq 0.$$ 

\textbf{Theorem 2.1.} Assume that the following three conditions hold for some measurable functions $\rho: E \times E \to (0, \infty)$ and $\phi: [0, \infty) \to (0, \infty)$ with $\lim_{t \to \infty} \phi(t) = 0$:
(i) There exist two constants $t_0, c_0 > 0$ such that
\[(P_{t_0} f(\xi))^2 \leq (P_{t_0} f^2(\eta))e^{c_0 \rho(\xi,\eta)^2}, \quad f \in B_b(E), \xi, \eta \in E;\]

(ii) For any $(X_0, Y_0) \in E \times E$, there exists a coupling $(X_t, Y_t)$ associated to $P_t$ such that
\[\rho(X_t, Y_t) \leq \phi(t)\rho(X_0, Y_0), \quad t \geq 0;\]

(iii) There exists $\varepsilon > 0$ such that $(\mu \times \mu)(e^{\varepsilon \rho^2}) < \infty$.

Then $\mu$ is the unique invariant probability measure and $P_t$ is hypercontractive. Consequently, $P_t$ is compact in $L^2(\mu)$ for large $t > 0$, and there exist constants $c, \lambda > 0$ such that
\[
\mu((P_t f) \log P_t f) \leq ce^{-\lambda t} \mu(f \log f), \quad t \geq 0, f \geq 0, \mu(f) = 1;
\]
\[\|P_t f - \mu(f)\|_{L^2(\mu)} \leq ce^{-\lambda t}\|f - \mu(f)\|_{L^2(\mu)}, \quad f \in L^2(\mu), t \geq 0.
\]

To prove this result, we introduce two propositions on the hypercontractivity and applications for bounded linear operators. The first is generalized from [16] where symmetric Markov operators are considered.

**Proposition 2.2.** Let $P$ be a bounded linear operator on $L^2(\mu)$ such that $P1 = 1$ and $\mu$ is $P$-invariant, i.e. $\mu(P f) = \mu(f)$ for $f \in L^2(\mu)$. If $\|P\|_{L^2(\mu) \rightarrow L^4(\mu)} < 2$, then

1. $\|P - \mu\|_{L^2(\mu)} := \sup\{\|P f - \mu(f)\|_{L^2(\mu)} : \mu(f^2) \leq 1\} < 1$;

2. $\|P^n\|_{L^2(\mu) \rightarrow L^4(\mu)} = 1$ for large enough $n \in \mathbb{N}$.

**Proof.** (1) Let $\delta(P) := \|P\|_{L^2(\mu) \rightarrow L^4(\mu)} < 2$. For any $f \in L^2(\mu)$ with $\mu(f^2) = 1$ and $\mu(f) = 0$, we intend to prove
\[
\mu((P f)^2) \leq \inf_{\varepsilon \in (0, 1)} \frac{\sqrt{8\varepsilon^2 + \delta(P)} - 3\varepsilon}{1 - \varepsilon}.
\]

Without loss of generality, we assume $\mu((P f)^3) \geq 0$, otherwise it suffices to replace $f$ by $-f$. For any $\varepsilon \in (0, 1)$, let $g_\varepsilon = \sqrt{\varepsilon} + \sqrt{1 - \varepsilon} f$. Then $\mu(g_\varepsilon^2) = 1$. Since $P1 = 1$, $\mu(P f) = \mu(f) = 0, \mu((P f)^3) \geq 0, \mu(g_\varepsilon^2) = 1$ and $\mu((P f)^4) \geq \mu((P f)^2)^2$, we have
\[
\delta(P) \geq \mu((P g_\varepsilon)^4)
\]
\[= \varepsilon^2 + (1 - \varepsilon)^2 \mu((P f)^4) + 6\varepsilon(1 - \varepsilon) \mu((P f)^2) + 4\varepsilon^2 \sqrt{1 - \varepsilon} \mu(P f) + 4\sqrt{\varepsilon} \varepsilon(1 - \varepsilon) \mu((P f)^3)
\]
\[\geq (1 - \varepsilon)^2 \mu((P f)^2)^2 + 6\varepsilon(1 - \varepsilon) \mu((P f)^2) + \varepsilon^2.
\]

This implies (2.2). According to the calculations in [16, pages 2632-2633], $\delta(P) < 2$ and (2.2) imply
\[
\|P - \mu\|_{L^2(\mu)}^2 \leq \inf_{\varepsilon \in (0, 1)} \frac{\sqrt{8\varepsilon^2 + \delta(P)} - 3\varepsilon}{1 - \varepsilon} < 1.
\]
(2) For \( f \in L^2(\mu) \) with \( \mu(f^2) = 1 \), let \( \hat{f} = f - \mu(f) \). We have \( \mu(P^m \hat{f}) = 0, m \geq 1 \). Let \( \theta := \|P - \mu\|_{L^2(\mu)} \). Then

\[
\mu((P^m \hat{f})^2) \leq \theta^{2m} \mu(f^2), \quad m \geq 1,
\]

so that

\[
\mu((P^{m+1}f)^4) = \mu(f)^4 + 4\mu(f)\mu((P^{m+1}\hat{f})^3) + 6\mu(f)^2\mu((P^{m+1}\hat{f})^2) + \mu((P^{m+1}\hat{f})^4)
\]
\[
\leq \mu(f)^4 + 4\|P\|^3_{L^2(\mu)\to L^3(\mu)}\mu(f)\|\mu((P^m \hat{f})^2)\|^3_{L^2(\mu)}
\]
\[
+ 6\mu(f)^2\|\mu((P^{m+1}\hat{f})^2)\|_{L^2(\mu)\to L^4(\mu)}\mu((P^m \hat{f})^2)^2
\]
\[
\leq \mu(f)^4 + 4\|P\|^3_{L^2(\mu)\to L^3(\mu)}\theta^m\|\mu(f)\|\mu((\hat{f}^2)^2)^3_{L^2(\mu)}
\]
\[
+ 6\theta^{2(m+1)}\mu(f)^2\mu(\hat{f}^2) + \|P\|^4_{L^2(\mu)\to L^4(\mu)}\theta^{4m}\mu(\hat{f}^2)^2.
\]

Since \( \theta \in (0, 1) \) due to (1), \( \|P\|^n_{L^2(\mu)\to L^q(\mu)} \leq \|P\|^n_{L^2(\mu)\to L^q(\mu)} < \infty \), and

\[
2\|\mu(f)\|\mu(\hat{f}^2)^2 \leq \mu(f)^2\mu(\hat{f}^2) + \mu(\hat{f}^2)^2,
\]

this implies that for large enough \( m \geq 1 \),

\[
\mu((P^{m+1}f)^4) \leq \mu(f)^4 + 2\mu(f)^2\mu(\hat{f}^2) + \mu(\hat{f}^2)^2 = \mu(\hat{f}^2)^2 = 1.
\]

Therefore, \( \|P^n\|_{L^2(\mu)\to L^4(\mu)} \leq 1 \) holds for large enough \( n \geq 1 \).

Next, we present a result on exponential convergence implied by the hypercontractivity, which is well known in the literature of symmetric Markov semigroups.

