STOCHASTIC CONTINUITY OF RANDOM FIELDS GOVERNED
BY A SYSTEM OF STOCHASTIC PDES

By Kai Du, Jiakun Liu and Fu Zhang

This paper constructs a solvability theory for a system of stochastic partial differential equations. On account of the Kolmogorov continuity theorem, solutions are looked for in certain Hölder-type classes in which a random field is treated as a space-time function taking values in $L^p$-space of random variables. A modified stochastic parabolicity condition involving $p$ is proposed to ensure the finiteness of the associated norm of the solution, which is showed to be sharp by examples. The Schauder-type estimates and the solvability theorem are proved.

1. Introduction. Random fields governed by systems of stochastic partial differential equations (SPDEs) have been used to model many physical phenomena in random environments such as the motion of a random string, stochastic fluid mechanics, the precessional motion of magnetisation with random perturbations, and so on; specific models can be found in Funaki (1983); Mueller and Tribe (2002); Mikulevicius and Rozovsky (2004); Hairer and Mattingly (2006); Brzeźniak, Goldys and Jegaraj (2013); Da Prato and Zabczyk (2014) and references therein. This paper concerns the smoothness properties of the random field

$$u = (u^1, \ldots, u^N)' : \mathbb{R}^d \times [0, \infty) \times \Omega \to \mathbb{R}^N$$

described by the following linear system of SPDEs:

$$(1.1) \quad du^\alpha = \left( a^j_{\alpha\beta} \partial_j u^\beta + b^i_{\alpha\beta} \partial_i u^\beta + c_{\alpha\beta} u^\beta + f^\alpha \right) dt + \left( \sigma^i_{\alpha\beta} \partial_i u^\beta + \nu^k_{\alpha\beta} u^\beta + g^k_{\alpha} \right) dw^k_t,$$

where $\{w^k\}$ are countable independent Wiener processes defined on a filtered complete probability space $(\Omega, \mathcal{F}, (\mathcal{F}_t)_{t \geq 0}, \mathbb{P})$, and Einstein’s summation convention is used with

$$i, j = 1, 2, \ldots, d; \quad \alpha, \beta = 1, 2, \ldots, N; \quad k = 1, 2, \ldots,$$

and the coefficients and free terms are all random fields. Regularity theory for system (1.1) can not only directly apply to some concrete models, see for example Zakai (1969); Funaki (1983); Walsh (1986); Mueller and Tribe (2002), but also provide with important estimates for solutions of suitable approximation to nonlinear systems in the literature such as Krylov (1997); Mikulevicius and Rozovsky (2012); Da Prato and Zabczyk (2014) and references therein.

The literature dedicated to the regularity theory for SPDEs (not systems) is quite extensive and fruitful. In the framework of Sobolev spaces, a complete $L^p$-theory ($p \geq 2$) has

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been developed, see Pardoux (1975); Krylov and Rozovsky (1977); Krylov (1996, 1999); van Neerven, Veraar and Weis (2012); Chen and Kim (2014) and references therein. However, the $L^p$-theory for systems of SPDEs is far from complete, though it has been fully solved for $p = 2$ by Kim and Lee (2013a), and for $p > 2$ some specific results were obtained by Mikulevicius and Rozovsky (2001, 2004); Kim and Lee (2013b), where the matrices $\sigma^{ik} = [\sigma^{ik}_{\alpha\beta}]_{N \times N}$ are assumed to be almost diagonal. The smoothness properties of random fields follow from Sobolev’s embedding theorem in this framework.

The present paper investigates into the regularity issues of system (1.1) from another aspect prompted by Kolmogorov’s continuity theorem. This theorem gives mild conditions under which a random fields has a continuous modification, and the point is to derive appropriate estimates on $L^p$-moments of increments of the random field. This boosts an idea that considers a random field to be a function of $(x, t)$ taking values in the space $L^p_\omega := L^p(\Omega)$ and introduces appropriate $L^p_\omega$-valued Hölder classes as the working spaces, for instance, the basic space used in Rozovsky (1975); Mikulevicius (2000); Du and Liu (2015) and also in the present paper defined to be the set of all jointly measurable random fields $u$ such that

$$
\|u\|_{C^\delta_p} := \left[ \sup_{t, x} \mathbb{E}|u(x, t)|^p \right]^\frac{1}{p} + \sup_{t, x \neq y} \frac{\mathbb{E}|u(x, t) - u(y, t)|^p}{|x - y|^{\delta p}} < \infty
$$

with some constants $\delta \in (0, 1)$ and $p \in [2, \infty)$. Each random field in this space $C^\delta_p$ is stochastically continuous in space, and if $\delta p > d$ it has a modification Hölder continuous in space by Kolmogorov’s theorem.

For the Cauchy problem for parabolic SPDEs (not systems), a $C^{2+\delta}_p$-theory was once an open problem proposed by Krylov (1999); based on the Hölder class $C^\delta_p$ it was partially addressed by Mikulevicius (2000) and generally solved by Du and Liu (2015, 2016) very recently. They proved that, under natural conditions on the coefficients, the solution $u$ and its derivatives $\partial u$ and $\partial^2 u$ belong to the class $C^\delta_p$ if $f$, $g$ and $\partial g$ belong to this space; Du and Liu (2015) further obtained the Hölder continuity in time of $\partial^2 u$. The main results of the theory are sharp in that they could not be improved under the same assumptions. Extensions to the Cauchy–Dirichlet problem of SPDEs can be found in Mikulevicius and Pragarauskas (2003, 2006), and for more related results, we refer the reader to, for instance, Chow and Jiang (1994); Bally, Millet and Sanz-Solé (1995); Tang and Wei (2016). Nevertheless, $C^{2+\delta}_p$-theory for systems of SPDEs is not known in the literature.

The purpose of this paper is to construct such a $C^{2+\delta}_p$-theory for systems of type (1.1) under mild conditions. Like the situation in the $L^p$ framework this extension is also nontrivial as some new features emerge in the system of SPDEs compared with single equations. It is well-known that the well-posedness of a second order SPDE is usually guaranteed by certain coercivity conditions. For system (1.1), Kim and Lee (2013a) recently obtained $W^n_2$-solutions under the following algebraic condition: there is a constant $\kappa > 0$ such that

$$
(2a^{ij}_{\alpha\beta} - \sigma^{ik}_{\gamma\alpha} \sigma^{jk}_{\gamma\beta}) \xi^i \xi^j \geq \kappa |\xi|^2 \quad \forall \xi \in \mathbb{R}^{d \times N}.
$$
Although it is a natural extension of the strong ellipticity condition for PDE systems \((\sigma \equiv 0)\), see for example Schlag (1996), and of the stochastic parabolicity condition for SPDEs \((N = 1)\), see for example Krylov (1999), the following example constructed by Kim and Lee (2013b) reveals that condition (1.2) is not sufficient to ensure the finiteness of \(L^p\) norm of the solution even the given data are smooth, and some structure condition stronger than (1.2) is indispensable to establish a general \(L^p\) or \(C^{2+\delta}\) theory for systems of type (1.1).

**Example 1.1.** Let \(d = 1, N = 2\) and \(p > 2\). Consider the following system:

\[
\begin{align*}
\text{(1.3)} \quad \begin{cases}
\frac{\text{d}u^{(1)}}{\text{d}t} = u^{(1)}_{xx} - \mu u^{(2)}_x \text{d}w_t, \\
\frac{\text{d}u^{(2)}}{\text{d}t} = u^{(2)}_{xx} + \mu u^{(1)}_x \text{d}w_t
\end{cases}
\end{align*}
\]

with the initial data

\[
\begin{align*}
u^{(1)}(x,0) = e^{-\frac{x^2}{2}}, \quad u^{(2)}(x,0) = 0,
\end{align*}
\]

where \(\mu\) is a given constant. In this case, condition (1.2) reads \(\mu^2 < 2\), but we will see that this is not sufficient to ensure the finiteness of \(\mathbb{E}|u(x,t)|^p\) with \(p > 2\). Set \(v = u^{(1)} + \sqrt{-1}u^{(2)}\), and the above system turns to a single equation:

\[
\text{(1.4)} \quad \frac{\text{d}v}{\text{d}t} = v_{xx} + \sqrt{-1}\mu v_x \text{d}w_t
\]

with \(v(x,0) = u^{(2)}(x,0)\). It can be verified directly by Itô’s formula that

\[
v(x,t) = \frac{1}{\sqrt{1 + (2 + \mu^2)t}} \exp\left\{ \frac{-\left(x + \sqrt{-1}\mu w_t\right)^2}{2[1 + (2 + \mu^2)t]} \right\}
\]

solves (1.4) with the given initial condition. So we can compute

\[
\text{(1.5)} \quad \mathbb{E}|u(x,t)|^p = \mathbb{E}|v(x,t)|^p
\]

\[
= \frac{1}{\sqrt{2\pi t}} \frac{1}{[1 + (2 + \mu^2)t]^{p/2}} e^{-\frac{p\mu^2}{2[1 + (2 + \mu^2)t]}} \int_{\mathbb{R}} e^{-\frac{y^2}{2t}} \left[1 - \frac{p\mu^2}{2[1 + (2 + \mu^2)t]} \right] \text{d}y.
\]

It is noticed that

\[
1 - \frac{p\mu^2}{1 + (2 + \mu^2)t} \to \frac{2 - (p - 1)\mu^2}{2 + \mu^2} \quad \text{as} \quad t \to \infty,
\]

which implies that if

\[
\mu^2 > \frac{2}{p - 1},
\]

the integral in (1.5) diverges for large \(t\), and \(\mathbb{E}|u(x,t)|^p = \infty\) for every \(x\).

A major contribution of this paper is the finding of a general coercivity condition that ensures us to construct a general \(C^{2+\delta}\)-theory for system (1.1). The basic idea is to impose an appropriate correction term involving \(p\) to the left-hand side of (1.2). More specifically, we introduce
Definition 1.2 (MSP condition). Let \( p \in [2, \infty) \). The coefficients \( a = (a_{ij}^{\alpha\beta}) \) and \( \sigma = (\sigma_{ij}^{\alpha\beta}) \) are said to satisfy the modified stochastic parabolicity (MSP) condition if there are measurable functions \( \lambda_{ij}^{\alpha\beta}: \mathbb{R}^d \times [0, \infty) \times \Omega \to \mathbb{R} \) with \( \lambda_{ij}^{\alpha\beta} = \lambda_{ji}^{\beta\alpha} \), such that

\[
A_{ij}^{\alpha\beta}(p, \lambda) := 2a_{ij}^{\alpha\beta} - \sigma_{ij}^{\gamma\alpha} \sigma_{ij}^{\gamma\beta} - (p - 2)(\sigma_{ij}^{\gamma\alpha} - \lambda_{ij}^{\gamma\alpha})(\sigma_{ij}^{\gamma\beta} - \lambda_{ij}^{\gamma\beta})
\]

satisfy the Legendre–Hadamard condition: there is a constant \( \kappa > 0 \) such that

\[
A_{ij}^{\alpha\beta}(p, \lambda) \xi_i \xi_j \eta^\alpha \eta^\beta \geq \kappa|\xi|^2|\eta|^2 \quad \forall \xi \in \mathbb{R}^d, \eta \in \mathbb{R}^N
\]
everywhere on \( \mathbb{R}^d \times [0, \infty) \times \Omega \).

In particular, the following criteria for the MSP condition, simply by taking \( \lambda_{ij}^{\alpha\beta} = 0 \) and \( \lambda_{ij}^{\alpha\beta} = (\sigma_{ij}^{\alpha\beta} + \sigma_{ji}^{\alpha\beta})/2 \) respectively, could be very convenient in applications.

