Dirk Blömker, Wael W. Mohammed

Modulation Equation for Stochastic Swift-Hohenberg Equation

Preprint Nr. 14/2011 — 05. September 2011
Institut für Mathematik, Universitätsstraße, D-86135 Augsburg

http://www.math.uni-augsburg.de/
MODULATION EQUATION FOR STOCHASTIC SWIFT-HOHENBERG EQUATION

DIRK BLÖMKER AND WAEL W. MOHAMMED

Abstract. The purpose of this paper is to study the influence of large or unbounded domains on a stochastic PDE near a change of stability, where a band of dominant pattern is changing stability. This leads to a slow modulation of the dominant pattern. Here we consider the stochastic Swift-Hohenberg equation and derive rigorously the Ginzburg-Landau equation as a modulation equation for the amplitudes of the dominating modes. We verify that small global noise has the potential to stabilize the modulation equation, and thus to destroy the dominant pattern.

1. Introduction

We consider the stochastic Swift-Hohenberg equation on an unbounded domain near its change of stability. This equation has been used as a toy model for the convective instability in Rayleigh-Bénard problem (see [8] or [10]). Now it is one of the celebrated models in the theory of pattern formation. For a scalar field $U(t,x)$ it takes the form

(SH) \[ \partial_t U = \mathcal{L}U + \varepsilon^2 \nu U - U^3 + \varepsilon \sigma \partial_t \beta, \]

where the linear differential operator is $\mathcal{L} = -(1 + \partial_x^2)^2$ and its eigenvalues are $-\lambda_k = -(1 - k^2)^2$ for $k \in \mathbb{R}$ corresponding to eigenfunctions $e^{ikx}$. The noise is the derivative of a standard Brownian motion $\{\beta(t)\}_{t \geq 0}$ in $\mathbb{R}$. In this article we restrict ourselves to the case of noise constant in space, because on one hand, this is the case where we are able to study the stabilization effect. On the other hand noise in space and time may lead to spatially unbounded solutions of (SH). So, this result is only the starting point for modulation equations on unbounded domains. The stochastic Swift-Hohenberg model was first studied in the context of amplitude equations with non-degenerate noise in [5] and later in [3].

For (SH) on the whole real line with degenerate additive noise, Axel Hutt and collaborators [11], [12] used a formal argument based on center manifold theory. They showed that noise constant in space leads to a deterministic amplitude equation, which is stabilized by the impact of additive noise. The aim of this paper is to make their results rigorous.

In a previous paper [6] we considered a similar setting. We studied the stochastic Swift-Hohenberg equation (SH) near its change of stability but on bounded domains. In this case the evolution is well approximation by an ODE for the amplitudes of the dominating pattern. With degenerate additive noise (i.e. the noise
does not act directly on the dominant modes) we established rigorously an amplitude
equation in this form (for a noise constant in the space and periodic boundary
conditions)
\[ \partial_T a = (\nu - \frac{3}{2}\sigma^2)a - 3|a|^2a, \]
where \( a \) is the complex-valued amplitude of the dominating modes in \( \ker L = \text{span}\{e^{ix}, e^{-ix}\} \). We approximated the solution of (SH) by
\[ U(t) = \varepsilon a(\varepsilon^2 t)e^{ix} + c.c. + \varepsilon Z_\varepsilon(\varepsilon^2 t) + O(\varepsilon^{4-}), \]
where the fast Ornstein-Uhlenbeck process \( Z_\varepsilon \) is defined later in (1). With “c.c.”
we always denote the complex conjugate.

equation (SH) near its change of stability on a large domain \([-L/\varepsilon, L/\varepsilon]\] with
additive noise, where the noise is assumed to be real-valued homogeneous space-
time noise. They showed that, under appropriate scaling, its solutions can be
approximated by the solution \( A \) of the stochastic Ginzburg-Landau equation.

\[ U(t, x) \approx \varepsilon A(\varepsilon^2 t, \varepsilon x)e^{ix} + c.c. \]

One severe problem is, that solutions of stochastic PDEs are not very regular in
space and time. They are at most Hölder continuous and only for (SH) we have
one spacial derivative. In [4] the amplitude \( A(T) \) was shown to split into a more
regular \( H^{1 \text{-part and a Gaussian.}} \)

For the deterministic Swift-Hohenberg equation on an unbounded domain (i.e.,
\( \sigma = 0 \)), Kirrmann, Mielke, and Schneider [13] approximated solutions of the Swift-
Hohenberg equation via the Ginzburg-Landau equation
\[ \partial_T A = 4\partial^2_X A + \nu A - 3|A|^2A, \]
but this method of approximation depends on high regularity of the modulation
equation, as they needed \( A \in C^{1,4}_b([0, T] \times \mathbb{R}) \), which means one bounded derivative
in time and four bounded spatial derivatives. For more results on the deterministic
Swift-Hohenberg equation, see for instance [7], [15], [16] and [18].