**Proposition 2.3.** Let \( P \) be a positivity-preserving linear operator on \( L^1(\mu) \) such that \( \mu \) is \( P \)-invariant and \( \|P\|_{L^p(\mu)\to L^q(\mu)} \leq 1 \) holds for some constants \( q > p > 1 \). Then

\[
\mu((Pf) \log Pf) \leq \frac{(p-1)q}{p(q-1)} \mu(f \log f), \quad f \geq 0, \mu(f) = 1.
\]

Consequently,

\[
\mu((Pf)^2) \leq \frac{(p-1)q}{p(q-1)} \mu(f^2), \quad f \in L^2(\mu), \mu(f) = 0.
\]

**Proof.** Let \( f \in L^2(\mu) \) with \( \mu(f) = 0 \). By applying (2.3) to \( f_s := \frac{1+sf}{1+s\mu(f)} \), multiplying with \( s^{-2} \) and letting \( s \to 0 \), we prove (2.4). So, it suffices to prove (2.3). For any \( \varepsilon \in (0, p-1) \), let

\[
r = \frac{p-1-\varepsilon}{(1+\varepsilon)(p-1)}, \quad \delta(\varepsilon) = \frac{p(q-1)\varepsilon}{(p-1-\varepsilon)q + \varepsilon p}.
\]

Then

\[
\frac{1}{1+\varepsilon} = r + \frac{1-r}{p}, \quad \frac{1}{1+\delta(\varepsilon)} = r + \frac{1-r}{q}.
\]
Since \( \|P\|_{L^1(\mu)} = 1 \) and \( \|P\|_{L^p(\mu) \to L^q(\mu)} \leq 1 \), Riesz-Thorin’s interpolation theorem implies \( \|P\|_{L^{1+\varepsilon}(\mu) \to L^{1+\delta}(\varepsilon)(\mu)} \leq 1 \). So, for any \( f \in \mathcal{B}_0(\mu) \) with \( \mu(f) = 1 \),
\[
\int_E (Pf)^{1+\delta(\varepsilon)} \, d\mu \leq 1, \quad \varepsilon \in (0, p-1).
\]
Since the equality holds for \( \varepsilon = 0 \), this implies
\[
\frac{d}{d\varepsilon} \bigg|_{\varepsilon = 0} \int_E (Pf)^{1+\delta(\varepsilon)} \, d\mu \leq 0,
\]
which is equivalent to (2.3).

**Proof of Theorem 2.1.** (a) According to [19, Proposition 3.1], (i) implies that \( \mu \) is the unique invariant probability measure of \( P_t \), and \( P_t \) has a density with respect to \( \mu \). So, by [22, Theorem 2.3], if \( \|P_t\|_{L^2(\mu) \to L^2(\mu)} < \infty \) then \( P_{t+0} \) is compact in \( L^2(\mu) \). Therefore, according to Propositions 2.2 and 2.3, it remains to prove \( \|P_t\|_{L^2(\mu) \to L^4(\mu)} < 2 \) for large enough \( t > 0 \).

(b) Let \( f \in \mathcal{B}_0(\mu) \) with \( \mu(f^2) \leq 1 \). By (i) and (ii) we have
\[
(P_{t+t_0}f(\xi))^2 \leq \mathbb{E}(P_{t_0}f(X_t))^2 \leq \mathbb{E}
\left[
(P_{t_0}f^2(Y_t))e^{c_0 \rho(X_t, Y_t)^2}
\right] 
\leq (P_{t+t_0}f^2(\eta))e^{c_0 \rho(t, \eta)^2}, \quad t \geq 0, (\xi, \eta) \in E \times E.
\]
Equivalently,
\[
(P_{t+t_0}f(\xi))^2 e^{-c_0 \rho(t, \eta)^2} \leq P_{t+t_0}f^2(\eta), \quad t \geq 0, (\xi, \eta) \in E \times E.
\]
Integrating with respect to \( \mu(d\eta) \) gives
\[
(P_{t+t_0}f(\xi))^2 \int_E e^{-c_0 \rho(t, \eta)^2} \mu(d\eta) \leq \int_E P_{t+t_0}f^2(\eta) \mu(d\eta) = \mu(f^2) \leq 1, \quad t \geq 0, \xi \in E.
\]
Thus,
\[
(P_{t+t_0}f(\xi))^4 \leq \frac{1}{\left( \int_E \exp[-c_0 \rho(t)^2 \rho(\xi, \eta)^2] \mu(d\eta) \right)^2}, \quad \mu(f^2) \leq 1, t \geq 0, \xi \in E.
\]
Then by Jensen’s inequality, for \( t \geq 0 \)
\[
\sup_{\mu(f^2) \leq 1} \int_E (P_{t+t_0}f(\xi))^4 \mu(d\xi) \leq \int_E \left( \int_E \mu(d\xi) \right)^2 \mu(d\eta) \leq \int_E \left( \int_E \mu(d\xi) \right)^2 \mu(d\eta).
\]
Since \( \lim_{t \to \infty} \phi(t) = 0 \), it follows from (iii) that
\[
\lim_{t \to \infty} \int_{E \times E} e^{2c_0 \rho(t)^2 \rho(\xi, \eta)^2} \mu(d\xi) \mu(d\eta) = 1.
\]
Combining this with (2.5) we prove \( \|P_t\|_{L^4(\mu)} < 2 \) for large enough \( t > 0 \).
3 Hypercontractivity for finite-dimensional SHS

In this section, we consider the equation (1.3) with $H = \mathbb{R}^{m+d}$ for some $m,d \geq 1$. Let $\| \cdot \|$ denote the operator norm. To verify conditions (i)-(iii) in Theorem 2.1, we make the following assumptions.

(A1) $\sigma$ is invertible and $\text{Rank}[B, AB, \cdots, A^{m-1}B] = m$.

(A2) $Z : \mathbb{R}^{m+d} \to \mathbb{R}^d$ is Lipschitz continuous.

(A3) There exist constants $r, \theta > 0$ and $r_0 \in (-\|B\|^{-1}, \|B\|^{-1})$ such that
\[
\langle r^2 (x - \bar{x}) + rr_0 B(y - \bar{y}), A(x - \bar{x}) + B(y - \bar{y}) \rangle + \langle Z(x, y) - Z(\bar{x}, \bar{y}), y - \bar{y} + rr_0 B^*(x - \bar{x}) \rangle
\leq -\theta (|x - \bar{x}|^2 + |y - \bar{y}|^2), \quad (x, y), (\bar{x}, \bar{y}) \in \mathbb{R}^{m+d}.
\]

The rank condition in (A1) is known as Kalman’s condition, when $\sigma$ is invertible it is equivalent to the Hörmander condition. We will prove the Harnack inequality in condition (i) using (A1) and (A2), and verify conditions (ii) and (iii) by Assumption (A3).

**Theorem 3.1.** Assume (A1), (A2) and (A3). Let $P_t$ be the Markov semigroup associated with (1.3). Then

1. $P_t$ has a unique invariant probability measure $\mu$ and $\mu(e^{\varepsilon |x|^2}) < \infty$ for some $\varepsilon > 0$;
2. $P_t$ is hypercontractive, i.e. $\|P_t\|_{2 \to 4} = 1$ for large $t > 0$;
3. $P_t$ is compact in $L^2(\mu)$ for large $t > 0$, and there exist constants $c, \lambda > 0$ such that (2.1) holds.

In a similar spirit of (1.2), under a generalized curvature condition [3] proved the following entropy-information inequality for some constants $c, \lambda > 0$:
\[
\mu((P_t f) \log P_t f + (P_t f)|\nabla \log P_t f|^2) \leq ce^{-\lambda t} \mu(f \log f + f|\nabla \log f|^2), \quad f \geq 0, \mu(f) = 1, t \geq 0.
\]
This does not imply the entropy inequality in (2.1).

According to Theorem 2.1 and Proposition 2.3, Theorem 3.1 follows from the following three lemmas which correspond to conditions (i)-(iii) respectively. The first lemma provides the desired Harnack inequality. Although the Harnack inequality has been investigated in [11, 20] for SHS, the resulting results are not enough for our purpose: the inequality established in [11] (see Corollary 4.2 therein) contains a worse exponential term, while the assumption (H) in [20] does not hold if $Z$ is not second order differentiable. So, we present below a new version of Harnack inequality for SHS using coupling by change of measures. See [18, Chapter 1] for more results on the coupling by change measures and applications.
Lemma 3.2. Assume (A1) and (A2). For any $t_0 > 0$, there exists a constant $c_0 > 0$ such that
\[
(P_{t_0}f^2(\xi)) \leq (P_{t_0}f^2(\eta))e^{c_0|\xi-\eta|^2}, \quad f \in \mathcal{B}_0(\mathbb{R}^{m+d}), \xi, \eta \in \mathbb{R}^{m+d}.
\]