Lemma 1.3. The MSP condition is satisfied if either

(i) \( 2a_{ij}^{\alpha\beta} - (p - 1)\sigma_{ij}^{\gamma\alpha} \sigma_{ij}^{\gamma\beta} \) or
(ii) \( 2a_{ij}^{\alpha\beta} - \sigma_{ij}^{\gamma\alpha} \sigma_{ij}^{\gamma\beta} + (p - 2)\sigma_{ij}^{\gamma\alpha} \sigma_{ij}^{\gamma\beta} \) with \( \tilde{\sigma}_{ij}^{\alpha\beta} := (\sigma_{ij}^{\alpha\beta} - \sigma_{ij}^{\beta\alpha})/2 \)

satisfies the Legendre–Hadamard condition.

Evidently, the MSP condition is invariant under change of basis of \( \mathbb{R}^d \) or under orthogonal transformation of \( \mathbb{R}^N \). Also, we employ the Legendre–Hadamard condition (see for example Giaquinta (1993)) that is more general than the strong ellipticity condition. The MSP condition coincides with the Legendre–Hadamard condition for PDE systems and the stochastic parabolicity condition for SPDEs, and when \( p = 2 \) it becomes

\[
(2a_{ij}^{\alpha\beta} - \sigma_{ij}^{\gamma\alpha} \sigma_{ij}^{\gamma\beta}) \xi_i \xi_j \eta^\alpha \eta^\beta \geq \kappa|\xi|^2|\eta|^2 \quad \forall \xi \in \mathbb{R}^d, \eta \in \mathbb{R}^N
\]

that is weaker than (1.2) used in Kim and Lee (2013a). Moreover, the case (ii) in Lemma 1.3 shows that the MSP condition is also reduced to (1.9) if the matrices \( B_{ik} = [\sigma_{ij}^{\alpha\beta}]_{N \times N} \) are close to be symmetric. Nevertheless, the generality of the MSP condition cannot be covered by these cases in Lemma 1.3, which is illustrated by Example 6.5 in the final section.

The significance of the MSP condition is not only that it is sufficient to establish our \( C^{2+\kappa} \)-theory, but also that in (1.7) the coefficient of the correction term \( p - 2 \) is optimal in that it cannot shrink to any smaller constant. This point is evidenced by Example 1.1. Indeed, if \( p > 2 \) is fixed and the coefficient \( p - 2 \) in (1.7) drops down a bit to \( p - 2 - \varepsilon > 0 \), we can choose the value of \( \mu \) satisfying

\[
\frac{2}{p - 1} < \mu^2 < \frac{2}{p - 1 - \varepsilon},
\]

then it is easily verified that system (1.3) satisfies (1.8) in this setting by taking \( \lambda_{ij}^{\alpha\beta} = 0 \). However, Example 1.1 has showed that when \( t \) is large enough \( \mathbb{E}|u(x, t)|^p \) becomes infinite.
for such a choice of $\mu$, let alone the $C^p_\delta$-norm of the solution. More examples in this respect are discussed in the final section.

Technically speaking, the MSP condition is explicitly used to derive a class of mixed norm estimates for the model system in the space $L^p(\Omega; W^m_2)$. A similar issue was addressed in Brzeźniak and Veraar (2012) for a nonlocal SPDE. Owing to Sobolev’s embedding the mixed norm estimates lead to the local boundedness of $E[|\partial^m u(x, t)|^p]$ by which we are able to prove the fundamental interior estimate of Schauder-type for system (1.1) by adopting a similar strategy that applied to SPDEs in our previous work Du and Liu (2015). Unlike the method of fundamental solutions used in Mikulevicius (2000), our approach combining a perturbation scheme from Wang (2006) with certain integral-type estimates as inspired by Trudinger (1986) and avoiding the use of Taylor expansions can apply to stochastic equations in great generality. Actually, Taylor expansions played a key role in various approaches to Schauder estimates for deterministic PDEs (see for example Safonov (1984); Trudinger (1986); Caffarelli (1989); Simon (1997); Wang (2006)) but seemed not to work well for SPDEs due to adaptedness issues, and the method of fundamental solutions usually required the leading coefficients $\sigma \equiv 0$ and $a$ to be deterministic.

It is worth noting that the MSP condition is far more general and more precise than the restrictive conditions that were used to obtain the $W^m_p$-solution of system (1.1) in (Kim and Lee, 2013b, Theorem 2.6). As it is successful in $C^{2+\delta}$-theory, it is interesting to ask if our MSP condition is also sufficient to obtain an $L^p$-theory for systems of type (1.1). Besides, it is yet to be known whether our results can be reproduced using Campanato’s technique; as a matter of fact, the latter has been a customary method to construct both Schauder and $L^p$ theory of PDE systems (see Giaquinta (1993); Schlag (1996); Dong and Zhang (2015) and references therein). On the other hand, the present paper actually provides with a new approach to classical Schauder estimates for parabolic systems.

The paper is organised as follows. In the next section we introduce some notation and state our main results. In Sections 3 and 4 we consider the model system

$$\begin{equation}
\begin{aligned}
du^\alpha &= (a_{ij}^{\alpha \beta} \partial_{ij} u^\beta + f_\alpha) dt + (\sigma_{ik}^{\alpha \beta} \partial_i u^\beta + g_\alpha^k) \, dw^k_t,
\end{aligned}
\end{equation}$$

where the coefficients $a$ and $\sigma$ are random but independent of $x$. We prove the crucial mixed norm estimates in §3, and then establish the interior Hölder estimate in §4. In Section 5 we complete the proofs of our main results. The final section is devoted to more comments and examples on the sharpness and flexibility of the MSP condition.

2. Main results. Let us first introduce our working spaces and associated notation. A Banach-space valued Hölder continuous function is defined analogously to the classical Hölder continuous function. Let $E$ be a Banach space, $\mathcal{O}$ a domain in $\mathbb{R}^d$ and $I$ an interval. We define the parabolic modulus

$$|X|_p = |x| + \sqrt{|t|} \quad \text{for } X = (x, t) \in Q := \mathcal{O} \times I.$$
For a space-time function \( u : Q \to E \), we define
\[
[u]_{m;Q}^{E} := \max\{\|\partial^k u(x)\|_E : (x, t) \in Q, |s| = m\},
\]
\[|u|_{m;Q}^{E} := \sup_{(x, t) \in Q} \|\partial^k u(x, t)\|_E,\]
\[|u|_{m+\delta;Q}^{E} := \sup_{|s| = m} \sup_{x, y \in Q} \|\partial^k u(x, t) - \partial^k u(y, t)\|_E / |x - y|^\delta,\]
\[|u|_{m+\delta;Q}^{E} := [u]_{m;Q}^{E} + [u]_{m+\delta;Q}^{E},\]
\[|u|_{(m+\delta)/2;Q}^{E} := \sup_{|s| = m} \sup_{x, y \in Q} \|\partial^k u(x) - \partial^k u(y)\|_E / |X - Y|^\delta,\]
\[|u|_{(m+\delta)/2;Q}^{E} := |u|_{m;Q}^{E} + |u|_{(m+\delta)/2;Q}^{E}.\]

with \( m \in \mathbb{N} := \{0, 1, 2, \ldots \} \) and \( \delta \in (0, 1) \), where \( s = (s_1, \ldots, s_d) \in \mathbb{N}^d \) with \( |s| = \sum_{i=1}^d s_i \), and all the derivatives of an \( E \)-valued function are defined with respect to the spatial variable in the strong sense, see Hille and Phillips (1957). In the following context, the space \( E \) is either i) an Euclidean space, ii) the space \( \ell^2 \), or iii) \( L^p_\omega := L^p(\Omega) \). We omit the superscript in cases (i) and (ii), and in case (iii), we introduce some new notation:
\[|u|_{m;Q}^{E} := \|u\|_{m+\delta;Q}^{E},\]
\[|u|_{m;Q}^{E} := \|u\|_{(m+\delta)/2;Q}^{E}.\]

As the random fields in this paper take values in different spaces like \( \mathbb{R}^N \) (say, \( u \) and \( f \)) or \( \ell^2 \) (say, \( g \)), we shall use \( \cdot \) uniformly for the standard norms in Euclidean spaces and in \( \ell^2 \), and \( L^p_\omega \) for both \( L^p(\Omega; \mathbb{R}^N) \) and \( L^p(\Omega; \ell^2) \); the specific meaning of the notation can be easily understood in context.

**Definition.** The Hölder classes \( C_{m+\delta}^m(Q; L^p_\omega) \) and \( C_{m+\delta/2}^m(Q; L^p_\omega) \) are defined as the sets of all predictable random fields \( u \) defined on \( Q \times \Omega \) and taking values in an Euclidean space or \( \ell^2 \) such that \( \|u\|_{m,\omega;Q}^{E} \) and \( \|u\|_{(m+\delta)/2,\omega;Q}^{E} \) are finite, respectively.

The following notation for special domains are frequently used:
\[B_r(x) = \{ y \in \mathbb{R}^d : |y - x| < r \}, \quad Q_r(x, t) = B_r(x) \times (t - r^2, t], \]
and \( B_r = B_r(0), Q_r = Q_r(0, 0), \) and also
\[Q_{r,T}(x) := B_r(x) \times (0, T], \quad Q_{r,T} = Q_{r,T}(0) \quad \text{and} \quad Q_T := \mathbb{R}^d \times (0, T].\]

**Assumption.** The following conditions are used throughout the paper unless otherwise stated:

i) For all \( i, j = 1, \ldots, d \) and \( \alpha, \beta = 1, \ldots, N \), the random fields \( a_{ij}^{\alpha\beta}, b_{ij}^{\alpha\beta}, c_{\alpha\beta} \) and \( f_{\alpha} \) are real-valued, and \( \sigma_{\alpha\beta}, \nu_{\alpha\beta} \) and \( g_{\alpha} \) are \( \ell^2 \)-valued; all of them are predictable.
ii) $a_{ij}^{i\beta}$ and $\sigma_{ij}^{i\beta}$ satisfy the MSP condition with some $p \in [2, \infty)$.

iii) For some $\delta \in (0, 1)$, the classical $C^\delta_x$-norms of $a_{ij}^{i\beta}$, $b_i^{i\beta}$ and $c_{i\beta}$, and the $C^{1+\delta}_x$-norms of $\sigma_{ij}^{i\beta}$ and $\nu_{i\beta}$ are all dominated by a constant $K$.

We are ready to state the main results of the paper. The first result is the a priori interior Hölder estimates for system (1.1).

**Theorem 2.1.** Under the above setting, there exist two constants $\rho_0 \in (0, 1)$ and $C > 0$, both depending only on $d, N, \kappa, K, p$ and $\delta$, such that if $u$ satisfies (1.1) in $Q_1(X)$ with $X = (x, t) \in \mathbb{R}^d \times [1, \infty)$, then

$$
\rho^{2+\delta} \| \partial^2 u \|_{(\delta, \delta/2, \rho; Q_\rho/2(X))} 
\leq C \left\{ \rho^2 \| f \|_{\delta, \rho; Q_\rho(X)} + \rho \| g \|_{1+\delta, \rho; Q_\rho(X)} + \rho^{-\frac{d}{2}} \left[ \mathbb{E} \| u \|_{L^p(Q_\rho(X))}^p \right]^\frac{1}{p} \right\}
$$

for any $\rho \in (0, \rho_0]$, provided the right-hand side is finite.

By rescaling one can obtain the local estimate around any point $X \in \mathbb{R}^d \times (0, \infty)$.