Our method of approximation relies on very low regularity of the modulation
equation, which is necessary when turning to spatial noise. Unfortunately, we still
need too much regularity for \( A \), as we need \( A \in C^0([0, T], H^{1/2+}) \). But as a solution
of the stochastic Ginzburg-Landau, \( A \) is at most Hölder continuous with exponent
less than 1/2.

The main aim of this paper is to show that the solution \( U(t, x) \) of (SH) is well
approximated by
\[ U(t, x) \simeq \varepsilon A(\varepsilon^2 t, \varepsilon x)e^{ix} + \varepsilon \tilde{A}(\varepsilon^2 t, \varepsilon x)e^{-ix} + \varepsilon Z_\varepsilon(\varepsilon^2 t), \]
where the complex amplitude \( A(T, X) \) is the solution of the Ginzburg-Landau equation
\[ (GL) \quad \partial_T A = 4\partial^2_X A + (\nu - \frac{3}{2}\sigma^2)A - 3|A|^2A, \]
and
\[ Z_\varepsilon(T) = \varepsilon^{-1}\sigma \int_0^T e^{-\varepsilon^{-2}(T-\tau)}d\tilde{\beta}(\tau), \]
is a fast Ornstein-Uhlenbeck process (OU, for short) with \( \tilde{\beta}(T) := \varepsilon \beta(\varepsilon^{-2}T) \) being
a rescaled version of the Brownian motion.
The remainder of this paper is organised as follows. In the next section we define the standard fractional Sobolev space $H^\alpha$. We also state and prove the relation between the norm in $H^\alpha$ and the norm in $C^0(\mathbb{R})$. In Section 3 we give a formal derivation of the modulation equation and state the main result. In Section 4 we recall the Green’s functions $G_t(x)$ of the Swift-Hohenberg operator, and give estimates on it. In Section 5 we bound the Ornstein-Uhlenbeck process $Z_\varepsilon(T)$. Finally, in Section 6 we give the proof of the main result.

2. The $H^\alpha$-spaces

In this section we define the well known Sobolev space $H^\alpha$, where we rely on weighted $L^2$-norms of Fourier transforms. We also recall the relation between the norm in $H^\alpha$ and the norm in $C^0(\mathbb{R})$ by stating the Sobolev embedding theorem.

**Definition 2.1.** For $\alpha \in \mathbb{R}$ we define the space $H^\alpha$ by

$$H^\alpha = \left\{ u : \mathbb{R} \to \mathbb{R} : \int_\mathbb{R} (1 + y^2)^\alpha |\mathcal{F}(u)(y)|^2 dy < \infty \right\},$$

with norm

$$\|u\|_\alpha^2 = \int_\mathbb{R} (1 + y^2)^\alpha |\mathcal{F}(u)(y)|^2 dy,$$

where $\mathcal{F}(u)$ is the Fourier transform of $u$, which takes the form

$$\mathcal{F}(u)(y) = \frac{1}{\sqrt{2\pi}} \int_\mathbb{R} u(k) e^{-iky} dk.$$

Note that in the space $H^\alpha$ functions still decay to 0 at $\infty$. Thus if $A \in H^\alpha$ we are still in a setting, where the solutions of (SH) and the amplitude $A$ decay to 0 for $|x| \to \infty$.

Let us now consider semigroups in the space $H^\alpha$.

**Lemma 2.2.** Let $A$ be a non-positive operator with eigenvalues $P(k)$ such that $P(k) \leq 0$ defined by $F(Au) = P(\cdot)F(u)$. Then for $t \geq 0$ and $u \in H^\alpha$

$$\|e^{tA}u\|_\alpha \leq \|u\|_\alpha. \quad (2)$$

It is well known that $e^{tA}$ defined by $F(e^{tA}u) = e^{tP}F(u)$ generates a contraction semigroup. Nevertheless, we give a proof for completeness of presentation.

**Proof.** We note from Definition 2.1 that (as $e^{-2tP(k)} \leq 1$)

$$\|e^{tA}u\|_\alpha^2 = \int_\mathbb{R} (1 + y^2)^\alpha |e^{-tP(y)}\mathcal{F}(u)(y)|^2 dy \leq \|u\|_\alpha^2. \quad \square$$

The next lemma states the relation between the norm $\|\cdot\|_\alpha$ and the supremum-norm in $C^0(\mathbb{R})$.