Proof. Let $(X_t, Y_t)$ solve the equation (1.3) with $(X_0, Y_0) = \eta \in \mathbb{R}^{m+d}$, and let $(\bar{X}_t, \bar{Y}_t)$ solve the following equation with $(\bar{X}_0, \bar{Y}_0) = \xi \in \mathbb{R}^{m+d}$:
\[
\begin{align*}
\frac{dX_t}{dt} &= (AX_t + BY_t) dt, \\
\frac{dY_t}{dt} &= \left\{Z(X_t, Y_t) + \frac{Y_0 - \bar{Y}_0}{t_0} + \frac{d}{dt}(t(t_0 - t)B^*e^{(t_0-t)A^*}b)\right\} dt + \sigma dW_t,
\end{align*}
\]
where $b \in \mathbb{R}^m$ is to be determined such that $(X_{t_0}, Y_{t_0}) = (\bar{X}_{t_0}, \bar{Y}_{t_0})$. It is easy to see that
\[
\begin{align*}
\frac{d}{dt}(X_t - \bar{X}_t) &= A(X_t - \bar{X}_t) + B(Y_t - \bar{Y}_t), \\
\frac{d}{dt}(Y_t - \bar{Y}_t) &= \frac{1}{t_0}(Y_0 - \bar{Y}_0) - \frac{d}{dt}(t(t_0 - t)B^*e^{(t_0-t)A^*}b).
\end{align*}
\]
Then
\[
Y_t - \bar{Y}_t = \frac{t_0 - t}{t_0}(Y_0 - \bar{Y}_0) - t(t_0 - t)B^*e^{(t_0-t)A^*}b,
\]
and
\[
X_t - \bar{X}_t = e^{At}(X_0 - \bar{X}_0) + \int_0^t e^{A(t-s)}B(Y_s - \bar{Y}_s)ds
\]
\[
= e^{At}(X_0 - \bar{X}_0) + \left(\int_0^t e^{A(t-s)}\frac{t_0 - s}{t_0}ds\right)B(Y_0 - \bar{Y}_0)
\]
\[
- \left(\int_0^t s(t_0 - s)e^{A(t-s)}BB^*e^{(t_0-s)A^*}ds\right)b.
\]

We now take
\[
b = Q_{t_0}^{-1}\left\{e^{t_0A}(X_0 - \bar{X}_0) + \left(\int_0^{t_0} \frac{t_0 - s}{t_0}e^{A(t_0-s)}ds\right)B(Y_0 - \bar{Y}_0)\right\},
\]
where, according to [13, §3], the rank condition in (A1) ensures the invertibility of the $m \times m$-matrix
\[
Q_{t_0} := \int_0^{t_0} s(t_0 - s)e^{A(t_0-s)}BB^*e^{(t_0-s)A^*}ds,
\]
see (1) in the proof of [20, Theorem 4.2] for details. Then (3.2)-(3.4) imply $(X_{t_0}, Y_{t_0}) = (\bar{X}_{t_0}, \bar{Y}_{t_0})$.

In order to establish the Harnack inequality using Girsanov’s theorem, let
\[
\psi_t = Z(X_t, Y_t) - Z(\bar{X}_t, \bar{Y}_t) + \frac{1}{t_0}(Y_0 - \bar{Y}_0) + \frac{d}{dt}(t(t_0 - t)B^*e^{(t_0-t)A^*}b), \quad t \in [0, t_0].
\]
Since $Z$ is Lipschitz continuous, (3.2), (3.3) and (3.4) imply
\begin{equation}
|\psi_t|^2 \leq c_1(|X_0 - \bar{X}_0|^2 + |Y_0 - \bar{Y}_0|^2) = c_1|\xi - \eta|^2, \quad t \in [0, t_0]
\end{equation}
for some constant $c_1 > 0$. Moreover, according to the definition of $\psi$, (3.1) can be reformulated as
\[
\begin{align*}
\begin{cases}
d\bar{X}_t = (A\bar{X}_t + B\bar{Y}_t)dt, \\
d\bar{Y}_t = Z(\bar{X}_t, \bar{Y}_t)dt + \sigma dW_t,
\end{cases}
\end{align*}
\]
where
\[
\bar{W}_t := W_t + \sigma^{-1} \int_0^t \psi_s ds, \quad t \in [0, t_0].
\]
Let
\begin{equation}
R := \exp \left[ - \int_0^{t_0} (\sigma^{-1} \psi_t, dW_t) - \frac{1}{2} \int_0^{t_0} |\sigma^{-1} \psi_s|^2 dt \right].
\end{equation}
By (3.5) and Girsanov’s theorem, $\bar{W}_t$ is a $d$-dimensional Brownian motion under the probability measure $dQ := RdP$. Therefore, by the weak uniqueness of the equation (1.3) and using $(X_{t_0}, Y_{t_0}) = (\bar{X}_{t_0}, \bar{Y}_{t_0})$, we obtain
\[
(P_{t_0} f(\xi))^2 = (\mathbb{E}[Rf(\bar{X}_{t_0}, \bar{Y}_{t_0})])^2 
= (\mathbb{E}[Rf(X_{t_0}, Y_{t_0})])^2 
\leq (\mathbb{E}R^2) \mathbb{E}f^2(X_{t_0}, Y_{t_0}) = (P_{t_0} f^2(\eta)) \mathbb{E}R^2.
\]
Noting that (3.5) and (3.6) imply $\mathbb{E}R^2 \leq c_0|\xi - \eta|^2$ for some constant $c_0 > 0$, we finish the proof. \qed

**Lemma 3.3.** If (A3) holds, then there exist two constants $c, \lambda > 0$ such that for any two solutions $(X_t, Y_t)$ and $(\bar{X}_t, \bar{Y}_t)$ of (1.3),
\[
|X_t - \bar{X}_t|^2 + |Y_t - \bar{Y}_t|^2 \leq c e^{-\lambda t}(|X_0 - \bar{X}_0|^2 + |Y_0 - \bar{Y}_0|^2), \quad t \geq 0.
\]
**Proof.** Obviously, $X_t - \bar{X}_t$ solves the ODE
\begin{equation}
\begin{align*}
\begin{cases}
\frac{d}{dt}(X_t - \bar{X}_t) = A(X_t - \bar{X}_t) + B(Y_t - \bar{Y}_t), \\
\frac{d}{dt}(Y_t - \bar{Y}_t) = (Z(X_t, Y_t) - Z(\bar{X}_t, \bar{Y}_t)) dt.
\end{cases}
\end{align*}
\end{equation}
Since $r_0 \in (-\|B\|^{-1}, \|B\|^{-1})$, for any $r > 0$ there exists a constant $C > 1$ such that
\begin{equation}
\begin{align*}
\frac{1}{C}(|X_t - \bar{X}_t|^2 + |Y_t - \bar{Y}_t|^2) 
\leq \Phi_t := \frac{r^2}{2} |X_t - \bar{X}_t|^2 + \frac{1}{2} |Y_t - \bar{Y}_t|^2 + rr_0 \langle X_t - \bar{X}_t, B(Y_t - \bar{Y}_t) \rangle 
\leq C(|X_t - \bar{X}_t|^2 + |Y_t - \bar{Y}_t|^2), \quad t \geq 0.
\end{align*}
\end{equation}
Combining this with (3.7) and (A3), we obtain
\[
d\Phi_t \leq -\theta(|X_t - \bar{X}_t|^2 + |Y_t - \bar{Y}_t|^2) \leq -\frac{\theta}{C} \Phi_t dt.
\]
Therefore, $\Phi_t \leq \Phi_0 e^{-\theta t/C}$. This together with (3.8) implies the desired estimate. \qed
Lemma 3.4. If (A3) holds, then $P_t$ has an invariant probability measure $\mu$ such that $\mu(e^{\varepsilon|\cdot|^2}) < \infty$ for some constant $\varepsilon > 0$.