The second theorem is regarding the global Hölder estimate and solvability for the Cauchy problem for system (1.1) with zero initial condition.

**Theorem 2.2.** Under the above setting, if $f \in C^\delta(Q_T; L^p_\omega)$ and $g \in C^{1+\delta}_x(Q_T; L^p_\omega)$ with $T > 0$, then system (1.1) with the initial condition

$$
u(x, 0) = 0 \quad \forall x \in \mathbb{R}^d
$$

admits a unique solution $u \in C^{2+\delta, \delta/2}_{x,t}(Q_T; L^p_\omega)$, and it satisfies the estimate

$$
\| u \|_{2+\delta, \delta/2, \rho; Q_T} \leq C e^{CT} \left( \| f \|_{\delta, \rho; Q_T} + \| g \|_{1+\delta, \rho; Q_T} \right),
$$

where the constant $C$ depends only on $d, N, \kappa, K, p$ and $\delta$.

**Remark.** Theorem 2.2 still holds true if the system is considered on the torus $\mathbb{T}^d = \mathbb{R}^d / \mathbb{Z}^d$ instead of $\mathbb{R}^d$.

**Remark.** The above theorems show that the solutions possess the Hölder continuity in time even with time-irregular coefficients and free terms. A similar property of classical PDEs is well-known in the literature, see for example Lieberman (1996); Dong and Zhang (2015) and references therein. In view of an anisotropic Kolmogorov continuity theorem (see Dalang, Khoshnevisan and Nualart (2007)) the solution obtained in Theorem 2.2 has a modification that is Hölder continuous jointly in space and time.
3. Integral estimates for the model system. Throughout this section we assume that $a_{ij}^{\alpha\beta}$ and $\sigma_{ij}^{\alpha\beta}$ depend only on $(t,\omega)$, but independent of $x$, satisfying the MSP condition (in this case $\lambda_{ij}^{\alpha\beta}$ is chosen to be independent of $x$) and

\begin{equation}
|a_{ij}^{\alpha\beta}|, |\sigma_{ij}^{\alpha\beta}| \leq K, \quad \forall t, \omega,
\end{equation}

and we consider the following model system

\begin{equation}
du^\alpha = (a_{ij}^{\alpha\beta} \partial_{ij} u^\beta + f_\alpha)dt + (\sigma_{ij}^{\alpha\beta} \partial_{ij} u^\beta + g_\alpha)dw^k_t.
\end{equation}

The aim of this section is to derive several auxiliary estimates for the model system which are used to prove the interior Hölder estimate in the next section.

In this section and the next, we may consider (3.2) in the entire space $\mathbb{R}^n \times \mathbb{R}$. On the one hand, we can always extend (1.1) and (3.2) to the entire space if we require $u(x, 0) = 0$. Indeed, the zero extensions of $u$, $f$ and $g$ (i.e., these functions are defined to all equal zero for $t < 0$) satisfy the equations in the entire space, where the extension of coefficients and Wiener processes are quite easy; for example, we can define $a_{ij}^{\alpha\beta}(t) = \delta_{ij}^{\alpha\beta}$ and $\sigma_{ij}^{\alpha\beta} = 0$ for $t < 0$, and $w_t := \tilde{w}_{-t}$ for $t < 0$ with $\tilde{w}$ being an independent copy of $w$. On the other hand, we mainly concern the local estimates for the equation (3.2) in the following two sections, so we can only focus on the estimates around the origin on account of translation. Indeed, we can reduce the estimates around a point $(x_0, t_0)$ to the estimates around the origin by use of the change of variables $(x, t) \mapsto (x-x_0, t-t_0)$.

Let $O \in \mathbb{R}^d$ and $H^m(O) = W^m_2(O)$ be the usual Sobolev spaces. Let $I \in \mathbb{R}$ and $Q = O \times I$. For $p, q \in [1, \infty]$, define

\[ L^p_\omega L^q_t H^m \times \mathbb{R}^N \]

In what follows, we denote $\partial^m u$ the set of all $m$-order derivatives of a function $u$. These $\partial^m u(x)$ for each $x$ are regarded as elements of a Euclidean space of proper dimension.

Our $C^{2+\delta}$-theory is grounded in the following mixed norm estimates for model system (3.2), in which the modified stochastic parabolicity condition (1.8) plays a key role.

**Theorem 3.1.** Let $p \in [2, \infty)$ and $m \geq 1$. Suppose $f \in L^p_t L^\infty_x H^{-m+1}_x(Q_T)$ and $g \in L^p_t L^\infty_x H^{-m}_x(Q_T)$. Then (3.2) with zero initial value admits a unique solution $u \in L^p_t L^\infty_x H^m_x(Q_T) \cap L^p_t L^\infty_x H^{m+1}_x(Q_T)$. Moreover, for any multi-index $s$ such that $|s| \leq m$,

\begin{equation}
\|\partial^s u\|_{L^p_t L^\infty_x L^2} + \|\partial^s u_x\|_{L^p_t L^2_x L^2} \leq C \left( \|\partial^p f\|_{L^p_t L^\infty_x H^{-1}_x} + \|\partial^p g\|_{L^p_t L^\infty_x L^2} \right),
\end{equation}

where the constant $C$ depends only on $d, p, T, \kappa, \sigma$, and $K$.

The proof of Theorem 3.1 is postponed to the end of this section. A quick consequence of this theorem is the following local estimates for model equations with smooth free terms.
Proposition 3.2. Let $m \geq 1$, $p \geq 2$, $r > 0$ and $0 < \theta < 1$, and let $u \in L^p_t L^r_x H^m_x(Q_r) \cap L^p_t L^2_x H^{m+1}_x(Q_r)$ solve (3.2) in $Q_r$ with $f \in L^p_t L^r_x H^{m-1}_x(Q_r)$ and $g \in L^p_t L^2_x H^m_x(Q_r)$. Then there is a constant $C = C(d, p, \kappa, m, \theta)$ such that

$$(3.4) \quad \|\partial^m u\|_{L^p_t L^r_x L^2(Q_r)} + \|\partial^m u_x\|_{L^p_t L^r_x L^2(Q_r)} \leq C r^{-m-1} \|u\|_{L^p_t L^r_x L^2(Q_r)}$$

$$+ C \sum_{k=0}^{m-1} r^{-m+k+1} \|D^k f\|_{L^p_t L^2_x L^2(Q_r)} + C \sum_{k=0}^{m} r^{-m+k} \|D^k g\|_{L^p_t L^2_x L^2(Q_r)}.$$ 

Consequently, for $2(m - |s|) > d$,

$$(3.5) \quad \|\sup_{Q_{2s}} |\partial^s u|\|_{L^p_t L^2_x L^2(Q_r)} \leq C r^{-|s|-d/2-1} \|u\|_{L^p_t L^r_x L^2(Q_r)}$$

$$+ C \sum_{k=0}^{m-1} r^{-|s|-n/2+k+1} \|D^k f\|_{L^p_t L^2_x L^2(Q_r)} + C \sum_{k=0}^{m} r^{-|s|-n/2+k} \|D^k g\|_{L^p_t L^2_x L^2(Q_r)}.$$ 

Proof. It suffices to prove (3.4) as (3.5) follows from (3.4) immediately by Sobolev’s embedding theorem (Adams and Fournier, 2003, Theorem 4.12). Moreover, for general $r > 0$, we can apply the obtained estimates for $r = 1$ to the rescaled function

$$v(x,t) := u(rx, r^2t), \quad \forall (x,t) \in \mathbb{R}^d \times \mathbb{R}$$

which solves the equation

$$(3.6) \quad dv^\alpha(x,t) = (a^{ij}_{\alpha\beta}(r^2t) \partial_{ij} v^\beta(x,t) + F_\alpha) dt + (\sigma^{ik}_{\alpha\beta}(r^2t) \partial_i v^\beta(x,t) + G^k_\alpha) \mathcal{D}^k_t,$$

with

$$F_\alpha(x,t) = r^2 f_\alpha(rx, r^2t), \quad G^k_\alpha(x,t) = r g(rx, r^2t), \quad \beta^k = r^{-1} w^k_{2t}.$$ 

Obviously, $\beta^k$ are mutually independent standard Wiener processes.

For any $\theta \in (0, 1)$, choose cut-off functions $\zeta^\ell \in C^\infty_0(\mathbb{R}^{d+1})$, $\ell = 1, 2$, satisfying i) $0 \leq \zeta^\ell \leq 1$, ii) $\zeta^1 = 1$ in $Q_{\sqrt{\theta}}$ and $\zeta^1 = 0$ outside $Q_1$, and iii) $\zeta^2 = 1$ in $Q_{2\theta}$ and $\zeta^2 = 0$ outside $Q_{\sqrt{\theta}}$. Then $v_t = \zeta^\ell u (\ell = 1, 2)$ satisfy

$$(3.7) \quad dv^\alpha_t = (a^{ij}_{\alpha\beta} \partial_{ij} v^\beta_t + \tilde{f}_{\ell,\alpha}) dt + (\sigma^{ik}_{\alpha\beta} \partial_i v^\beta_t + \tilde{g}_{\ell,\alpha}) dw^k_t, \quad \ell = 1, 2,$$

where

$$\tilde{f}_{\ell,\alpha} = \frac{\partial \zeta^\ell}{\partial x_j} f_\alpha - a^{ij}_{\alpha\beta} (\zeta^\ell_x u^\beta_j)_x + a^{ij}_{\alpha\beta} \zeta^\ell_x u^\beta_j + (\partial_i \zeta^\ell) u^\alpha, \quad \tilde{g}^{ik}_{\ell,\alpha} = \zeta^\ell g^k_{\alpha} - \sigma^{ik}_{\alpha\beta} \zeta^\ell_x u^\beta, \quad \ell = 1, 2.$$ 

Applying Proposition 3.1 to (3.7) for $\ell = 1, s = 0$ and for $\ell = 2, |s| = 1$, we have

$$\|u\|_{L^p_t L^r_x L^2(Q_{s\theta})} + \|u_x\|_{L^p_t L^r_x L^2(Q_{s\theta})} \leq C \left( \|u\|_{L^p_t L^r_x L^2(Q_1)} + \|f\|_{L^p_t L^r_x L^2(Q_1)} + \|g\|_{L^p_t L^2_x L^2(Q_1)} \right);$$

$$\|\partial^s u\|_{L^p_t L^r_x L^2(Q_\theta)} + \|\partial^s u_x\|_{L^p_t L^r_x L^2(Q_\theta)} \leq C \left( \|\partial^s u\|_{L^p_t L^r_x L^2(Q_{s\theta})} + \|f\|_{L^p_t L^r_x H^{m-1}_x(Q_{s\theta})} + \|\partial^s g\|_{L^p_t L^2_x L^2(Q_{s\theta})} \right), \quad |s| = 1.$$
Combining these two estimates, we have (3.4) for \( m = 1 \). Higher order estimates follows from induction. The proof is complete. \hfill \square

Another consequence of Theorem 3.1 is the following lemma concerning the estimates for equation (3.2) with the Cauchy–Dirichlet boundary conditions:

\[
\begin{align*}
\{ \quad & u(x, 0) = 0, \quad \forall x \in B_r; \\
& u(x, t) = 0, \quad \forall (x, t) \in \partial B_r \times (0, T].
\end{align*}
\]

**Proposition 3.3.** Let \( f = f^0 + \partial_t f^1 \) and \( f^0, f^1, \ldots, f^d, g \in L^p_x L^2_t H^m_x(Q_r) \) for all \( m \geq 0 \). Then problem (3.2) and (3.8) admits a unique solution \( u \in L^p_x L^2_t H^m_x(Q_r) \), and for each \( t \in (0, r^2) \), \( u(\cdot, t) \in L^p(\Omega; C^m(B_r; \mathbb{R}^N)) \) with any \( m \geq 0 \) and \( \varepsilon \in (0, r) \). Moreover, there is a constant \( C = C(n, p) \) such that

\[
\|u\|_{L^p_x L^2_t H^m_x(Q_{r, r^2})} \leq C \left( r^2 \|f^0\|_{L^p_x L^2_t H^m_x(Q_{r, r^2})} + r \|f^1, \ldots, f^d, g\|_{L^p_x L^2_t H^m_x(Q_{r, r^2})} \right).
\]

**Proof.** The existence, uniqueness and smoothness of the solution of problem (3.2) and (3.8) follow from (Kim and Lee, 2013a, Theorem 4.8), and (3.9) from (3.3) and rescaling. We remark that, although the results in Kim and Lee (2013a) used condition (1.2), Lemma 3.4 below ensures that those results remain valid for the model equation (3.2) under condition (1.9) that is implied by the MSP condition. \hfill \square

The following lemma is standard (cf. Giaquinta (1993)).