**Lemma 2.3.** For $\alpha > \frac{1}{2}$ there is a constant $C > 0$ such that

$$\|u\|_\infty \leq C\|u\|_\alpha \quad \text{for all } u \in H^\alpha. \quad (3)$$

**Proof.** Sobolev embedding theorems (see Theorem 5.4 in [1]). \quad \square

The following Lemma is necessary in order to estimate the nonlinearity. It states that $H^\alpha$ is up to the constant a Banach algebra for $\alpha > \frac{1}{2}$. 

Lemma 2.4. For $\alpha > \frac{1}{2}$ and $m \in \mathbb{N}$ there exist a constant $C > 0$ such that
\begin{equation}
\|u^m\|_{\alpha} \leq C\|u\|^m_{\alpha} \quad \text{for } u \in \mathcal{H}^\alpha.
\end{equation}

Proof. See proof of Theorem 4 in [17]. \hfill \square

3. Formal Derivation and the Main Result

In this section let us discuss a formal derivation of the amplitude equation or modulation equation corresponding to Equation (SH). This is based on the approach in [13] and uses high regularity of the amplitude $A$. Let us first rescale (SH). If we assume that
\begin{equation}
U(t, x) = \varepsilon u(\varepsilon^2 t, \varepsilon x),
\end{equation}
then Equation (SH) takes the form
\begin{equation}
(SH_\varepsilon)
\partial_{\tau} u = \mathcal{L}_\varepsilon u + \nu u - u^3 + \varepsilon^{-1}\sigma \partial_{\tau} \tilde{\beta}(T),
\end{equation}
with differential operator $\mathcal{L}_\varepsilon = -\varepsilon^{-2}(1 + \varepsilon^2 \partial_x^2)^2$ on the slow time $T = \varepsilon^2 t$ and the "slow" space $X = \varepsilon x$. Now define $w$ via
\begin{equation}
u u = w(T, X) + Z_\varepsilon(T),
\end{equation}
where $Z_\varepsilon$ was defined in (1). Plugging (5) into $(SH_\varepsilon)$, we obtain
\begin{equation}
\partial_{\tau} w = \mathcal{L}_\varepsilon w + \nu w - w^3 - 3wZ_\varepsilon - 3wZ_\varepsilon^2 + \nu Z_\varepsilon - Z_\varepsilon^3.
\end{equation}

Leaving out the error term for simplicity of presentation, we make the following ansatz:
\begin{equation}
w_A(T, X) = A(T, X)e^{ix} + \varepsilon^2 B(T, X)e^{2ix} + \varepsilon^2 H(T, X)e^{3ix} + \varepsilon^2 J(T, X) + \text{c.c.},
\end{equation}
where c.c. denotes the complex conjugate. The higher order terms of order $O(\varepsilon^2)$ are used to cancel various terms that appear due to the nonlinearity. We assume that all functions are sufficiently smooth.

Plugging (7) into (6) and using the relation
\begin{equation}
\mathcal{L}_\varepsilon(f(X)e^{\frac{ix}{2}X}) = -[\varepsilon^{-2}(1 - n^2)f + 4i\varepsilon^{-1}n(1 - n^2)f] + (2 - 6n^2)f + 4i\varepsilon n f + \varepsilon^2 f_{\text{c.c.}} + \varepsilon^3 f_{\text{c.c.}},
\end{equation}
in order to obtain
\begin{align}
\partial_{\tau} A e^{ix} + \text{c.c.} &= [4A^3 - 4i\varepsilon A^n]e^{ix} - [9B - 24i\varepsilon B^2]e^{2ix} - [64H - 96i\varepsilon H^2]e^{3ix} - J + \nu A e^{ix} - A^3 e^{3ix} - 3|A|^2 A e^{ix} - 3|A|^2 A e^{-ix} - \bar{A}^3 e^{-3ix} - 3Z_e(|A|^2 e^{2ix} + 2|A|^2 + 2A^2 e^{-2ix}) - 3Z_e^2(|A|e^{ix} + \bar{A} e^{-ix}) + c.c. + \nu Z_e - Z_e^3 + O(\varepsilon^2). \\
\end{align}

Removing all unwanted $O(1)$-terms by defining
\begin{equation}
B = -\frac{1}{3}Z_e A^2, \quad H = -\frac{1}{64}A^3, \quad \text{and } J = \nu Z_e - Z_e^3 - 6Z_e |A|^2,
\end{equation}
we obtain
\begin{equation}
\partial_{\tau} A e^{ix} + \text{c.c.} = [4A^3 - 4i\varepsilon A^n + \nu A - 3|A|^2 A - 3Z_e^2 A] \cdot e^{ix} + 24i\varepsilon B^2 e^{2ix} + 96i\varepsilon H^2 e^{3ix} + \text{c.c.} + O(\varepsilon^2).
\end{equation}
Before we proceed this formal derivation, let us state the following two Lemmas on the approximation of $Z_e$. In the following we will rely on the important fact that
due to averaging we can replace $Z^2$ approximately by the constant $\sigma^2/2$. Here we state the result in a way, which is useful for the mild formulation later.