Proof. Let $(X_t, Y_t)$ solve (1.3) with $(X_0, Y_0) = 0 \in \mathbb{R}^{m+d}$. By a standard tightness argument, it suffices to prove

$$
\sup_{t \geq 0} \mathbb{E} e^{\varepsilon(|X_t|^2 + |Y_t|^2)} < \infty
$$

for some constant $\varepsilon > 0$. Since $r_0 \in (-\|B\|^{-1}, \|B\|^{-1})$, for any $r > 0$ there exists a constant $C > 1$ such that

$$
\frac{1}{C} (|X_t|^2 + |Y_t|^2) \leq \Psi_t := \frac{r_0^2}{2} |X_t|^2 + \frac{1}{2} |Y_t|^2 + r r_0 \langle X_t, B Y_t \rangle
$$

$$
\leq C(|X_t|^2 + |Y_t|^2), \quad t \geq 0.
$$

Moreover, (A3) with $(\bar{x}, \bar{y}) = 0$ implies

$$
\langle r^2 x + r r_0 B y, A x + B y \rangle + \langle Z(x, y) - Z(0, 0), y + r r_0 B^* x \rangle \leq -\theta(|x|^2 + |y|^2), \quad (x, y) \in \mathbb{R}^{m+d}.
$$

Then there exist constants $c_1, c_2 > 0$ such that

$$
\langle r^2 x + r r_0 B y, A x + B y \rangle + \langle Z(x, y), y + r r_0 B^* x \rangle
$$

$$
\leq |Z(0, 0)| \cdot |y + r B^* x| - \theta(|x|^2 + |y|^2) \leq c_1 - c_2 (|x|^2 + |y|^2), \quad (x, y) \in \mathbb{R}^{m+d}.
$$

Thus, by (1.3), Itô’s formula and (3.10), we may find out two constants $c_3, c_4 > 0$ such that

$$
d\Psi_t \leq (c_3 - c_4 (|X_t|^2 + |Y_t|^2)) dt + \langle Y_t + r B^* X_t, \sigma dW_t \rangle
$$

$$
\leq (c_3 - c_4 \Psi_t) dt + \langle Y_t + r B^* X_t, \sigma dW_t \rangle.
$$

By Itô’s formula, for any $\varepsilon > 0$ there exists a local martingale $M_t$ such that

$$
de^{\varepsilon \Psi_t} \leq \varepsilon e^{\varepsilon \Psi_t} (c_3 - c_4 \Psi_t + \frac{\varepsilon^2}{2} |\sigma^* (Y_t + r B^* X_t)|^2) dt + dM_t.
$$

Noting that (3.10) implies $|\sigma^* (Y_t + r B^* X_t)|^2 \leq c_5 \Psi_t$ for some constant $c_5 > 0$, by taking $\varepsilon = \frac{c_4}{c_5}$ we obtain

$$
de^{\varepsilon \Psi_t} \leq \varepsilon e^{\varepsilon \Psi_t} (c_3 - \frac{1}{2} c_4 \Psi_t) dt + dM_t \leq (c_6 - e^{\varepsilon \Psi_t}) dt + dM_t
$$

for some constant $c_6 \geq 1$. Since $e^{\varepsilon \Psi_0} = 1$, it follows that

$$
\mathbb{E} e^{\varepsilon \Psi_t} \leq c_6, \quad t \geq 0.
$$

Because of (3.10), this implies (3.9) for small $\varepsilon > 0$. 

\[\square\]
4 Hypercontractivity for infinite-dimensional SHS

When $\mathbb{H}_2$ is infinite-dimensional and $\sigma$ is not Hilbert-Schmidt, $\sigma W_t$ is ill defined on $\mathbb{H}_2$, so that the usual strong solution of (1.3) does not make sense. Alternatively, we consider the mild solution. To this end, we reformulate (1.3) on $\mathbb{H} := \mathbb{H}_1 \times \mathbb{H}_2$ as follows:

\[
\begin{align*}
\left\{ \begin{array}{l}
\frac{dX_t}{dt} = (AX_t + BY_t - L_1 X_t) dt, \\
\frac{dY_t}{dt} = \{Z(X_t, Y_t) - L_2 Y_t\} dt + \sigma dW_t,
\end{array} \right.
\]

where $A : \mathbb{H}_1 \rightarrow \mathbb{H}_1$, $B : \mathbb{H}_2 \rightarrow \mathbb{H}_1$ and $\sigma : \mathbb{H}_2 \rightarrow \mathbb{H}_2$ are bounded linear operators; $(L_i, \mathcal{D}(L_i))$ is a positive definite self-adjoint operator on $\mathbb{H}_i$, $i = 1, 2$; and $Z : \mathbb{H}_i \rightarrow \mathbb{H}_2$ is measurable. This equation reduces to (1.3) if we regard $A - L_1$ as one operator and combine $Z(x, y)$ with $-L_2 y$. The unbounded operator $L_2$ plays a crucial role in the study of mild solutions (see [5]), while $L_1$ is the counterpart of $L_2$ for the first component process $X_t$, and the bounded operator $A$ stands for a perturbation of $L_1$, see (B3) below.

Let $\langle \cdot, \cdot \rangle$, $|\cdot|$ and $\|\cdot\|$ denote, respectively, the inner product, the norm and the operator norm on a Hilbert space. Moreover, for a linear operator $(L, \mathcal{D}(L))$ on a Hilbert space, and for $\lambda \in \mathbb{R}$, we write $L \geq \lambda$ if $\langle f, Lf \rangle \geq \lambda |f|^2$ holds for all $f \in \mathcal{D}(L)$.

To prove the hypercontractivity using Theorem 2.1, we will need the following assumptions.

\begin{enumerate}
\item[(B1)] $\sigma$ is invertible, $L_2$ has discrete spectrum with eigenbasis $\{e_i\}_{i \geq 1}$ and corresponding eigenvalues $0 < \lambda_1 \leq \lambda_2 \leq \cdots$ including multiplicities satisfy $\sum_{i=1}^{\infty} \frac{1}{\lambda_i} < \infty$.
\item[(B2)] There exist two constants $K_1, K_2 > 0$ such that

$$|Z(x, y) - Z(\bar{x}, \bar{y})| \leq K_1|x - \bar{x}| + K_2|y - \bar{y}|, \quad (x, y), (\bar{x}, \bar{y}) \in \mathbb{H}.$$ 

\item[(B3)] $L_1 - A \geq \lambda_1 - \delta$ for some constant $\delta \geq 0$, $BL_2 = L_1 B$, $AL_1 = L_1 A$, and for any $t > 0$

\[
Q_t := \int_0^t e^{sA}BB^*e^{sA^*} ds
\]

is an invertible operator on $\mathbb{H}_1$.
\end{enumerate}

It is well known that (B1) and (B2) imply the existence and uniqueness of mild solutions for (4.1), see [5]. Let $P_t$ be the associated Markov semigroup.

**Theorem 4.1.** Assume (B1), (B2) and (B3). If

\[
\lambda_1 > \lambda' := \frac{1}{2} \left( \delta + K_2 + \sqrt{(K_2 - \delta)^2 + 4K_1\|B\|} \right),
\]

then all assertions in Theorem 3.1 hold.
As shown in the proof of Theorem 3.1, we need to verify conditions (i)-(iii) in Theorem 2.1. Let \((X_t, Y_t)\) be a mild solution to (4.1). We have

\[
\begin{align*}
X_t &= e^{-(L_1-A+\delta)t}X_0 + \int_0^t e^{-(L_1-A+\delta)(t-s)}(\delta X_s + BY_s)ds, \\
Y_t &= e^{-L_2t}Y_0 + \int_0^t e^{-L_2(t-s)}Z(X_s, Y_s)ds + \xi_t,
\end{align*}
\]

where

\[
\xi_t := \int_0^t e^{-L_2(t-s)}\sigma dW_s, \quad t \geq 0.
\]

Due to (B1), for any \(T > 0\), the process

\[
M_T^T := \int_0^t e^{-L_2(T-s)}\sigma dW_s, \quad t \in [0, T]
\]

is a square integrable martingale on \(\mathbb{H}\) with quadratic variation process

\[
\langle M_T^T \rangle_t = \int_0^t \|e^{-L_2(T-s)}\sigma\|_{HS}^2 ds \leq \|\sigma\|^2 \sum_{i=1}^{\infty} \frac{1}{2\lambda_i} =: \alpha_0 < \infty, \quad t \in [0, T],
\]

where \(\| \cdot \|_{HS}\) is the Hilbert-Schmidt norm. This implies

\[
\mathbb{E}\exp\left[\frac{|M_T^T|^2}{2 + \alpha_0}\right] \leq C, \quad T > 0, t \in [0, T]
\]

for some constant \(C > 0\). Indeed, since

\[
d|M_T^T|^2 = 2\langle M_T^T, dM_T^T \rangle + d\langle M_T^T \rangle_t, \quad t \in [0, T],
\]

by Itô’s formula, for any \(r > 0\) we have

\[
d\left\{ \exp\left[ r\frac{|M_T^T|^2 + 1}{\langle M_T^T \rangle_t + 1} \right] \right\} = \exp\left[ r\frac{|M_T^T|^2 + 1}{\langle M_T^T \rangle_t + 1} \right] \cdot \frac{2r}{\langle M_T^T \rangle_t + 1} \langle M_T^T, dM_T^T \rangle
\]

\[
- \exp\left[ r\frac{|M_T^T|^2 + 1}{\langle M_T^T \rangle_t + 1} \right] \left\{ \frac{r|M_T^T|^2 + 1 - r\langle M_T^T \rangle_t - r - 2r^2|M_T^T|^2}{\langle M_T^T \rangle_t + 1} \right\} d\langle M_T^T \rangle_t, \quad t \in [0, T].
\]