**Lemma 3.4.** If the real numbers \( A^{ij}_{\alpha\beta} \) satisfy the Legendre–Hadamard condition, then there exists a constant \( \epsilon > 0 \) depending only on \( d, N \) and \( \kappa \) such that

\[
\int_{\mathbb{R}^d} A^{ij}_{\alpha\beta} \partial_i u^\alpha \partial_j u^\beta \geq \epsilon \int_{\mathbb{R}^d} |\partial u|^2
\]

for any \( u \in H^1(\mathbb{R}^d; \mathbb{R}^N) \).

The rest of this section is devoted to the proof of Theorem 3.1.

**Proof of Theorem 3.1.** According to Theorem 2.3 in Kim and Lee (2013a) the model system (3.2) with zero initial value admits a unique solution

\[
u \in L^p_x L^\infty_x H^m_x(Q_T) \cap L^p_x L^2_t H^{m+1}_x(Q_T).
\]

Then by a standard localizing method, \( u \in L^p_x L^\infty_x H^m_x(Q_T) \cap L^p_x L^2_t H^{m+1}_x(Q_T) \) is the direct result of estimate (3.3). So it remains to prove estimate (3.3) for \( m = 0 \).

By Itô’s formula, we derive

\[
d|u|^2 = \left[ - (2a^{ij}_{\alpha\beta} - \sigma^{i\alpha}_{\gamma\beta} \sigma^{j\beta}_{\gamma\beta}) \partial_i u^\alpha \partial_j u^\beta + 2a^{ij}_{\alpha\beta} \partial_i (u^\alpha \partial_j u^\beta) \right] dt + \left( u^\alpha f_\alpha + 2\sigma^{i\beta}_{\alpha\beta} \partial_i u^\alpha g_\alpha^k \right) dt + 2 \left( \sigma^{i\beta}_{\alpha\beta} u^\alpha \partial_i u^\beta + u^\alpha g_\alpha^k \right) dw_t^k.
\]
Integrating with respect to \(x\) over \(\mathbb{R}^d\) and using the divergence theorem, we have

\[
\begin{align*}
\text{(3.11)} \quad \frac{d}{dt} \|u(\cdot, t)\|_{L_2}^2 \\
&= \int_{\mathbb{R}^d} \left[ -2a_{ij}^\alpha - \sigma^i_{\gamma\alpha} \sigma^j_{\gamma\beta} \partial_i u^\gamma \partial_j u^\beta + u^\alpha f_\alpha + 2\sigma^{ik}_{\alpha\beta} \partial_i u^\beta g^k_\alpha + |g|^2 \right] dx dt \\
&\quad + \int_{\mathbb{R}^d} 2\left( \sigma^{ik}_{\alpha\beta} u^\alpha \partial_i u^\beta + u^\alpha g^k_\alpha \right) dx \, dw^k_t.
\end{align*}
\]

Applying Itô’s formula to \(\|u(\cdot, t)\|_{L_2}^p\) gives

\[
\begin{align*}
\frac{d}{dt} \|u(\cdot, t)\|_{L_2}^p \\
&= \frac{p}{2} \|u\|_{L_2}^{p-2} \int_{\mathbb{R}^d} \left[ -2a_{ij}^\alpha - \sigma^i_{\gamma\alpha} \sigma^j_{\gamma\beta} \partial_i u^\gamma \partial_j u^\beta + u^\alpha f_\alpha + 2\sigma^{ik}_{\alpha\beta} \partial_i u^\beta g^k_\alpha + |g|^2 \right] dx dt \\
&\quad + \frac{p(p-2)}{2} 1(\|u\|_{L_2}^2 \neq 0) \|u\|_{L_2}^{p-4} \sum_k \left[ \int_{\mathbb{R}^d} \left( \sigma^{ik}_{\alpha\beta} u^\alpha \partial_i u^\beta + u^\alpha g^k_\alpha \right) dx \right]^2 dt \\
&\quad + p\|u\|_{L_2}^{p-2} \int_{\mathbb{R}^d} \left( \sigma^{ik}_{\alpha\beta} u^\alpha \partial_i u^\beta + u^\alpha g^k_\alpha \right) dx \, dw^k_t.
\end{align*}
\]

Recalling the MSP condition for the definition of \(\lambda^i_{\alpha\beta}\) and that \(\lambda^i_{\alpha\beta} = \lambda^i_{\beta\alpha}\), we compute

\[
\sigma^{ik}_{\alpha\beta} u^\alpha \partial_i u^\beta = (\sigma^i_{\gamma\alpha} - \lambda^i_{\alpha\beta}) u^\alpha \partial_i u^\beta + \lambda^i_{\alpha\beta} u^\alpha \partial_i u^\beta = (\sigma^i_{\gamma\alpha} - \lambda^i_{\alpha\beta}) u^\alpha \partial_i u^\beta + \frac{1}{2} \lambda^i_{\alpha\beta} \partial_i (u^\alpha u^\beta),
\]

so by the integration by parts,

\[
\int_{\mathbb{R}^d} \sigma^{ik}_{\alpha\beta} u^\alpha \partial_i u^\beta dx = \int_{\mathbb{R}^d} (\sigma^i_{\gamma\alpha} - \lambda^i_{\alpha\beta}) u^\alpha \partial_i u^\beta dx.
\]

Using the MSP condition and Lemma 3.4, we can dominate the highest order terms:

\[
\begin{align*}
- \|u\|_{L_2}^2 \int_{\mathbb{R}^d} (2a_{ij}^\alpha - \sigma^i_{\gamma\alpha} \sigma^j_{\gamma\beta}) \partial_i u^\alpha \partial_j u^\beta dx + (p-2) \sum_k \left( \int_{\mathbb{R}^d} \sigma^{ik}_{\alpha\beta} u^\alpha \partial_i u^\beta dx \right)^2 \\
\leq - \|u\|_{L_2}^2 \int_{\mathbb{R}^d} (2a_{ij}^\alpha - \sigma^i_{\gamma\alpha} \sigma^j_{\gamma\beta}) \partial_i u^\alpha \partial_j u^\beta dx \\
\quad + (p-2)\|u\|_{L_2}^2 \sum_{k, \gamma} \int_{\mathbb{R}^d} \left[ (\sigma^{ik}_{\alpha\beta} - \lambda^i_{\alpha\beta}) \partial_i u^\beta \right]^2 dx \\
= - \|u\|_{L_2}^2 \int_{\mathbb{R}^d} \left[ 2a_{ij}^\alpha - \sigma^i_{\gamma\alpha} \sigma^j_{\gamma\beta} + (p-2) (\sigma^i_{\gamma\alpha} - \lambda^i_{\gamma\alpha})(\sigma^{ik}_{\gamma\beta} - \lambda^{ik}_{\gamma\beta}) \right] \partial_i u^\alpha \partial_j u^\beta dx \\
\leq - \epsilon \|u\|_{L_2}^2 \|\partial u\|_{L_2}^2.
\end{align*}
\]
Actually, here is the only place we use the MSP condition. So we have

\[
\begin{align*}
(3.12) \quad d\|u(\cdot, t)\|_{L^2_{p}}^p & \leq \frac{p}{2} \|u\|_{L^2_{p}}^p \left( -c \|\partial u\|_{L^2_{p}}^2 + \|u\|_{H^1_{p}}^2 + C\|g\|_{L^2_{p}}^2 + C\|\partial u\|_{L^2_{p}} \|g\|_{L^2_{p}} \right) dt \\
& \quad + p\|u\|_{L^2_{p}}^{p-2} \int_{\mathbb{R}^d} \left( \sigma_{i\alpha} u^\alpha \partial_i u^\beta + u^\alpha \sigma^k_{i\alpha} \right) dx \, dw^k_t \\
& \leq \left[ -\frac{pe}{4} \|u\|_{L^2_{p}}^{p-2} \|\partial u\|_{L^2_{p}}^2 + C\|u\|_{L^2_{p}}^p + C\|u\|_{L^2_{p}}^{p-2} (\|f\|_{H^1_{p-1}}^2 + \|g\|_{L^2_{p}}^2) \right] dt \\
& \quad + p\|u\|_{L^2_{p}}^{p-2} \int_{\mathbb{R}^d} \left( \sigma_{i\alpha} u^\alpha \partial_i u^\beta + u^\alpha \sigma^k_{i\alpha} \right) dx \, dw^k_t.
\end{align*}
\]

Integrating with respect to time on \([0, s]\) for any \(s \in [0, T]\), and keeping in mind the initial condition \(u(x, 0) \equiv 0\), we know that

\[
\begin{align*}
\|u(s)\|_{L^2_{p}}^p & \leq C \int_0^s \left[ \|u(t)\|_{L^2_{p}}^p + \|u\|_{L^2_{p}}^{p-2} (\|f\|_{H^1_{p-1}}^2 + \|g\|_{L^2_{p}}^2) \right] dt \\
& \quad + \int_0^s p\|u\|_{L^2_{p}}^{p-2} \int_{\mathbb{R}^d} \left[ \sigma_{i\alpha} u^\alpha \partial_i u^\beta + u^\alpha \sigma^k_{i\alpha} \right] dx \, dw^k_t, \quad \text{a.s.}
\end{align*}
\]

Let \(\tau \in [0, T]\) be a stopping time such that

\[
\mathbb{E} \sup_{t \in [0, \tau]} \|u(t)\|_{L^2_{p}}^p + \mathbb{E}\left( \int_0^\tau \|\partial u(t)\|_{L^2_{p}}^2 dt \right)^{\frac{p}{2}} < \infty.
\]

Then it is easily verified that the last term on the right-hand side of (3.13) is a martingale with parameter \(s\). Taking the expectation on both sides of (3.13), and by Young’s inequality and Gronwall’s inequality, we can obtain that

\[
\begin{align*}
(3.14) \quad \sup_{t \in [0, T]} \mathbb{E}\|u(t \wedge \tau)\|_{L^2_{p}}^p & + \mathbb{E}\int_0^\tau \|u(t)\|_{L^2_{p}}^{p-2} \|\partial u(t)\|_{L^2_{p}}^2 dt \\
& \leq C\mathbb{E}\int_0^\tau \|u(t)\|_{L^2_{p}}^{p-2} (\|f\|_{H^1_{p-1}}^2 + \|g\|_{L^2_{p}}^2) dt.
\end{align*}
\]