**Lemma 3.1.** For every $\kappa_0 > 0$ and $p > 1$ there is a constant $C > 0$, depending only on $p$, $\kappa_0$, and $T_0$, such that

\[ E \sup_{T \in [0, T_0]} |Z_\varepsilon(T)|^p \leq C\varepsilon^{-\kappa_0}, \]

where the fast OU $Z_\varepsilon(T)$ is defined in (1).

**Lemma 3.2.** Let $y$ be a complex function with $y = O(\varepsilon^{-r})$ in $\mathcal{H}^\alpha$ and initial condition $\|y(0)\|_\infty = O(\varepsilon^{-r})$ for some $r \geq 0$.

If $Y(T, s) = e^{A(T-s)\varepsilon^2} y(s)$ and $dY(T, s) = e^{4(T-s)\varepsilon^2} G(s) ds$ with $G = O(\varepsilon^{-r})$ in $\mathcal{H}^\alpha$, then for any small $\kappa_0 \in (0, 1)$

\[ \int_0^T Y(T, s) \{Z_\varepsilon^2 - \frac{\sigma^2}{2}\} d\tau = O(\varepsilon^{1-r-2\kappa_0}). \]

Note that $X = O(\varepsilon^p)$ in $\mathcal{H}^\alpha$ if for $p \geq 1$ there is a $C > 0$ such that $\sup_{[0, T_0]} \|X\|_\alpha^p \leq C\varepsilon^{p\kappa}$. Moreover $X = O(\varepsilon^{p\kappa})$ for $\kappa > 0$.

These two Lemmas on averaging will be proved in Section 5 later.

Now let us complete our formal derivation. Collecting all coefficients in front of $e^{ix}$ in (10), yields

\[ \partial_T A = 4A^\alpha + \nu A - 3|A|^2 A - 3Z_\varepsilon^2 A + O(\varepsilon). \]

Using the averaging result of Lemma 3.2, we obtain

\[ \partial_T A = 4\partial_X^2 A + (\nu - \frac{3}{2}\sigma^2) A - 3|A|^2 A + O(\varepsilon). \]

Neglecting all small terms in $\varepsilon$, yields (GL).

The main result of this paper is the following approximation result for the stochastic Swift-Hohenberg Equation (SH) through the Ginzburg-Landau Equation (GL).

**Theorem 3.3.** (Approximation) Let $U(t, x)$ be a solution of (SH), $w_A(T, X)$ the formal approximation defined as

\[ w_A(T, X) = A(T, X)e^{iX\frac{1}{2}} + c.c, \]

where $A(T, X)$ is a solution of (GL) such that $A \in C^0([0, T_0], \mathcal{H}^\alpha)$ for $\alpha > \frac{1}{2}$. Suppose for the initial condition $\|U(0) - \varepsilon A(0)e^{ix} - \varepsilon A(0)e^{-ix}\|_\infty \leq \varepsilon e^{1-3\kappa_0} \Phi_\varepsilon$ for some fixed $d > 0$ and for $\kappa_0 \in (0, \frac{1}{4})$ such that $\varepsilon^{-1}\Phi_\varepsilon^{1/2} \to 0$ for $\varepsilon \to 0$.

Then for each $T_0 > 0$ and $p > 1$ there exist $C > 0$, depending on $\sup_{[0, T_0]} \|A\|_\alpha$, such that

\[ \mathbb{P}\left\{ \sup_{t \in [0, \varepsilon^{-2}T_0]} \|U(t, x) - \varepsilon w_A(\varepsilon^2 t, \varepsilon x) - \varepsilon Z_\varepsilon(\varepsilon^2 t)\|_\infty > C\varepsilon^{1-4\kappa_0} \Phi_\varepsilon \right\} \leq C\varepsilon^p, \]

where $Z_\varepsilon(T)$ is the fast OU defined in (1) and

\[ \Phi_\varepsilon = \left\{ \begin{array}{ll}
\varepsilon^2 & \text{if } \alpha > 3/2, \\
\varepsilon^2 \ln(1/\varepsilon) & \text{if } \alpha = 3/2, \\
\varepsilon^{2\alpha-1} & \text{if } \alpha < 3/2.
\end{array} \right. \]
4. Green’s Function and Semigroup Estimation

For the first part of this section we follow the ideas of Collet and Eckmann [7] which they apply to a slightly different operator. We define the Green’s functions $G_t(x)$ of the Swift-Hohenberg operator, and we give estimates on it.