Since \(\langle M_T^T \rangle_t \leq \alpha_0\), when \(r \in (0, \frac{1}{2 + \alpha_0})\) the process \(\exp\left[ r\frac{|M_T^T|^2 + 1}{\langle M_T^T \rangle_t + 1} \right]\) for \(t \in [0, T]\) is a supermartingale. In particular, by taking \(r = \frac{1}{2 + \alpha_0}\) we prove (4.4).

Since \(\xi_T = M_T^T\) for any \(T > 0\), (4.4) implies

\[
\sup_{t \geq 0} \mathbb{E}\exp\left[ \frac{|\xi_t|^2}{2 + \alpha_0} \right] \leq C.
\]

We are now ready to prove the following four lemmas which imply Theorem 4.1 according to Theorem 2.1.
Lemma 4.2. Assume (B1), (B2) and (B3). For any \( t_0 > 0 \), there exists a constant \( c_0 > 0 \) such that
\[
(P_{t_0} f)^2(\xi) \leq (P_{t_0} f^2(\eta))e^{c_0|\xi - \eta|^2}, \quad f \in B_b(\mathbb{H}), \xi, \eta \in \mathbb{H} := \mathbb{H}_1 \times \mathbb{H}_2.
\]

Proof. Let \((X_t, Y_t)\) solve (4.1) with \((X_0, Y_0) = \eta\), and let \((\bar{X}_t, \bar{Y}_t)\) solve the following equation for \((\bar{X}_0, \bar{Y}_0) = \xi:\)
\[
\begin{align*}
    d\bar{X}_t &= (A\bar{X}_t + BY_t - L_1\bar{X}_t)dt, \\
    d\bar{Y}_t &= \left\{ Z(X_t, Y_t) - L_2\bar{Y}_t + \frac{1}{t_0}e^{-L_2t}(Y_0 - \bar{Y}_0) + e^{-L_2t} \frac{d}{dt}(t(t_0 - t)B^*e^{(t_0-t)A^*}b) \right\}dt + \sigma dW_t,
\end{align*}
\]
where \(b \in \mathbb{H}_1\) will be determined latter such that \((X_{t_0}, Y_{t_0}) = (\bar{X}_{t_0}, \bar{Y}_{t_0})\). We have
\[
\begin{align*}
    d(X_t - \bar{X}_t) &= \left\{ A(X_t - \bar{X}_t) + B(Y_t - \bar{Y}_t) - L_1(X_t - \bar{X}_t) \right\}dt, \\
    d(Y_t - \bar{Y}_t) &= -\left\{ L_2(Y_t - \bar{Y}_t) + \frac{1}{t_0}e^{-L_2t}(Y_0 - \bar{Y}_0) + e^{-L_2t} \frac{d}{dt}(t(t_0 - t)B^*e^{(t_0-t)A^*}b) \right\}dt.
\end{align*}
\]
Then
\[
Y_t - \bar{Y}_t = \frac{t_0 - t}{t_0}e^{-L_2t}(Y_0 - \bar{Y}_0) - (t(t_0 - t)e^{-L_2t}B^*e^{(t_0-t)A^*}b, \quad t \in [0, t_0],
\]
and, since \(BL_2 = L_1B, AL_1 = L_1A\),
\[
X_t - \bar{X}_t = e^{(A-L_1)t}(X_0 - \bar{X}_0) + \int_0^t \frac{t_0 - s}{t_0}e^{(A-L_1)(t-s)}Be^{-L_2s}(Y_0 - \bar{Y}_0)ds \\
- \int_0^t s(t_0 - s)e^{(A-L_1)(t-s)}Be^{-L_2s}B^*e^{A^*(t_0-s)}b ds
\]
\[
= e^{-tL_1}\left\{ e^{At}(X_0 - \bar{X}_0) + \int_0^t \frac{t_0 - s}{t_0}e^{A(t_0-s)}B(Y_0 - \bar{Y}_0)ds \\
- \int_0^t s(t_0 - s)e^{A(t_0-s)}BB^*e^{A^*(t_0-s)}b ds \right\}.
\]
According to (B3), the operator
\[
\tilde{Q}_{t_0} := \int_0^{t_0} s(t_0 - s)e^{A(t_0-s)}BB^*e^{A^*(t_0-s)}ds
\]
is invertible on \(\mathbb{H}_1\). So, letting
\[
b = \tilde{Q}_{t_0}^{-1}\left\{ e^{At_0}(X_0 - \bar{X}_0) + \int_0^{t_0} \frac{t_0 - s}{t_0}e^{A(t_0-s)}B(Y_0 - \bar{Y}_0)ds \right\},
\]
we conclude from (4.6) and (4.7) that \((X_{t_0}, Y_{t_0}) = (\bar{X}_{t_0}, \bar{Y}_{t_0})\). Moreover, there exists a constant \(C_1 > 0\) such that
\[
|X_t - \bar{X}_t| + |Y_t - \bar{Y}_t| \leq C_1(|X_0 - \bar{X}_0| + |Y_0 - \bar{Y}_0|), \quad t \in [0, t_0].
\]
Since $A, B$ are bounded, $\sigma$ is reversible, and $Z$ is Lipschitz continuous, this implies that the process
\[
\psi_t := \sigma^{-1}\left\{ Z(X_t, Y_t) - Z(\tilde{X}_t, \tilde{Y}_t) + \frac{1}{t_0} e^{-L_{2t}}(Y_0 - \tilde{Y}_0) + e^{-L_{2t}} \frac{d}{dt} \left( t(t_0 - t)B^* e^{(t_0 - t)A^*}b \right) \right\}
\]
satisfies
\[
|\psi_t|^2 \leq C_2(|X_0 - \tilde{X}_0|^2 + |Y_0 - \tilde{Y}_0|^2), \quad t \in [0, t_0]
\]
for some constant $C_2 > 0$. By the Girsanov theorem,
\[
\tilde{W}_t := W_t + \int_0^t \psi_s \, ds, \quad t \in [0, t_0]
\]
is a cylindrical Brownian motion on $\mathbb{H}_2$ under the probability measure $dQ := R \, d\mathbb{P}$, where
\[
R := \exp \left[-\int_0^{t_0} \langle \psi_s, dW_s \rangle - \frac{1}{2} \int_0^{t_0} |\psi_s|^2 \, ds \right].
\]
Rewrite the equation for $(\tilde{X}_t, \tilde{Y}_t)$ as
\[
\begin{aligned}
d\tilde{X}_t &= (AX_t + BY_t - L_1 \tilde{X}_t) \, dt,
d\tilde{Y}_t &= \left\{ Z(\tilde{X}_t, \tilde{Y}_t) - L_2 \tilde{Y}_t \right\} \, dt + \sigma d\tilde{W}_t.
\end{aligned}
\]
By the weak uniqueness of the mild solutions to (4.1) and $(X_{t_0}, Y_{t_0}) = (\tilde{X}_{t_0}, \tilde{Y}_{t_0})$, we obtain
\[
(P_{t_0} f(\xi))^2 = (\mathbb{E}_Q f(\tilde{X}_{t_0}, \tilde{Y}_{t_0}))^2 \leq (\mathbb{E}[Rf(X_{t_0}, Y_{t_0})])^2 \leq (P_{t_0} f^2)(\eta) \mathbb{E} R^2 \leq (P_{t_0} f^2)(\eta) e^{c_0 |\xi - \eta|^2}
\]
for some constant $c_0 > 0$.

\[\Box\]

**Lemma 4.3.** Assume (B1), (B2) and (B3). Let $(X_t, Y_t)$ solve (4.3) for $X_0 = Y_0 = 0$. If $\lambda_1 > \lambda'$, then there exists a constant $\varepsilon > 0$ such that $\sup_{t \geq 0} \mathbb{E} e^{\varepsilon (|X_t|^2 + |Y_t|^2)} < \infty$.