On the other hand, by the Burkholder–Davis–Gundy (BDG) inequality (cf. Revuz and Yor (1999)), we can derive from (3.13) that

\[
\begin{align*}
(3.15) \quad \mathbb{E} \sup_{t \in [0, \tau]} \|u(t)\|_{L^2_{p}}^p & + \mathbb{E}\int_0^\tau \|u(t)\|_{L^2_{p}}^{p-2} \|\partial u(t)\|_{L^2_{p}}^2 dt \\
& \leq C\mathbb{E}\int_0^\tau \left[ \|u(t)\|_{L^2_{p}}^p + \|u(t)\|_{L^2_{p}}^{p-2} (\|f\|_{H^1_{p-1}}^2 + \|g\|_{L^2_{p}}^2) \right] dt \\
& \quad + C\mathbb{E}\left\{ \int_0^\tau \|u\|_{L^2_{p}}^{2(p-2)} \sum_k \left[ \int_{\mathbb{R}^d} \left( \sigma_{i\alpha} u^\alpha \partial_i u^\beta + u^\alpha \sigma^k_{i\alpha} \right) dx \right]^2 dt \right\}^{\frac{1}{2}}.
\end{align*}
\]
and by Hölder’s inequality, the last term on the right-hand side of the above inequality is dominated by

\[
C \mathbb{E} \left[ \int_0^T \| \mathbf{u} \|_{L_x^2}^{2(p-2)} \left( \| \mathbf{u} \|_{L_x^2}^2 \| \partial_t \mathbf{u} \|_{L_x^2}^2 + \| \mathbf{u} \|_{L_x^2} \| \mathbf{g} \|_{L_x^2}^2 \right) \, dt \right]^{\frac{1}{2}}
\]

\[
\leq C \mathbb{E} \left\{ \sup_{t \in [0,T]} \| \mathbf{u}(t) \|_{L_x^2}^{p/2} \left[ \int_0^T \left( \| \mathbf{u} \|_{L_x^2}^{p-2} \| \partial_t \mathbf{u} \|_{L_x^2}^2 + \| \mathbf{u} \|_{L_x^2}^{p-2} \| \mathbf{g} \|_{L_x^2}^2 \right) \, dt \right]^{\frac{1}{2}} \right\}
\]

\[
\leq \frac{1}{2} C \mathbb{E} \sup_{t \in [0,T]} \| \mathbf{u}(t) \|_{L_x^2}^p + C \mathbb{E} \left[ \int_0^T \left( \| \mathbf{f} \|_{H^{-1}}^2 + \| \mathbf{g} \|_{L_x^2}^2 \right) \, dt \right]^{\frac{p}{2}}.
\]

which along with (3.14) and (3.15) yields that

\[
\mathbb{E} \sup_{t \in [0,T]} \| \mathbf{u}(t) \|_{L_x^2}^p \leq C \mathbb{E} \int_0^T \left( \| \mathbf{f} \|_{H^{-1}}^2 + \| \mathbf{g} \|_{L_x^2}^2 \right) \, dt
\]

\[
\leq C \mathbb{E} \left[ \sup_{t \in [0,T]} \| \mathbf{u}(t) \|_{L_x^2}^{p-2} \int_0^T \left( \| \mathbf{f} \|_{H^{-1}}^2 + \| \mathbf{g} \|_{L_x^2}^2 \right) \, dt \right]
\]

\[
\leq \frac{1}{2} C \mathbb{E} \sup_{t \in [0,T]} \| \mathbf{u}(t) \|_{L_x^2}^p + C \mathbb{E} \left[ \int_0^T \left( \| \mathbf{f} \|_{H^{-1}}^2 + \| \mathbf{g} \|_{L_x^2}^2 \right) \, dt \right]^{\frac{p}{2}}.
\]

Thus we gain the estimate

\[
(3.16) \quad \frac{1}{C} \mathbb{E} \sup_{t \in [0,T]} \| \mathbf{u}(t) \|_{L_x^2}^p \leq \mathbb{E} \left[ \int_0^T \left( \| \mathbf{f} \|_{H^{-1}}^2 + \| \mathbf{g} \|_{L_x^2}^2 \right) \, dt \right]^{\frac{p}{2}} =: F
\]

with \( C = C(d, \kappa, K, p, T) \).

In order to estimate \( \| \partial_t \mathbf{u} \|_{L_x^2}^p \), we go back to (3.11). Bearing in mind Condition (1.8) (actually here we only need the weaker one (1.9)) we can easily get that

\[
\| \mathbf{u}(\tau) \|_{L_x^2}^2 + \kappa \int_0^\tau \| \partial_t \mathbf{u}(\tau) \|_{L_x^2}^2 \, d\tau \leq \int_0^\tau \int_{\mathbb{R}^d} \left( a^\alpha \partial_\alpha \mathbf{f} + 2 \sigma_{\alpha \beta} \partial_\alpha \mathbf{u} \partial_\beta \mathbf{u} + |\mathbf{g}|^2 \right) \, dx \, dt
\]

\[
+ \int_0^\tau \int_{\mathbb{R}^d} 2(\sigma_{\alpha \beta} \partial_\alpha \mathbf{u} \partial_\beta \mathbf{u} + \mathbf{u}^\alpha \mathbf{u}^\beta) \, dx \, dw_t^k.
\]

Computing \( \mathbb{E}[\cdot]^{p/2} \) on both sides of the above inequality and by Hölder’s inequality and
the BDG inequality, we derive that
\[
\mathbb{E} \left( \int_0^\tau \| \partial u(t) \|^2_{L^2_x} \, dt \right)^{\frac{p}{2}} \\
\leq \frac{1}{4} \mathbb{E} \left( \int_0^\tau \| u(t) \|^2_{H^1_x} \, dt \right)^{\frac{p}{2}} + CF + C \mathbb{E} \left[ \int_0^\tau \int_{\mathbb{R}^d} \left( \sigma_{\alpha \beta} u^\alpha \partial_t u^\beta + u^\alpha g^\alpha \right) \, dx \, du^\alpha \right]^{\frac{p}{2}} \\
\leq \frac{1}{4} \mathbb{E} \left( \int_0^\tau \| u(t) \|^2_{H^1_x} \, dt \right)^{\frac{p}{2}} + CF + C \mathbb{E} \left[ \sum_k \int_0^\tau \left( \int_{\mathbb{R}^d} \left( \sigma_{\alpha \beta} u^\alpha \partial_t u^\beta + u^\alpha g^\alpha \right) \, dx \right)^2 \right]^{\frac{p}{4}} \\
\leq \frac{1}{4} \mathbb{E} \left( \int_0^\tau \| u(t) \|^2_{H^1_x} \, dt \right)^{\frac{p}{2}} + CF + C \mathbb{E} \left[ \int_0^\tau \| u(t) \|_{L^2_x}^2 \left( \| \partial u(t) \|_{L^2_x}^2 + \| g(t) \|_{L^2_x}^2 \right) \, dt \right]^{\frac{p}{4}} \\
\leq \frac{1}{2} \mathbb{E} \left( \int_0^\tau \| \partial u(t) \|^2_{L^2_x} \, dt \right)^{\frac{p}{2}} + C \mathbb{E} \sup_{t \in [0, \tau]} \| u(t) \|_{L^2_x}^p + CF.
\]
which along with (3.16) implies
\[
\mathbb{E} \sup_{t \in [0, \tau]} \| u(t) \|_{L^2_x}^p + \mathbb{E} \left( \int_0^\tau \| \partial u(t) \|^2_{L^2_x} \, dt \right)^{\frac{p}{2}} \leq CF,
\]
where the constant $C$ depends only on $d, p, T, \kappa,$ and $K$, but is independent of $\tau$. Finally, we take the stopping time $\tau$ to be
\[
\tau_n := \inf \left\{ s \geq 0 : \sup_{t \in [0, s]} \| u(t) \|_{L^2_x}^2 + \int_0^s \| \partial u(t) \|_{L^2_x}^2 \, dt \geq n \right\} \wedge T,
\]
and letting $n$ tend to infinity we obtain the estimate (3.3) with $m = 0$. Theorem 3.1 is proved. \hfill \Box

4. Interior Hölder estimates for the model system. The aim of this section is to prove the interior Hölder estimates for the model equation (3.2). The conditions (1.8) and (3.1) are also assumed throughout this section. Take $f \in C_0^\infty(\mathbb{R}^d \times \mathbb{R}; L^p_\omega)$ and $g \in C_0^\infty(\mathbb{R}^d \times \mathbb{R}; L^p_\omega)$ such that the modulus of continuity
\[
\omega(r) := \text{ess sup}_{t \in \mathbb{R}, |x-y| \leq r} \left( \| f(x, t) - f(y, t) \|_{L^p_\omega} + \| \partial g(x, t) - \partial g(y, t) \|_{L^p_\omega} \right)
\]
satisfies the Dini condition:
\[
\int_0^1 \frac{\omega(r)}{r} \, dr < \infty.
\]

**Theorem 4.1.** Let $u \in C_{x,t}^{3,1}(Q; L^p_\omega)$ satisfy (3.2). Under the above setting, there is a positive constant $C$, depending only on $d, \kappa,$ and $p$, such that for any $X, Y, \in Q_{1/4}$,
\[
\| \partial^2 u(X) - \partial^2 u(Y) \|_{L^2_x} \leq C \left[ \delta M + \int_0^\delta \frac{\omega(r)}{r} \, dr + \delta \int_\delta^1 \frac{\omega(r)}{r^2} \, dr \right],
\]
where $\delta := |X - Y|_p$ and
\[
M := \| u \|_{L^p_\omega L^2_x L^2(\Omega_1)} + \| f \|_{L^p_\omega L^2_x L^2(\Omega_1)} + \| g \|_{L^p_\omega L^2_x H^1_x(\Omega_1)}.
\]

Then the interior Hölder estimate are straightforward:

**Corollary 4.2.** Under the same setting of Theorem (4.1) and given \( \delta \in (0,1) \), there is a constant \( C > 0 \), depending only on \( d, \kappa \) and \( p \), such that

\[
\| \partial^2 u \|_{(\delta/2, \delta) \times \partial Q_{1/4}} \leq C \left[ \| u \|_{L^\infty_0 L^2 L^2_0(Q_1)} + \frac{\| f \|_{\delta, p; Q_1} + \| g \|_{1+\delta, p; Q_1}}{\delta (1 - \delta)} \right],
\]

provided the right-hand side is finite.

**Proof of Theorem 4.1.** Letting \( \varphi : \mathbb{R}^n \to \mathbb{R} \) be a nonnegative and symmetric mollifier (see Appendix) and \( \varphi^\varepsilon(x) = \varepsilon^n \varphi(x/\varepsilon) \), we define \( u^{\alpha \varepsilon} = \varphi^\varepsilon * u^\alpha \), \( f^\varepsilon = \varphi^\varepsilon * f^\alpha \) and \( g^\varepsilon = \varphi^\varepsilon * g^\alpha \). Then it is easily checked that \( f^\varepsilon \) and \( \partial g^\varepsilon \) are also Dini continuous and has the same continuity modulus \( \varepsilon \) with \( f \) and \( \partial g \), and

\[
\| f^\varepsilon - f \|_{0, p; \mathbb{R}^n} + \| g^\varepsilon - g \|_{1, p; \mathbb{R}^n} \to 0,
\]

\[
\| \partial^2 u^\varepsilon(X) - \partial^2 u(X) \|_{L^2_p} \to 0 \quad \forall X \in \mathbb{R}^n \times \mathbb{R},
\]
as \( \varepsilon \to 0 \). On the other hand, from Fubini’s theorem one can check that \( u^\varepsilon \) satisfies the model equation (3.2) in the classical sense with free terms \( f^\varepsilon \) and \( g^\varepsilon \). Therefore, it suffices to prove the theorem for the mollified functions, and the general case is straightforward by passing the limits.