**Definition 4.1.** Define the Green’s function $G_t(x)$ of the operator $L$ for $t > 0$ and $x \in \mathbb{R}$ as

$$G_t(x) = \int_{-\infty}^{\infty} e^{ikx} e^{-t(1-2k^2+k^4)} dk. \tag{15}$$

The next Lemma states that the Green’s function $G_t(x)$ is bounded with respect to the norm $\| \cdot \|_{L^1}$.

**Lemma 4.2.** There exist a constant $C > 0$ such that for all $t > 0$

$$\|G_t\|_{L^1} \leq C. \tag{16}$$

In order to prove this Lemma, let us state and prove the following two Lemmas:

**Lemma 4.3.** Define the function $g_\tau(y)$ as

$$g_\tau(y) = \int_{-\infty}^{\infty} e^{imy} e^{-Q_1(m,\tau)} dm,$$

where $Q_1(m, \tau) = \tau^{-2} - 2m^2 + \tau^2 m^4$. Then there exist a constant $C > 0$ such that for $0 < \tau \leq 1$

$$\sup_{y \in \mathbb{R}} |(4 + y^2)g_\tau(y)| \leq C.$$

**Proof.** Using integration by parts, we obtain

$$(4 + y^2)g_\tau(y) = \int_{0}^{\infty} P_1(m, \tau) e^{imy} e^{-Q_1(m,\tau)} dm + \int_{-\infty}^{0} P_1(m, \tau) e^{imy} e^{-Q_1(m,\tau)} dm$$

$$:= I_1 + I_2,$$

where $P_1(m, \tau) = 12m^2\tau^2 - 16m^6\tau^4 + 32m^4\tau^2 - 16m^2$. For $m \geq 0$ and $0 < \tau \leq 1$ we not that

$$Q_1(m, \tau) = (m\tau - 1)^2(m + \tau^{-1})^2 \geq (m - \tau^{-1})^2,$$

and

$$P_1(m, \tau) = \tau^2m^2[12 - 16(m - \tau^{-1})^2(1 + \tau m)^2].$$

Hence,

$$|P_1(m, \tau)| \leq C[1 + (\tau m)^4][1 + (m - \tau^{-1})^2].$$

Thus,

$$|P_1(m + \tau^{-1}, \tau)| \leq C[1 + (\tau m + 1)^4][1 + m^2] \leq C(1 + m^6).$$

Now we bound $I_1$ and $I_2$ separately. For the first integral $I_1$ we obtain

$$I_1 = \int_{-\tau^{-1}}^{\infty} P_1(r + \tau^{-1}, \tau) e^{i(r+\tau^{-1})y} e^{-Q_1(r+\tau^{-1},\tau)} dr$$

$$\leq \int_{-\tau^{-1}}^{\infty} P_1(r + \tau^{-1}, \tau) e^{i(r+\tau^{-1})y} e^{-r^2} dr,$$
where we substituted \( r = m - \tau^{-1} \). Thus
\[
|I_1| \leq \int_{-\tau^{-1}}^{\infty} (c + cr^6)e^{-r^2} dr \leq \int_{-\infty}^{\infty} (c + cr^6)e^{-r^2} dr = C.
\]
For the second integral \( I_2 \), we put \(-m\) instead of \( m\) to obtain
\[
I_2 = \int_{0}^{\infty} P_1(m, \tau)e^{-imy}e^{-Q_1(m, \tau)} dm,
\]
where \( P_1 \) and \( Q_1 \) are even polynomials in \( m \). Analogously to the first integral, we derive
\[
|I_2| \leq C.
\]
Hence, from the bounds on \( I_1 \) and \( I_2 \) we obtain \( \sup_{y \in \mathbb{R}} |(4 + y^2)g_\tau(y)| \leq C \) for \( 0 < \tau \leq 1 \).