**Proof.** By (B2), there exists a constant $c > 0$ such that
\[
|Z(x, y)| \leq c + K_1 |x| + K_2 |y|, \quad x, y \in \mathbb{H}.
\]
Combining this with (4.3), and noting that (B1) and (B3) imply $L_1 - A + \delta \geq \lambda_1$ and $L_2 \geq \lambda_1$, we obtain
\[
\begin{aligned}
|X_t| &\leq \int_0^t e^{-\lambda_1(t-s)} (\delta |X_s| + \|B\| \cdot |Y_s|) \, ds,
|Y_t| &\leq \int_0^t e^{-\lambda_1(t-s)} (c + K_1 |X_s| + K_2 |Y_s|) \, ds + |\xi_t|.
\end{aligned}
\]
(4.9)

By (B2) and (B3), we have
\[
\alpha := \frac{1}{2\|B\|} \left( \delta - K_2 + \sqrt{(K_2 - \delta)^2 + 4K_1 \|B\|} \right) \in (0, \infty).
\]

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Obviously, the definitions of $\alpha$ and $\lambda'$ in (4.2) imply
\begin{equation}
\lambda'\alpha = \alpha \delta + K_1, \quad \alpha \|B\| + K_2 = \lambda'.
\end{equation}
So,
\begin{equation}
(\alpha \delta + K_1)s + (\alpha \|B\| + K_2)t = \lambda'(\alpha s + t), \quad s, t \geq 0.
\end{equation}
Combining this with (4.9), we obtain
\begin{align*}
\alpha |X_t| + |Y_t| &\leq \int_0^t e^{-\lambda_1(t-s)} \left\{ c + (\alpha \delta + K_1)|X_s| + (\alpha \|B\| + K_2)|Y_s| \right\} ds + |\xi_t| \\
&\leq \lambda' \int_0^t e^{-\lambda_1(t-s)} (\alpha |X_s| + |Y_s|) ds + |\xi_t| + \frac{c}{\lambda_1}.
\end{align*}
By Gronwall's inequality, this implies
\begin{equation}
\alpha |X_t| + |Y_t| \leq |\xi_t| + \frac{c}{\lambda_1} + \lambda' \int_0^t e^{-\lambda_1(t-s)} \left( |\xi_s| + \frac{c}{\lambda_1} \right) ds \\
\leq |\xi_t| + c_1 + \lambda' \int_0^t e^{-\lambda_1(t-s)} |\xi_s| ds, \quad t \geq 0
\end{equation}
for some constant $c_1 > 0$ and $\lambda := \lambda_1 - \lambda' > 0$.

Finally, applying Jensen’s inequality to the probability measure $\nu(ds) := \lambda e^{-\lambda(t-s)} ds$ on $(-\infty, t]$, we obtain
\begin{align*}
\exp \left[ \varepsilon \left( \lambda' \int_0^t e^{-\lambda_1(t-s)} |\xi_s| ds \right)^2 \right] &\leq \exp \left[ \frac{\varepsilon}{\lambda^2} \left( \lambda' \int_{-\infty}^t 1_{[0, t]}(s) |\xi_s| \nu(ds) \right)^2 \right] \\
&\leq \int_{-\infty}^t \exp \left[ \frac{\varepsilon (\lambda')^2}{\lambda^2} 1_{[0, t]}(s) |\xi_s|^2 \right] \nu(ds) \\
&\leq c_2 + c_2 \int_0^t e^{-\lambda_1(t-s)} \exp \left[ c_2 \varepsilon |\xi_s|^2 \right] ds, \quad t, \varepsilon \geq 0
\end{align*}
for some constant $c_2 > 0$. Combining this with (4.5) and (4.11), we finish the proof. \qed

**Lemma 4.4.** Assume (B1), (B2) and (B3). If $\lambda_1 > \lambda'$, then $P_t$ has a unique invariant probability measure $\mu$, and $\mu(e^{c|\cdot|^2}) < \infty$ holds for some constant $\varepsilon > 0$.

**Proof.** According to [19, Proposition 3.1], the Harnack inequality in Lemma 4.2 implies that $P_t$ has at most one invariant probability measure. So, it suffices to prove the existence of $\mu$ with $\mu(e^{c|\cdot|^2}) < \infty$ for some constant $\varepsilon > 0$.

Let $(X_t, Y_t)_{t \geq 0}$ solve (4.1) for $X_0 = Y_0 = 0$. For every $t \geq 0$, let $\mu_t$ be the distribution of $(X_t, Y_t)$, which is a probability measure on $\mathbb{H}$. By the Markov property, if $\mu_t$ converges weakly to a probability measure $\mu$ as $t \to \infty$, then $\mu$ is an invariant probability measure of $P_t$ and, by Lemma 4.3 and Fatou’s lemma, $\mu(e^{c|\cdot|^2}) < \infty$ holds for some constant $\varepsilon > 0$. Therefore, it remains to prove the weak convergence of $\mu_t$ as $t \to \infty$. 

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Consider the $L^1$-Wasserstein distance
\[
W(\nu_1, \nu_2) := \inf_{\pi \in \mathcal{C}(\nu_1, \nu_2)} \int_{\mathbb{H} \times \mathbb{H}} |\cdot| d\pi
\]
for two probability measures $\nu_1$ and $\nu_2$ on $\mathbb{H} \times \mathbb{H}$, where $\mathcal{C}(\nu_1, \nu_2)$ is the set of all couplings of these two measures. If $\mu_t$ is a $W$-Cauchy family as $t \to \infty$, i.e.
\[
\lim_{t_1, t_2 \to \infty} W(\mu_{t_1}, \mu_{t_2}) = 0,
\]
then it converges weakly as $t \to \infty$, see e.g. [4, Theorem 5.4 and Theorem 5.6].

To prove (4.12), for any $t_2 > t_1 > 0$, let $(X_t, Y_t)_{t \geq 0}$ solve (4.1) for $X_0 = Y_0 = 0$, and let $(\tilde{X}_t, \tilde{Y}_t)_{t \geq t_2 - t_1}$ solve the following equation with $\tilde{X}_{t_2-t_1} = \tilde{Y}_{t_2-t_1} = 0$:
\[
\begin{aligned}
\frac{d\tilde{X}_t}{dt} &= (A\tilde{X}_t + B\tilde{Y}_t - L_1\tilde{X}_t)dt, \\
\frac{d\tilde{Y}_t}{dt} &= \{Z(\tilde{X}_t, \tilde{Y}_t) - L_2\tilde{Y}_t\}dt + \sigma dW_t, \quad t \geq t_2 - t_1.
\end{aligned}
\]

Then the distribution of $(X_{t_2}, Y_{t_2})$ is $\mu_{t_2}$ while that of $(\tilde{X}_{t_2}, \tilde{Y}_{t_2})$ is $\mu_{t_1}$. By the definition of $W$, we have
\[
W(\mu_{t_1}, \mu_{t_2}) \leq \mathbb{E}(|X_{t_2} - \tilde{X}_{t_2}| + |Y_{t_2} - \tilde{Y}_{t_2}|).
\]

On the other hand, (4.1), (4.13), (B2) and (B3) imply that for any $t \geq t_2 - t_1$,
\[
\begin{aligned}
|X_t - \tilde{X}_t| &\leq e^{-\lambda_1(t-t_2+t_1)}|X_{t_2-t_1}| + \int_{t_2-t_1}^{t} e^{-\lambda_1(t-s)}(\delta|X_s - \tilde{X}_s| + \|B\| \cdot |Y_s - \tilde{Y}_s|)ds, \\
|Y_t - \tilde{Y}_t| &\leq e^{-\lambda_1(t-t_2+t_1)}|Y_{t_2-t_1}| + \int_{t_2-t_1}^{t} e^{-\lambda_1(t-s)}(K_1|X_s - \tilde{X}_s| + K_2|Y_s - \tilde{Y}_s|)ds.
\end{aligned}
\]