Based on the above analysis and the smoothness of mollified functions, we may suppose that (cf. Du and Liu (2015))

(A) \( f, g \in L^p_0 L^2 H^k_x(\partial Q_R) \cap C^k_x(\partial Q_R; L^p_0) \) for all \( k \in \mathbb{Z}_+ \) and \( R > 0 \).

We can also set \( \Omega = 0 \) without loss of generality. With \( \rho = 1/2 \), we define

\[
Q^\ell := Q^\rho_{\rho} = Q^\rho_{\rho}(0, 0), \quad \ell \in \mathbb{N} = \{0, 1, 2, \ldots \},
\]
and introduce the following boundary value problems:

\[
\begin{aligned}
\begin{cases}
\partial u^\alpha \partial \ell = [a_{ij}\partial^i u^{\beta \ell} + f^\alpha(0, t)] \, dt + [\sigma_{ijk} \partial^i \partial^j u^{\beta \ell} + g^k(0, t)] \, dw^k
\end{cases}
\end{aligned}
\tag{4.1}
\]

where \( \partial_{\rho} Q^\ell \) denotes the parabolic boundary of the cylinder \( Q^\ell \). The existence and interior regularity of \( u^\ell \) can be direct yielded by Proposition 3.3.

Given a point \( Y = (y, s) \in Q_{1/4} \), there is an \( \ell_0 \in \mathbb{N} \) such that

\[
\delta := |Y|_{\rho} \in [\rho^{\ell_0+2}, \rho^{\ell_0+1}].
\]

So we have

\[
\begin{aligned}
\| \partial^2 u(Y) - \partial^2 u(0) \|_{L^2_p} \\
\leq \| \partial^2 u^{\ell_0}(0) - \partial^2 u(0) \|_{L^2_p} + \| \partial^2 u^{\ell_0}(Y) - \partial^2 u(Y) \|_{L^2_p} + \| \partial^2 u^{\ell_0}(Y) - \partial^2 u^{\ell_0}(0) \|_{L^2_p}
\end{aligned}
\tag{4.2}
\]

As \( N_1 \) and \( N_1' \) are similar, we are going to derive the estimates for \( N_1 \) and \( N_2 \).
CLAIM 4.3. \( \| \partial^m (u^\ell - u^{\ell+1}) \|_{0,p,Q^{\ell+2}} \leq C (d, \kappa, p) \rho^{(2-m)\ell-m} \varpi(\rho^\ell) \), where \( m \in \mathbb{N} \).

PROOF. Applying Proposition 3.2 to (4.1), we have

\[
\| \partial^m (u^\ell - u^{\ell+1}) \|_{0,p,Q^{\ell+2}} \leq C \rho^{-m\ell-m} \left( \int_{Q^{\ell+1}} |u^\ell - u^{\ell+1}|^2 \right)^{1/2} =: I_{\ell,m}
\]

(hereafter we denote \( \int_Q = \frac{1}{|Q|} \int_Q \) with \( |Q| \) being the Lebesgue measure of the set \( Q \subset \mathbb{R}^{n+1} \)), and by Proposition 3.3,

\[
J_\ell := \left( \int_{Q^{\ell+1}} |u^\ell - u|^2 \right)^{1/2} \leq C \rho^{2\ell} \varpi(\rho^\ell).
\]

So we gain that

\[
I_{\ell,m} \leq C \rho^{-m\ell-m} (J_\ell + J_{\ell+1}) \leq C \rho^{(2-m)\ell-m} \varpi(\rho^\ell).
\]

The claim is proved. \( \square \)

CLAIM 4.4. \( N_1 \leq C (d, \kappa, p) \int_0^{\rho^\ell_0} \frac{\varpi(r)}{r} \) \( dr \).

PROOF. It follows from Claim 4.3 that

\[
\sum_{\ell \geq \ell_0} \| \partial^2 u^\ell(0) - \partial^2 u^{\ell+1}(0) \|_{L^p} \leq C \sum_{\ell \geq \ell_0} \varpi(\rho^\ell) \leq C \int_0^{\rho^\ell_0} \frac{\varpi(r)}{r} \) \( dr \),
\]

which implies that \( \partial^2 u^\ell(0) \) converges in \( L^p \) as \( \ell \to \infty \), if the limit is \( \partial^2 u(0) \), then

\[
N_1 = \| \partial^2 u^{\ell_0}(0) - \partial^2 u(0) \|_{L^p} \leq \sum_{\ell \geq \ell_0} \| \partial^2 u^\ell(0) - \partial^2 u^{\ell+1}(0) \|_{L^p} \leq C \int_0^{\rho^\ell_0} \frac{\varpi(r)}{r} \) \( dr \).
\]

So it suffices to show that \( \lim_{\ell \to \infty} \| \partial^2 u^\ell(0) - \partial^2 u(0) \|_{L^2} = 0 \). From Proposition 3.2 with \( p = 2 \), we have

\[
\sup_{Q^{\ell+1}} \| \partial^2 u^\ell - \partial^2 u \|_{L^2} \leq C \rho^{-4\ell} \mathbb{E} \int_{Q^\ell} |u^\ell - u|^2 + C \mathbb{E} \int_{Q^\ell} (|f(x, t) - f(0, t)|^2 + |g(x, t) - g(0, t)|^2 + |\partial g(x, t) - \partial g(0, t)|^2) \) \( dX \)
\]

\[
+ C \sum_{k=1}^{[\ell/2]+1} \rho^{2k} \mathbb{E} \int_{Q^\ell} (|\partial^k f|^2 + |\partial^{k+1} g|^2).
\]
Thus, \( \lim_{\ell \to \infty} \int_{Q_{\ell}} |u^\ell - u|^2 \) and for \(-\) right-hand side tend to zero as \( \ell \to \infty \), and by Proposition 3.3,

\[
\rho^{-\ell} E \int_{Q_{\ell}} |u^\ell - u|^2 \\
\leq C E \int_{Q_{\ell}} (|f(x,t) - f(0,t)|^2 + \rho^{-2\ell} |g(x,t) - g(0,t) - x^\ell \partial_\ell g(0,t)|^2) \, dX \\
\leq C \varpi(\rho^\ell) \to 0, \quad \text{as} \ \ell \to \infty.
\]

Thus, \( \lim_{\ell \to \infty} \| \partial^2 u^\ell(0) - \partial^2 u(0) \|_{L^2_y} = 0 \). The claim is proved. \( \square \)

**Claim 4.5.** \( N_2 \leq C(d, \kappa, p) \rho^\alpha \left( M + \int_{\rho^\alpha}^1 \frac{\varpi(r)}{r^2} \, dr \right) \).

**Proof.** Define \( h^\ell = u^\ell - u^{\ell-1} \) for \( \ell = 1, 2, \ldots, \ell_0 \), then

\[
N_2 = \| \partial^2 u^0(Y) - \partial^2 u^0(0) \|_{L^\infty_y} \\
\leq \| \partial^2 u^0(Y) - \partial^2 u^0(0) \|_{L^\infty_y} + \sum_{\ell=1}^{\ell_0} \| \partial^2 h^\ell(Y) - \partial^2 h^\ell(0) \|_{L^\infty_y}.
\]

As \( \partial_{ij} u^0 \) satisfies a homogeneous system in \( Q_1 \) for any \( i, j = 1, \ldots, d \), it follows from Proposition 3.2 that

\[
\| \partial (\partial_{ij} u^0) \|_{0,p;Q_{1/4}} \leq C \| \partial_{ij} u^0 \|_{L^\infty_y L^2_x(Q_{1/2})} \\
\leq C (\| \partial_{ij} u^0 \|_{L^\infty_y L^2_x(Q_{1/2})} + \| \partial_{ij} u^0 \|_{L^\infty_y L^2_x(Q_{1/2})}) \\
\leq C \| u^0 \|_{L^\infty_y L^2_x(Q_{1/2})} + \| f \|_{L^\infty_y L^2_x(Q_{1/2})} + \| g \|_{L^\infty_y L^2_x(H^s_x(Q_{1/2}))} = CM,
\]

and for \(-1/16 < s < t \leq 0 \) and \( x \in B_{1/4} \),

\[
\| \partial^2 u^{\alpha,0}(x,t) - \partial^2 u^{\alpha,0}(x,s) \|_{L^\infty_y} = \left\| \int_s^t \partial_{ij} \partial_{ij} \partial^2 u^{\alpha,0} \, d\tau + \int_s^t \partial_{ij} \partial_{ij} \partial^2 u^{\alpha,0} \, d\tau \right\|_{L^\infty_y} \\
\leq C \sqrt{t-s} (\| \partial^3 u^0 \|_{0,p;Q_{1/4}} + \| \partial^4 u^0 \|_{0,p;Q_{1/4}}^2) \\
\leq CM \sqrt{t-s}.
\]

So we have

\[
\| \partial^2 u^{\alpha,0}(Y) - \partial^2 u^{\alpha,0}(0) \|_{L^\infty_y} \leq CM |Y|_p \leq CM \rho^\alpha.
\]

Next, by Claim 4.3,

\[
\| \partial^3 h^\ell \|_{0,p;Q^{\ell+1}_t} + \| \partial^4 h^\ell \|_{0,p;Q^{\ell+1}_t} \leq C \rho^{-2\ell} \varpi(\rho^{\ell-1}),
\]

thus, for \(-2^{(\ell_0+1)} \leq t \leq 0 \) and \( |x| \leq \rho^{\ell_0+1} \),

\[
\| \partial^2 h^\ell(x,0) - \partial^2 h^\ell(0,0) \|_{L^\infty_y} \leq C \rho^{\ell_0-\ell} \varpi(\rho^{\ell-1})
\]
and
\[
\|\partial^2 h^{\alpha,\ell}(x, t) - \partial^2 h^{\alpha,\ell}(x, 0)\|_{L^p_\omega} = \left\| \int_0^t \int_0^{\sigma_{\alpha\beta}^i \partial_i (\partial^2 h^{\alpha,\ell})} \right\|_{L^p_\omega} \\
\leq C(\rho_0 \|\partial^3 h^{\ell}\|_{0,p;Q_{1/4}} + \rho_0^{2c_0} \|\partial^4 h^{\ell}\|_{0,p;Q_{1/4}}) \\
\leq C\rho_0^{\ell-1} \varpi(\rho^{\ell-1}).
\]
Therefore,
\[
N_2 \leq CM\rho_0 + C\sum_{\ell=1}^{\ell_0} \rho_0^{\ell-1} \varpi(\rho^{\ell-1}) \leq C\rho_0 \left( M + \int_{\rho_0^{c_0}}^{1} \frac{\varpi(r)}{r^2} \, dr \right).
\]
The claim is proved.

Combining (4.2) and Claims 4.4 and 4.5, we conclude Theorem 4.1.

5. Hölder estimates for general systems. This section is devoted to the proofs of Theorems 2.1 and 2.2. We need two technical lemmas whose proofs can be found in, for example, Du and Liu (2015).

**Lemma 5.1.** Let \( \varphi : [0, T] \to [0, \infty) \) satisfy
\[
\varphi(t) \leq \theta \varphi(s) + \sum_{i=1}^{m} A_i(s - t)^{-\eta_i} \quad \forall \, 0 \leq t < s \leq T
\]
for some nonnegative constants \( \theta, \eta_i \) and \( A_i \) \((i = 1, \ldots, m)\), where \( \theta < 1 \). Then
\[
\varphi(0) \leq C \sum_{i=1}^{m} A_i T^{-\eta_i},
\]
where \( C \) depends only on \( \eta_1, \ldots, \eta_m \) and \( \theta \).