**Lemma 4.4.** Define the function \( h_\eta(y) \) as
\[
h_\eta(y) = \int_{-\infty}^{\infty} e^{iky}e^{-Q_2(k, \eta)} dk,
\]
where \( Q_2(k, \eta) = \eta^4 - 2\eta^2k^2 + k^4 \). Then there exist a constant \( C > 0 \) such that for \( 0 < \eta < 1 \)
\[
\sup_{y \in \mathbb{R}} |(1 + y^2)h_\eta(y)| \leq C.
\]

**Proof.** Using integration by parts, we obtain
\[
(1 + y^2)h_\eta(y) = \int_{1}^{\infty} P_2(k, \eta)e^{iky}e^{-Q_2(k, \eta)} dk + \int_{-\infty}^{-1} P_2(k, \eta)e^{iky}e^{-Q_2(k, \eta)} dk
\]
\[
+ \int_{-1}^{1} P_2(k, \eta)e^{iky}e^{-Q_2(k, \eta)} dk := I_{11} + I_{12} + I_{13},
\]
where \( P_2(k, \eta) = 1 + 12k^2 - 4\eta^2 - 16k^6 + 32k^4\eta^2 - 16k^2\eta^4 \). We note that for \( k \geq 1 \)
and \( 0 < \eta < 1 \)
\[
Q_2(k, \eta) = (k - \eta)^2(k + \eta)^2 \geq (k - \eta)^2, \quad \text{and} \quad |P_2(k, \tau)| \leq c(1 + k^6).
\]
We now bound all three terms separately. To bound \( I_{11} \) and \( I_{12} \), we follow exactly the same steps as in the case of Lemma 4.3. For the third term
\[
|I_{13}| \leq \int_{-1}^{1} |P_2(k, \eta)||dk| \leq c \int_{-1}^{1} (1 + k^6)|dk| = C.
\]
Hence, combining all three estimates on \( I_{11}, I_{12} \) and \( I_{13} \) we obtain for \( 0 < \eta < 1 \)
that \( \sup_{y \in \mathbb{R}} |(1 + y^2)h_\eta(y)| \leq C \).

**Proof of Lemma 4.2.** In order to prove (16), we consider two cases:

**First case** \( t \geq 1 \).

In this case we note that
\[
\mathcal{G}_t(x) = \tau g_\tau(\tau x),
\]
with \( \tau = t^{-1/2} \) and
\[
\|\mathcal{G}_t\|_{L^1} = \int_{-\infty}^{\infty} |\tau g_\tau(\tau x)| dx \leq \sup_{y \in \mathbb{R}} \left| (4 + y^2)g_\tau(y) \right| \cdot \int_{-\infty}^{\infty} \frac{1}{4+y^2} d\tilde{y},
\]
where \( y = \tau x \). Using Lemma 4.3, we obtain (16) for \( t \geq 1 \).
Second case \( t \in (0, 1) \).
In this case we note that
\[
\mathcal{G}_t(x) = \eta^{-1} h_\eta(\eta^{-1} x),
\]
with \( \eta = t^{-\frac{1}{4}} \) and
\[
\|\mathcal{G}_t\|_{L^1} = \int_{-\infty}^{\infty} \frac{1}{1+y^2} \left| (1+y^2) h_\eta(y) \right| dy \leq \sup_{y \in \mathbb{R}} \left| (1+y^2) h_\eta(y) \right| \int_{-\infty}^{\infty} \frac{1}{1+y^2} dy,
\]
where \( y = \eta^{-1} x \). Using Lemma 4.4, we obtain (16) for \( t \in (0, 1) \).

\[\square\]

Lemma 4.5. There exists a constant \( C > 0 \) such that,
\[
\| e^{tL} u \|_{\infty} \leq C \| u \|_{\infty} \text{ for all } t \geq 0 \text{ and } u \in C^0(\mathbb{R}).
\]
Proof. As
\[
e^{tL} u(x) = \frac{1}{2\pi} \int_{-\infty}^{\infty} u(y) \mathcal{G}_t(x-y) dy.
\]
We obtain
\[
\| e^{tL} u \|_{\infty} \leq C \| u \|_{\infty} \| \mathcal{G}_t \|_{L^1}.
\]
Using Lemma 4.2, yields (17).

\[\square\]

Corollary 4.6. There exists a constant \( C > 0 \) such that
\[
\| e^{TL} u \|_{\infty} \leq C \| u \|_{\infty} \text{ for all } T \geq 0 \text{ and } u \in C^0(\mathbb{R}).
\]
Proof. We note that
\[
e^{TL} u(X) = e^{-2T(1+\epsilon\partial_x)^2} u(X) = e^{-2T(1+\partial_x^2)} u(\epsilon X) = e^{tL} u_\epsilon(X),
\]
where \( u_\epsilon(X) = u(\epsilon X) \). Using Lemma 4.5, we obtain
\[
\| e^{TL} u \|_{\infty} = \| e^{tL} u_\epsilon \|_{\infty} \leq C \| u_\epsilon \|_{\infty} = C \| u \|_{\infty}.
\]

\[\square\]

The following Lemma provides a result on how to change from semigroup \( e^{TL} \), to \( e^{t\partial_x^2} \), when they are applied to \( A e^{ix\epsilon^{-1}} \).