Then by (4.10), for $t \geq t_2 - t_1$
\[
\begin{aligned}
\alpha|X_t - \tilde{X}_t| + |Y_t - \tilde{Y}_t| \\
&\leq e^{-\lambda_1(t+t_1-t_2)}(\alpha|X_{t_1}| + |Y_{t_1}|) + \lambda' \int_{t_2-t_1}^{t} e^{-\lambda_1(t-s)}(\alpha|X_s - \tilde{X}_s| + |Y_s - \tilde{Y}_s|)ds.
\end{aligned}
\]

By Gronwall’s inequality, we obtain
\[
\begin{aligned}
\alpha|X_t - \tilde{X}_t| + |Y_t - \tilde{Y}_t| &\leq (\alpha|X_{t_1}| + |Y_{t_1}|)e^{-\lambda_1 t_1}\left(1 + \lambda' \int_{t_2-t_1}^{t} e^{\lambda'(t_2-s)}ds\right) \\
&\leq 2(\alpha|X_{t_1}| + |Y_{t_1}|)e^{-(\lambda_1 - \lambda') t_1}.
\end{aligned}
\]

Since $\sup_{t \geq 0} \mathbb{E}(|X_t| + |Y_t|) < \infty$ due to Lemma 4.3, this together with (4.14) implies (4.12). The proof is therefore finished. 

\[\square\]
Lemma 4.5. Assume (B1), (B2) and (B3). If $\lambda_1 > \lambda'$, then there exists a constant $C > 0$ such that for any mild solutions $(X_t, Y_t)$ and $(\tilde{X}_t, \tilde{Y}_t)$ of the equation (4.1),

$$|X_t - \tilde{X}_t| + |Y_t - \tilde{Y}_t| \leq C(|X_0 - \tilde{X}_0| + |Y_0 - \tilde{Y}_0|) e^{-(\lambda_1 - \lambda')t}, \quad t \geq 0.$$ 

\textbf{Proof.} Similarly to the proof of (4.15), we have

$$\alpha |X_t - \tilde{X}_t| + |Y_t - \tilde{Y}_t| \leq e^{-\lambda t}(\alpha |X_0 - \tilde{X}_0| + |Y_0 - \tilde{Y}_0|) + \lambda' \int_0^t e^{-\lambda_1(t-s)}(\alpha |X_s - \tilde{X}_s| + |Y_s - \tilde{Y}_s|) ds, \quad t \geq 0.$$ 

By Gronwall’s inequality,

$$\alpha |X_t - \tilde{X}_t| + |Y_t - \tilde{Y}_t| \leq e^{-(\lambda_1 - \lambda')t}(\alpha |X_0 - \tilde{X}_0| + |Y_0 - \tilde{Y}_0|), \quad t \geq 0.$$ 

This completes the proof. \hfill \Box

5 Some Examples

In this section, we present three examples to illustrate Theorems 3.1 and 4.1, where the first includes the kinetic Fokker-Planck equation discussed in [14] for $V(x) = -\frac{1}{2}|x|^2 + \nabla W$ with small $\|\nabla^2 W\|_\infty$, the second is highly degenerate in the sense that $m$ can be much larger than $d$, and the last is an infinite-dimensional model.

\textbf{Example 5.1.} Let $d = m$ and $\sigma$ be invertible, $A = 0$, $B = I$, and $Z(x, y) = \nabla W(x) - x - y$ for some $W \in C^2(\mathbb{R}^d)$. If $\|\nabla^2 W\|_\infty < 1$ is small enough such that

$$(5.1) \quad 1 > \inf_{r_0 \in (0,1)} \left\{ \frac{\|\nabla^2 W\|_\infty^2}{2r_0(1 - \|\nabla^2 W\|_\infty)(1 + \sqrt{1 + 4r_0})} + \frac{r_0}{2} \left(1 + \sqrt{1 + 4r_0}\right) \right\},$$

then all assertions in Theorem 3.1 hold. In particular, (5.1) holds if $\|\nabla^2 W\|_\infty \leq \frac{1}{2}$.

\textbf{Proof.} It is trivial that (A1) and (A2) hold. To verify (A3), let $r > 0$ and $r_0 \in (0, 1) = (0, \|B\|^{-1})$. By $A = 0$, $B = I$ and the formulation of $Z$, we have

$$\left< \langle r^2(x - \bar{x}) + rr_0B(y - \bar{y}), A(x - \bar{x}) + B(y - \bar{y}) \rangle + \langle Z(x, y) - Z(\bar{x}, \bar{y}), y - \bar{y} + rr_0B^*(x - \bar{x}) \rangle \right>$$

$$= (r^2 - 1 - rr_0)\langle x - \bar{x}, y - \bar{y} \rangle + rr_0|y - \bar{y}|^2 + \langle \nabla W(x) - \nabla W(\bar{x}), y - \bar{y} + rr_0(x - \bar{x}) \rangle$$

$$- rr_0|x - \bar{x}|^2 - |y - \bar{y}|^2.$$ 

Take

$$(5.2) \quad r = \frac{1}{2} \left(1 + \sqrt{1 + 4r_0}\right)$$
such that \( r^2 - 1 - rr_0 = 0 \), we obtain
\[
\langle r^2(x - \bar{x}) + rr_0B(y - \bar{y}), A(x - \bar{x}) + B(y - \bar{y}) \rangle + \langle Z(x, y) - Z(\bar{x}, \bar{y}), y - \bar{y} + rr_0B^*(x - \bar{x}) \rangle \leq -(rr_0 - \|\nabla^2W\|_\infty r_0 - \gamma)|x - \bar{x}|^2 - \left(1 - rr_0 - \frac{\|\nabla W\|^2_\infty}{4\gamma}\right)|y - \bar{y}|^2, \quad \gamma > 0.
\]
Therefore, \((A_3)\) holds for some constants \( r_0 \in (0, 1) \) and \( \theta > 0 \) if
\[
1 > \inf_{r_0 \in (0, 1)} \inf_{\gamma \in (0, rr_0 - \|\nabla^2W\|_\infty r_0)} \left(rr_0 + \frac{\|\nabla W\|^2_\infty}{4\gamma}\right),
\]
which is equivalent to (5.1) due to (5.2). It remains to prove (5.1) for \( \|\nabla^2W\|_\infty \leq \frac{1}{2} \). Since (5.1) is trivial for \( \|\nabla^2W\|_\infty = 0 \), we assume that \( \|\nabla^2W\|_\infty \in (0, \frac{1}{2}) \). In this case we simply take \( r_0 = \|\nabla^2W\|_\infty \) such that
\[
\frac{\|\nabla^2W\|^2_\infty}{2r_0(1 - \|\nabla^2W\|_\infty)(1 + \sqrt{1 + 4r_0})} + \frac{r_0}{2}(1 + \sqrt{1 + 4r_0}) < \|\nabla^2W\|_\infty \left(\frac{1}{2} + \frac{1}{2}(1 + \sqrt{3})\right) \leq \frac{1}{2}(1 + \frac{1}{2}\sqrt{3}) < 1.
\]

Example 5.2. Let \( \sigma \) be invertible, \( m = kd \) for some natural number \( k \geq 2 \), and
\[
By = (0, \cdots, 0, y) \in \mathbb{R}^{kd}, \quad y \in \mathbb{R}^d,
\]
\[
Z(x, y) = b(y) - x_k, \quad y \in \mathbb{R}^d, x = (x_1, x_2, \cdots, x_k) \in \mathbb{R}^{kd},
\]
\[
A(x_1, x_2, \cdots, x_k) = (\gamma x_2 - x_1, \gamma x_3 - x_2, \cdots, \gamma x_k - x_{k-1}, 0), \quad x_1, \cdots, x_k \in \mathbb{R}^d,
\]
where \( \gamma \neq 0 \) is a constant, and \( b: \mathbb{R}^d \to \mathbb{R}^d \) satisfies
\[
|b(y) - b(\bar{y})| \leq K|y - \bar{y}|, \quad \langle b(y) - b(\bar{y}), y - \bar{y} \rangle \leq -\beta|y - \bar{y}|^2, \quad y, \bar{y} \in \mathbb{R}^d
\]
for some constants \( K, \beta > 0 \). If
\[
0 < |\gamma| < 1, \quad \frac{2\beta}{2 + K^2},
\]
then assertions in Theorem 3.1 hold.