**Lemma 5.2.** Let \( p \geq 1, \ R > 0 \) and \( 0 \leq s < r \). There exists a constant \( C > 0 \), depending only on \( d \) and \( p \), such that
\[
\left\| [u]_{s,p;Q_R} \right\| \leq C \varepsilon^{-s} \left\| [u]_{r,p;Q_R} \right\| + C \varepsilon^{-s/d} \left\| \mathbb{E}\|u\|_{L^2(Q_R)}^p \right\|^{1/p}
\]
for any \( u \in C^r(Q_R; L^p_\omega) \) and \( \varepsilon \in (0, R) \).

Now we prove the a priori interior Hölder estimates for system (1.1).

**Proof of Theorem 2.1.** With a change of variable, we may move the point \( X \) to the origin. Let \( \rho/2 \leq r < R \leq \rho \) with \( \rho \in (0, 1/4) \) to be defined. Take a nonnegative cut-off function \( \zeta \in C^\infty_0(\mathbb{R}^{d+1}) \) such that \( \zeta = 1 \) on \( Q_r, \zeta = 0 \) outside \( Q_R \), and for \( \gamma \geq 0, \)
\[
[\zeta]_{(\gamma,\gamma/2);\mathbb{R}^d} \leq C(d) (R - r)^{-\gamma}.
\]
Set $v = \zeta u$, and
\[
\tilde{a}_{ij}^{\alpha\beta}(t) = a^{ij}_{\alpha\beta}(0, t), \quad \tilde{\sigma}_{ij}^{k}(t) = a^{ik}_{\alpha\beta}(0, t),
\]
then $v = (v^1, \ldots, v^N)$ satisfies
\[
dv^\alpha = \left(\tilde{a}_{ij}^{\alpha\beta} \partial_{ij} v^\beta + \tilde{f}_\alpha\right) dt + \left(\overline{\sigma}_{ij}^{k} \partial_{ij} v^\beta + \overline{g}^k\right) dw^k
\]
where
\[
\tilde{f}_\alpha = (a^{ij}_{\alpha\beta} - \tilde{a}_{ij}^{\alpha\beta}) \zeta \partial_{ij} u^\beta + (b_{ij}^\alpha\zeta - 2\tilde{a}_{ij}^{\alpha\beta} \partial_{ij} \zeta) \partial_i u^\beta
\]
\[
+ (c_{\alpha\beta} \zeta - b_{ij}^\alpha \partial_i \zeta - a_{ij}^{\alpha\beta} \partial_{ij} \zeta) u^\beta + \zeta v^\alpha + \zeta \hat{f}_\alpha,
\]
\[
\overline{g}^k = (a^{ik}_{\alpha\beta} - \tilde{\sigma}_{ij}^{k}) \zeta \partial_i u^\beta + (v^k \zeta - a_{ij}^{ik} \partial_{ij} \zeta) u^\beta + \zeta g^\alpha.
\]
Obviously, $\tilde{a}_{ij}^{\alpha\beta}$ and $\overline{\sigma}_{ij}^{k}$ satisfy the MSP condition with $\lambda = \lambda(0, t)$. So by Lemma 5.2,
\[
\frac{1}{2} \|[\tilde{f}]_{\delta, p; Q_R}\|_{\delta, p; Q_R} \leq (\varepsilon + K\rho^5) \|[\tilde{u}]_{\delta, p; Q_R} + C_1(R - r)^{-2-\delta-d/2}\|[u]_{L^2_\omega L^2_\zeta(Q_R)}
\]
\[
+ \|[\tilde{f}]_{\delta, p; Q_R} + C_1(R - r)^{-\delta}\|[\tilde{f}]_{0, p; Q_R},
\]
\[
\frac{1}{2} \|[\overline{g}]_{\delta, p; Q_R}\|_{\delta, p; Q_R} \leq (\varepsilon + K\rho^5) \|[\overline{u}]_{2+\delta, p; Q_R} + C_1(R - r)^{-2-\delta-d/2}\|[u]_{L^2_\omega L^2_\zeta(Q_R)}
\]
\[
+ \|[\overline{g}]_{1+\delta, p; Q_R} + C_1(R - r)^{-1-\delta}\|[g]_{0, p; Q_R},
\]
where $C_1 = C_1(d, K, p, \varepsilon)$. Applying Corollary 4.2, we gain that
\[
\frac{1}{2} \|[\tilde{u}]_{\delta, p; Q_R}\|_{\delta, p; Q_R} \leq C_2(\varepsilon + K\rho^5) \|[\tilde{u}]_{\delta, p; Q_R} + C_1(R - r)^{-2-\delta-d/2}\|[u]_{L^2_\omega L^2_\zeta(Q_R)}
\]
\[
+ \|[\tilde{f}]_{\delta, p; Q_R} + C_1(R - r)^{-\delta}\|[\tilde{f}]_{0, p; Q_R} + \|[\overline{g}]_{1+\delta, p; Q_R} + C_1(R - r)^{-1-\delta}\|[g]_{0, p; Q_R},
\]
where $C_2 = C_2(d, \kappa, K, p, \delta)$. Set $\varepsilon = (2C_2)^{-1}$, then
\[
C_2(\varepsilon + K\rho^5) \leq \frac{1}{2} \text{ for any } \rho \leq (4C_2K)^{-\delta} =: \rho_0.
\]
Thus, by Lemma 5.1 we have
\[
\|[\partial^2 u]_{\delta, 2; p; Q_{\rho/2}} \leq C(\rho^{-2-\delta-d/2}\|[u]_{L^2_\omega L^2_\zeta(Q_{\rho})} + \rho^{-\delta}\|[f]_{\delta, p; Q_{\rho}} + \rho^{-1-\delta}\|[g]_{1+\delta, p; Q_{\rho}}),
\]
where the constant $C$ depends only on $d, \kappa, K, p$, and $\delta$. The proof is complete. \hfill \Box

**Proof of Theorem 2.2.** The solvability of the Cauchy problem follows from the *a priori* estimate (2.2) by the standard method of continuity (see (Gilbarg and Trudinger, 2001, Theorem 5.2)), so it suffices to prove the *a priori* estimate (2.2).

We may extend the equations to $R^d \times (-\infty, T] \times \Omega$ by letting $u(x, t), f(x, t)$ and $g(x, t)$ be zero if $t \leq 0$. Take $t \in (0, T]$ and $R = \rho_0/2$, where $\rho_0$ is determined in Theorem 2.1.
Applying the estimate (2.1) on the cylinders centered at \((x, s)\) for all \(s \in (-1, r]\), we can obtain that
\[
\|\partial^2 u\|_{L^p((\delta, \delta/2), p; Q_{R, r}(x))} \leq C\left(\|u\|_{L^p_{\alpha} L^{2}_{\beta} (Q_{2R, r}(x))} + \|f\|_{\delta, p; Q_{2R, r}(x)} + \|g\|_{1+\delta, p; Q_{r}(x)}\right)
\]
\[
\leq C\left(\|\partial u\|_{L^p_{\alpha} L^{2}_{\beta} (Q_{2R, r}(x))} + \|f\|_{\delta, p; Q_{r}} + \|g\|_{1+\delta, p; Q_{r}}\right),
\]
then by Lemma 5.2,
\[
(5.1) \quad \|u\|_{(2+\delta, \delta/2), p; Q_{R, r}(x)} \leq C\left(\|u\|_{L^p_{\alpha} L^{2}_{\beta} (Q_{2R, r}(x))} + \|f\|_{\delta, p; Q_{r}} + \|g\|_{1+\delta, p; Q_{r}}\right).
\]
Define
\[
M_{x, R}^{p}(u) = \sup_{0 \leq t \leq \tau} \left(\int_{B_{R}(x)} \mathbb{E}|u(y, t)|^{p} \, dy\right)^{\frac{1}{p}}, \quad M_{R}^{p}(u) = \sup_{x \in \mathbb{R}^{d}} M_{x, R}^{p}(u).
\]
Obviously, \(\|u\|_{L^p_{\alpha} L^{2}_{\beta} (Q_{2R, r}(x))} \leq C(d, p, R) M_{R}^{p}(u)\). So (5.1) implies
\[
(5.2) \quad \sup_{x \in \mathbb{R}^{d}} \|u\|_{(2+\delta, \delta/2), p; Q_{R, r}(x)} \leq C(M_{R}^{p}(u) + \|f\|_{\delta, p; Q_{r}} + \|g\|_{1+\delta, p; Q_{r}}).
\]
To get rid of \(M_{R}^{p}(u)\), we apply Itô’s formula to \(|u|^{p}\):
\[
d|u|^{p} = p|u|^{p-1}\left[u^{\alpha}(\alpha \partial_{\alpha} u^{\beta} + b^{ij} \partial_{i} u^{\beta} + c_{\alpha\beta} u^{\beta} + f_{\alpha}) + \frac{1}{2} \sum_{k} (\sigma_{\alpha\beta}^{ik} \partial_{i} u^{\beta} + g_{\alpha}^{k})^{2}\right] dt
\]
\[
+ \frac{p(p-2)}{2} \mathbb{1}_{\{u \neq 0\}} |u|^{p-2} \sum_{k} (\sigma_{\alpha\beta}^{ik} u^{\alpha} \partial_{i} u^{\beta} + u^{\alpha} g_{\alpha}^{k})^{2} \, dt + dM_{t},
\]
where \(M_{t}\) is a martingale. Integrating on \(Q_{R, r}(x) \times \Omega\) and by the Hölder inequality, we can derive that
\[
\sup_{t \in [0, \tau]} \mathbb{E} \int_{B_{R}(x)} |u(y, t)|^{p} \, dy \leq C_{3} \mathbb{E} \int_{Q_{R, r}(x)} (|\partial^2 u|^{p} + |u|^{p} + |f|^{p} + |g|^{p}) \, dX
\]
with \(C_{3} = C_{3}(d, N, K, p)\), which implies that
\[
M_{x, R}^{p}(u) \leq C_{3} \tau \left(\|u\|_{2, p; Q_{R, r}(x)} + \|f\|_{0, p; Q_{r}} + \|g\|_{0, p; Q_{r}}\right)
\]
\[
\leq C_{3} \tau \left(\sup_{x \in \mathbb{R}^{d}} \|u\|_{(2+\delta, \delta/2), p; Q_{R, r}(x)} + \|f\|_{0, p; Q_{r}} + \|g\|_{0, p; Q_{r}}\right),
\]
Substituting the last relation into (5.2) and taking \(\tau = (2CC_{3})^{-1}\), we get
\[
\sup_{x \in \mathbb{R}^{d}} \|u\|_{(2+\delta, \delta/2), p; Q_{r}(x)} \leq C\left(\|f\|_{\delta, p; Q_{r}} + \|g\|_{1+\delta, p; Q_{r}}\right),
\]
and equivalently,
\[
(5.3) \quad \|u\|_{(2+\delta, \delta/2), p; Q_{r}} \leq C_{1}\left(\|f\|_{\delta, p; Q_{r}} + \|g\|_{1+\delta, p; Q_{r}}\right).
\]
with $C_\tau = C_\tau(d, \kappa, K, p, \delta) \geq 1$.