Lemma 4.7. There is a constant \( C > 0 \) such that for all \( T > 0 \) and all \( A \in \mathcal{H}^\alpha \) with \( \alpha > \frac{1}{2} \)
\[
\sup_{X \in \mathbb{R}} \left| e^{TL} A(X)e^{ix\epsilon^{-1}} - (e^{t\partial_x^2} A)(X)e^{ix\epsilon^{-1}} \right| \leq C \| A \|_\alpha \phi_\epsilon,
\]
where \( \phi_\epsilon \) is defined in (14).

Proof. We write \( e^{tL} A(\epsilon x)e^{ix} \) as a convolution with the Green’s function of \( \mathcal{L} \), as in (18),
\[
e^{tL} A(\epsilon x)e^{ix} = \frac{1}{2\pi} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} e^{ik(x-y)} e^{-t\lambda k} A(\epsilon y) e^{iy} dy dk
= \frac{1}{2\pi} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} e^{i(k-1)(x-y)} e^{-t\lambda k} A(\epsilon y) dy dk \cdot e^{ix}
= \frac{1}{2\pi} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} e^{ik(x-y)} e^{-t\lambda_{k+1}} A(y) dy dk \cdot e^{ix},
\]
In order to bound $\Theta$ it is sufficient to bound
\begin{equation}
(19) \quad e^{T\mathcal{L}_{x}}A(X)e^{iXe^{-1}} = \frac{1}{2\pi} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} e^{ik(ex-y)}e^{-T(ek^{2}+2k)} A(y)dy \cdot e^{ix}.
\end{equation}

Analogously, we can write $(e^{4T\partial_{x}^{2}}A)(X)e^{iXe^{-1}}$ as
\begin{equation}
(20) \quad (e^{4T\partial_{x}^{2}}A)(X)e^{iXe^{-1}} = \frac{1}{2\pi} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} e^{ik(ex-y)}e^{-4Tk^{2}} A(y)dy \cdot e^{ix}.
\end{equation}

Let
\[ \Theta = e^{T\mathcal{L}_{x}}A(X)e^{iXe^{-1}} - (e^{4T\partial_{x}^{2}}A)(X)e^{iXe^{-1}}. \]
Hence,
\begin{align*}
\Theta &= \frac{1}{2\pi} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} A(y)e^{ik(ex-y)} \left[ e^{-T(ek^{2}+2k)} - e^{-4Tk^{2}} \right] dy \cdot e^{ix} \\
&= \frac{1}{2\pi} \int_{-\infty}^{\infty} \mathcal{F}(A)(k) \left[ e^{-T(ek^{2}+2k)} - e^{-4Tk^{2}} \right] e^{ikx} dk \cdot e^{ix}.
\end{align*}

Using Cauchy-Schwarz inequality, yields
\[ |\Theta|^2 \leq C\|A\|^{2} \int_{-\infty}^{\infty} \Psi(k)dk, \]
where
\[ \Psi(k) = \frac{1}{(1+ek^{2})^{2}} e^{-8Tk^{2}} \left[ e^{-T(ek^{2}+4ek^{3})} - 1 \right]^{2}. \]
In order to bound $\Theta$ it is sufficient to bound
\begin{align*}
\int_{-\infty}^{\infty} \Psi(k)dk &= \int_{0}^{1} \Psi(k)dk + \int_{1}^{\infty} \Psi(k)dk + \int_{-\infty}^{-1} \Psi(k)dk + \int_{-\infty}^{-1} \Psi(k)dk \\
&= I_{1} + I_{2} + I_{3} + I_{4},
\end{align*}
where we consider all terms separately. For $I_{1}$, we note that $\varepsilon k^{3}(\varepsilon k + 4)$ is non-negative for all $k \in [0, \frac{1}{\varepsilon}^{-1}]$. Thus, we can use the following inequality, which follows directly from the intermediate value theorem:
\begin{equation}
(21) \quad |e^{3} - 1| \leq |x| \max\{1, e^{3}\}.
\end{equation}
Hence,
\begin{align*}
I_{1} &\leq \int_{0}^{1} \frac{1}{(1+ek^{2})^{2}} e^{-8Tk^{2}} \left[ \varepsilon T k^{3}(\varepsilon k + 4) \right]^{2} dk \\
&\leq C\varepsilon^{2} \int_{0}^{1} \frac{k^{2}}{(1+ek^{2})^{2}} (Tk^{2})^{2} e^{-8Tk^{2}} dk,
\end{align*}
where we used $(\varepsilon k + 4) < 5$ for all $k \in [0, \frac{1}{\varepsilon}^{-1}]$. Now, using the fact
\begin{equation}
(22) \quad \sup_{x > 0} \{e^{m}e^{-z}\} < \infty \quad \text{for all} \quad m \geq 0,
\end{equation}
we get
\[ I_{1} \leq C\varepsilon^{2} \int_{0}^{1} \frac{k^{2}}{(1+ek^{2})^{2}} dk \leq C\varepsilon^{2} + C\varepsilon^{2} \int_{1}^{\frac{1}{\varepsilon}^{-1}} k^{2-2\alpha} dk \leq C\phi_{\varepsilon}. \]
Let us now turn to $I_2$. Substituting $k = -k$, yields