Proof. It is easy to see that when \( \gamma \neq 0 \), the rank condition in \((A1)\) holds. Since \( b \) is Lipchitz continuous and \( \sigma \) is invertible, by Theorem 3.1 it suffices to verify \((A3)\). We simply take
$r = 1$. For any $r_0 \in (0, 1) = (0, \|B\|^{-1})$, we have

$$\langle r^2(x - \bar{x}) + rr_0B(y - \bar{y}), A(x - \bar{x}) + B(y - \bar{y}) \rangle + \langle Z(x, y) - Z(\bar{x}, \bar{y}), y - \bar{y} + rr_0B^*(x - \bar{x}) \rangle$$

$$= r_0|y - \bar{y}|^2 + \sum_{i=1}^{k-1} \left\{ \gamma(x_i - \bar{x}_i, x_{i+1} - \bar{x}_{i+1}) - |x_i - \bar{x}_i|^2 \right\}$$

$$+ \langle b(y) - b(\bar{y}), y - \bar{y} + r_0(x_k - \bar{x}_k) \rangle - r_0|x_k - \bar{x}_k|^2$$

$$\leq -(\beta - r_0)|y - \bar{y}|^2 - r_0|x_k - \bar{x}_k|^2 + r_0K|y - \bar{y}| \cdot |x_k - \bar{x}_k|$$

$$- \sum_{i=1}^{k-1} \left\{ |x_i - \bar{x}_i|^2 - \frac{|\gamma|}{2} |x_i - \bar{x}_i|^2 - \frac{|\gamma|}{2} |x_{i+1} - \bar{x}_{i+1}|^2 \right\}$$

$$\leq -\sum_{i=1}^{k-1} (1 - |\gamma|)|x_i - \bar{x}_i|^2 - \left( r - \frac{|\gamma|}{2} - \frac{r_0K^2}{4\alpha} \right)|x_k - \bar{x}_k|^2 - (\beta - r_0 - \alpha r_0)|y - \bar{y}|^2, \ \alpha > 0.$$ 

So, (A3) holds for some $\theta > 0$ provided $|\gamma| < 1$ and

$$\sup_{r_0 \in (0, 1 \wedge \frac{\beta}{1+\alpha})} \left( r_0 - \frac{|\gamma|}{2} - \frac{K^2r_0}{4\alpha} \right) > 0.$$ 

Letting $r_0 \uparrow 1 \wedge \frac{\beta}{1+\alpha}$, we conclude that (A3) holds provided $|\gamma| < 1$ and

$$\sup_{\alpha > 0} \left( 1 \wedge \frac{\beta}{1+\alpha} \right) \left( 1 - \frac{K^2}{4\alpha} \right) > \frac{|\gamma|}{2}.$$ 

By taking $\alpha = \frac{1}{2}K^2$ we see that this inequality follows from (5.4). \hfill \Box

Finally, we present an example for Theorem 4.1 in the spirit of Example 5.2 that $H_2$ is a subspace of $H_1$.

**Example 5.3.** Let $\{u_i\}_{i \geq 1}$ be an orthonormal basis on $H_1$, and let $H_2 = \text{span}\{u_{2i} : i \geq 1\}$. Take $B = I_{H_2}$ and

$$L_1u_{2i} = \lambda_iu_{2i}, \ \ L_1u_{2i-1} = \lambda_iu_{2i-1}, \ \ i \geq 1,$$

where $0 < \lambda_i \uparrow \infty$ with $\sum_{i \geq 1} \lambda_i^{-1} < \infty$. Moreover, let $L_2 = L_1|_{H_2}$ and

$$Ax = \gamma \lambda_1 \sum_{i=1}^{\infty} \langle x, u_{2i} \rangle u_{2i-1}, \ \ x \in H_1$$

for some constant $\gamma \in \mathbb{R}$. Finally, let $Z$ satisfy

$$|Z(x, y) - Z(\bar{x}, \bar{y})| \leq \alpha \lambda_1|x - \bar{x}| + \beta \lambda_1|y - \bar{y}|$$

for some constants $\alpha, \beta \geq 0$. Then all assertions in Theorem 3.1 hold provided

$$\sqrt{1 + \gamma^2} + 4\beta + \sqrt{(2\beta - 1 - \sqrt{1 + \gamma^2})^2 + 8\alpha} < 7.$$ 

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Proof. It is easy to see that $BL_2 = L_1B, AL_1 = L_1A$. According to Theorem 4.1, it suffices to prove

(a) For some $\delta > 0$ such that $L_1 - A \geq \lambda_1 - \delta$ and the condition (4.2) hold.

(b) For any $t_0 > 0$, $Q_{t_0}$ is invertible on $\mathbb{H}_1$.

Proof of (a) We have

$$\langle (L_1 - A)x, x \rangle = \langle L_2 \pi x, \pi x \rangle - \langle Ax, x \rangle$$

$$\geq \lambda_1 \sum_{i \geq 1} \langle x, u_{2i} \rangle^2 - \gamma \sum_{i \geq 1} \langle x, u_{2i} \rangle \langle x, u_{2i-1} \rangle$$

$$\geq (\lambda_1 - \delta) \sum_{i \geq 1} \langle x, u_{2i} \rangle^2 - \frac{\gamma^2}{4\delta} \sum_{i \geq 1} \langle x, u_{2i-1} \rangle^2, \ x \in \mathbb{H}_1.$$  

Taking

$$\delta = \frac{1 + \sqrt{1 + \gamma^2}}{2} \lambda_1$$

such that $\frac{\gamma^2}{4\delta} = \delta - \lambda_1$, we have $L_1 - A \geq \lambda_1 - \delta$ as required, and the condition (5.5) is equivalent to (4.2).

Proof of (b) We may simply assume $\gamma \lambda_1 = 1$, so that

$$A^* x = \sum_{i=1}^{\infty} \langle x, u_{2i-1} \rangle u_{2i}, \ x \in \mathbb{H}_1.$$  

Since $A^2 = (A^*)^2 = 0$ and $BB^*$ is the orthogonal projection onto $\mathbb{H}_2$, for any $x \in \mathbb{H}_1$ we have

$$e^{sA}BB^*e^{sA^*}x = (I + sA)BB^*\{x + sA^*x\}$$

$$= \sum_{i=1}^{\infty} \left( \langle x, u_{2i} \rangle + s\langle x, u_{2i-1} \rangle \right) \{u_{2i} + su_{2i-1}\}.$$  

Then

$$\langle Q_{t_0}x, x \rangle = \sum_{i=1}^{\infty} \int_0^{t_0} \left\{ \langle x, u_{2i} \rangle^2 + 2s\langle x, u_{2i-1} \rangle \langle x, u_{2i} \rangle + s^2\langle x, u_{2i-1} \rangle^2 \right\} ds$$

$$= t_0 \sum_{i=1}^{\infty} \left\{ \langle x, u_{2i} \rangle^2 + t_0 \langle x, u_{2i-1} \rangle \langle x, u_{2i} \rangle + \frac{t_0^2}{3} \langle x, u_{2i-1} \rangle^2 \right\}$$

$$\geq t_0 \sum_{i=1}^{\infty} \left\{ (1 - r)\langle x, u_{2i} \rangle^2 + \left( \frac{1}{3} - \frac{1}{4r} \right) \frac{t_0^2}{3} \langle x, u_{2i-1} \rangle^2 \right\}, \ r > 0.$$  

Taking $r \in (0, 1)$ but close enough to 1, we conclude that $\langle Q_{t_0}x, x \rangle \geq c|x|^2$ holds for some constant $c > 0$ and all $x \in \mathbb{H}_1$. Therefore, $Q_{t_0}$ is invertible. \qed
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References