Let us conclude the proof by induction. Assume that there is a constant $C_S \geq 1$ for some $S > 0$ such that

$$
\|u\|_{(2+\delta,\delta/2),p;Q_S} \leq C_S(\|f\|_{\delta,p;Q_S} + \|g\|_{1+\delta,p;Q_S}).
$$

Then applying (5.3) to $v(x, t) = 1_{\{t \geq 0\}} \cdot |u(x, t+S) - u(x, S)|$, one can easily derive that

$$
\|v\|_{(2+\delta,\delta/2),p;Q_S} \leq C_\tau(\|f\|_{\delta,p;Q_{S+\tau}} + \|g\|_{1+\delta,p;Q_{S+\tau}} + \tilde{C}\|u(\cdot, S)\|_{2+\delta,p;R^d})
\leq 2C_\tau \tilde{C}C_S(\|f\|_{\delta,p;Q_{S+\tau}} + \|g\|_{1+\delta,p;Q_{S+\tau}}),
$$

with $\tilde{C} = \tilde{C}(N, K) \geq 1$, so

$$
\|u\|_{(2+\delta,\delta/2),p;Q_{S+\tau}} \leq \|v\|_{(2+\delta,\delta/2),p;Q_{S+\tau}} + \|u\|_{(2+\delta,\delta/2),p;Q_S}
\leq 3C_\tau \tilde{C}C_S(\|f\|_{\delta,p;Q_{S+\tau}} + \|g\|_{1+\delta,p;Q_{S+\tau}}),
$$

that means $C_{S+\tau} \leq 3C_\tau \tilde{C}C_S$. As $\tau$ is fixed, by iteration we have $C_S \leq C e^{CS}$ with $C = C(d, N, \kappa, K, p, \delta)$, and the theorem is proved.

6. More comments on the MSP condition. In this section we discuss more examples on the sharpness and flexibility of the MSP condition (Definition 1.2). We always let $d = 1$ and assume that the coefficient matrices $A = [a_{\alpha\beta}]$ and $B = [\sigma_{\alpha\beta}]$ are constant. We write $M \gg 0$ if the matrix $M$ is positive definite.

Under the above setting the MSP condition can be written into the following form if we set $[\lambda_{\alpha\beta}^{(k)}] = (B + B')/2 - \Lambda$ in (1.7).

**Condition 6.1.** There is a symmetric $N \times N$ real matrix $\Lambda$ such that

$$
A + A' - B'B - (p-2)(T_B + \Lambda)'(T_B + \Lambda) \gg 0
$$

where $T_B := (B - B')/2$ is the skew-symmetric component of $B$.

**Example 6.2.** Consider the following system

$$
\begin{cases}
du^{(1)} = u_{xx}^{(1)} + (\lambda u_{xx}^{(1)} - \mu u_x^{(2)}) \, dw_t, \\
u^{(2)} = u_{xx}^{(2)} + (\mu u_x^{(1)} + \lambda u_{xx}^{(2)}) \, dw_t
\end{cases}
$$

with $x \in T = R/(2\pi Z)$, real constants $\lambda$ and $\mu$, and with the initial data

$$
u^{(1)}(x, 0) + \sqrt{-1}u^{(2)}(x, 0) = \sum_{n \in Z} e^{-n^2} \cdot e^{\sqrt{-1}nx}.
$$

Evidently, if $\lambda^2 + \mu^2 < 2$, then system (6.2) satisfies the condition (1.2), and from the result of Kim and Lee (2013a), it has a unique solution $u = (u^{(1)}, u^{(2)})'$ in the space $L^2(\Omega; C([0, T]; H^m(T)))$ with any $m \geq 0$ and $T > 0$.

To apply our results to (6.2), we should assume it to satisfy Condition 6.1. In the next two lemmas, we first simplify the condition into a specific constraint on $\lambda$ and $\mu$, and then prove it to be optimal.
Lemma 6.3. Let \( p \geq 2 \). The coefficients of system (6.2) satisfies Condition 6.1 if and only if they satisfy (6.1) with \( \Lambda = 0 \), namely,

\[
\lambda^2 + (p - 1) \mu^2 < 2.
\]

Proof. By orthogonal transform, \( A + A' - B'B - (p - 2)(T_B + \Lambda)'(T_B + \Lambda) \) is positive definite if and only if

\[
2 - (\lambda^2 + \mu^2) - (p - 2)\lambda_{\text{max}} > 0,
\]

where \( \lambda_{\text{max}} \) is the larger eigenvalue of \( (T_B + \Lambda)'(T_B + \Lambda) \). For \( \Lambda = \mu \begin{bmatrix} a & c \\ c & b \end{bmatrix} \), we have

\[
(T_B + \Lambda)'(T_B + \Lambda) = \mu^2 \begin{bmatrix} a^2 + (c - 1)^2 & ac + bc + a - b \\ ac + bc + a - b & b^2 + (c + 1)^2 \end{bmatrix}
\]

whose larger eigenvalue is

\[
\lambda_{\text{max}} = \frac{\mu^2}{2}(a^2 + b^2 + 2c^2 + 2) + \frac{\mu^2}{2}\sqrt{(a^2 - b^2 - 4c)^2 + 4(ac + bc + a - b)^2}.
\]

Obviously, \( \lambda_{\text{max}} \geq \mu^2 \).

Once (6.5) holds for some \( \Lambda \), we get (6.4), namely (6.1) holds for \( \Lambda = 0 \). Now we prove the only if part. The proof of if part is trivial.

Therefore, if (6.4) is satisfied, then \( \sup_{x \in T} \mathbb{E}\|u(x, t)\|^p < \infty \) for any \( t \geq 0 \); if it is not, even some weaker norm of \( u(\cdot, t) \) is infinite for large \( t \) as showed in the following lemma.

Lemma 6.4. Let \( p > 2 \) and \( \lambda^2 + \mu^2 < 2 \). If \( \varepsilon := \lambda^2 + (p - 1) \mu^2 - 2 > 0 \), then

\[
\mathbb{E}\|u(\cdot, t)\|_{L^p(T)}^p \rightarrow \infty
\]

for any \( t > 2/\varepsilon \).

Proof. Denote \( v = u^{(1)} + \sqrt{-1}u^{(2)} \) that can be verified to satisfy

\[
dv = v_{xx} \, dt + (\lambda + \sqrt{-1} \mu) v_x \, dw_t
\]

with the initial condition \( v(x, 0) = \sum_{n \in \mathbb{Z}} e^{-n^2} e^{\sqrt{-1} nx} \) for \( x \in T \). By Fourier analysis, we can express

\[
v(x, t) = \sum_{n \in \mathbb{Z}} v_n(t) e^{\sqrt{-1} nx},
\]

where \( v_n(\cdot) \) satisfies the following SDE:

\[
dv_n = v_n[-n^2 \, dt + (-\mu + \sqrt{-1} \lambda) n \, dw_t], \quad v_n(0) = e^{-n^2}.
\]

From the theory of SDEs, we have

\[
v_n(t) = e^{-\frac{1}{2} \int_0^t n^2 - \mu \, dw_s} \cdot e^{\sqrt{-1}(\lambda \mu n^2 t + \lambda n \omega)}.
\]
where \( f(t) := 2 + (2 + \mu^2 - \lambda^2)t \). So we derive
\[
|v_n(t)|^2 = \exp \left\{ -f(t)n^2 - 2\mu nw_t \right\} \\
= \exp \left\{ -f(t) \left( n + \frac{\mu w_t}{f(t)} \right)^2 + \frac{\mu^2|w_t|^2}{f(t)} \right\},
\]
and by Parseval’s identity,
\[
|v_n(t)|^2 = \exp \left\{ -f(t)n^2 - 2\mu nw_t \right\} \\
\geq \exp \left\{ -f(t) \left( n + \frac{\mu w_t}{f(t)} \right)^2 + \frac{\mu^2|w_t|^2}{f(t)} \right\}.
\]
Thus, we have
\[
\mathbb{E}\|u(\cdot, t)\|_{L^2(T)}^p = \mathbb{E}\|v(\cdot, t)\|_{L^2(T)}^p \\
\geq (2\pi)^p \mathbb{E} \exp \left\{ -\frac{pf(t)}{2} + \frac{pp^2|w_1|^2}{2f(t)} \right\} \\
= (2\pi)^p e^{-pf(t)/2} \mathbb{E} \exp \left\{ \frac{pp^2|w_1|^2}{2f(t)} \right\} \\
= (2\pi)^p e^{-pf(t)/2} \mathbb{E} \exp \left\{ \frac{pp^2|w_1|^2}{2[2 + \mu^2 - \lambda^2 + 2t^{-1}]} \right\} \\
= (2\pi)^{p-1/2} e^{-pf(t)/2} \int_{\mathbb{R}} \exp \left\{ -\frac{y^2}{2} \left[ 1 - \frac{pp^2}{2 + \mu^2 - \lambda^2 + 2t^{-1}} \right] \right\} dy.
\]
The last integral diverges if
\[
1 - \frac{pp^2}{2 + \mu^2 - \lambda^2 + 2t^{-1}} < 0.
\]
This immediately concludes the lemma. \( \Box \)

Indeed, some specific choices of \( \Lambda \) in Condition 6.1 like \( \Lambda = 0 \) usually lead to a class of convenient and even optimal criteria in applications. For instance, the above discussion shows how the skew-symmetric component of \( B \) substantially affects the \( L^p \)-norm of the solution of system (6.2). But in general, the choice of \( \Lambda \) still heavily depends on the structure of the concrete problem.

**Example 6.5.** Let \( p \geq 3 \) and \( \lambda > \mu > 0 \). Consider
\[
A = \begin{bmatrix} 1 + \lambda^2 & 0 \\ 0 & 1 + \mu^2 \end{bmatrix} \quad \text{and} \quad B = \begin{bmatrix} 0 & -\mu \\ \lambda & 0 \end{bmatrix}.
\]
For the sake of simplicity, we restrict the choice of $\Lambda$ in the form $\begin{bmatrix} 0 & c \\ c & 0 \end{bmatrix}$. Then we have

$$
A + A' - B' B - (p - 2)(T_B + \Lambda)' (T_B + \Lambda)
$$

$$
= \text{diag} \left\{ 2 + \lambda^2 - (p - 2) \left( c + \frac{\lambda + \mu}{2} \right)^2, \ 2 + \mu^2 - (p - 2) \left( c - \frac{\lambda + \mu}{2} \right)^2 \right\}
$$

$$
= : \text{diag} \{ g(c), h(c) \}.
$$

As $p \geq 3$ and $\lambda > \mu > 0$, it is easily to check that

$$
\max_{c \in \mathbb{R}} \{ g(c) \wedge h(c) \} = 2 + \frac{\lambda^2 + \mu^2}{2} - \frac{(p - 2)(\lambda + \mu)^2}{4} - \frac{(\lambda - \mu)^2}{4(p - 2)},
$$

where the maximum is attained when $g(c) = h(c)$, i.e.,

$$
c = \frac{\lambda - \mu}{2(p - 2)}.
$$

So one can easily assign some specific values to $p$, $\lambda$ and $\mu$ to let $A$ and $B$ satisfy Condition 6.1 but not with $\Lambda = 0$, for example, $(p, \lambda, \mu) = (3, 3, 1)$. This shows that the choice $\Lambda = 0$ does not always lead to the minimal requirements.

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K. Du
J. Liu
School of Mathematics and Applied Statistics
University of Wollongong
Wollongong NSW 2522
Australia
E-mail: kaid@uow.edu.au
        jiaxunl@uow.edu.au

F. Zhang
College of Science
University of Shanghai for Science and Technology
Shanghai 200093
China
E-mail: fuzhang@fudan.edu.cn