$$I_2 = \int_0^{\frac{1}{2}} \frac{1}{(1+|k|^2)^n} e^{-STk^2} \left[ e^{T(k^2+2)} - 1 \right]^2 \, dk.$$ 

We note that $\varepsilon k^3(4-\varepsilon k)$ is non-negative for all $k \in [0, \frac{1}{2}\varepsilon^{-1}]$. Using (21), yields

$$I_2 \leq \int_0^{\frac{1}{2}} \frac{1}{(1+|k|^2)^n} e^{-STk^2} \left[ 4\varepsilon T k^3 e^{4\varepsilon T k^3} + 1 \right]^2 \, dk \leq C\varepsilon^2 \int_0^{\frac{1}{2}} \frac{k^2}{(1+|k|^2)^n} \, dk \leq C \phi_k^2.$$ 

To bound $I_3$:

$$I_3 \leq C \int_0^{\frac{1}{2}} \frac{1}{(1+|k|^2)^n} \left[ e^{-T(k^2+2)} + e^{-STk^2} \right]^2 \, dk \leq C \int_0^{\frac{1}{2}} \frac{1}{(1+|k|^2)^n} \, dk \leq C \varepsilon^{2\alpha-1} \text{ for } \alpha > \frac{1}{2}.$$ 

Analogously for $I_4$:

$$I_4 \leq C \varepsilon^{2\alpha-1} \text{ for } \alpha > \frac{1}{2}.$$ 

Collecting all four results together, we obtain

$$\|\Theta\|_\infty^2 \leq C\|A\|_\alpha^2 \phi_k^2.$$ 

Let us now state a bound for the semigroup $e^{T\mathcal{L}x}$, when applied to $B(X)e^{inX\varepsilon^{-1}}$. The case $n = \pm 1$ was treated in Lemma 4.7 before.

**Lemma 4.8.** Let $n \in \mathbb{Z} \setminus \{\pm 1\}$ and $\alpha > \frac{1}{2}$. Then there are two constants $C > 0$ and $c_n > 0$, depending on $n$, such that, for $T > 0$ and $B \in \mathcal{H}_\alpha$,

$$\sup_{X \in \mathbb{R}} \left| e^{T\mathcal{L}x} B(X)e^{inX\varepsilon^{-1}} \right|^2 \leq C\|B\|_\alpha^2 \left( e^{-c_n T \varepsilon^{-2}} + \varepsilon^{2\alpha-1} \right).$$

**Proof.** Writing $e^{t\mathcal{L}B(\varepsilon x)}e^{inx}$ as a convolution with the Green’s function of $\mathcal{L}$ as in Lemma 4.7

$$e^{t\mathcal{L}B(\varepsilon x)}e^{inx} = \frac{1}{2\pi} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} e^{ik(x-y)} e^{-t\lambda_k+n} B(y) dy \, dk \cdot e^{inx}.$$ 

Hence, using the definition of $\lambda_k$ and $X = \varepsilon x$, we obtain

$$e^{T\mathcal{L}x} B(X)e^{inX\varepsilon^{-1}} = \frac{1}{2\pi} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} e^{ik(X-y)} e^{-t[1-(\varepsilon k+n)]^2} B(y) dy \, dk \cdot e^{inx}.$$ 

Taking the absolute value $|\cdot|$ on both sides and using Cauchy-Schwarz inequality, yields

$$\left| e^{T\mathcal{L}x} B(X)e^{inX\varepsilon^{-1}} \right|^2 \leq C\|B\|_\alpha^2 \int_{-\infty}^{\infty} \frac{1}{(1+|k|^2)^n} e^{-2t[1-(\varepsilon k+n)]^2} \, dk.$$
It remains to bound the integral in (24):
\[
\int_{-\infty}^{\infty} \Phi(k)dk \leq \int_{0}^{\frac{1}{2\varepsilon}} \Phi(k)dk + \int_{-\frac{1}{2\varepsilon}}^{0} \Phi(k)dk + 2\int_{\frac{1}{2\varepsilon}}^{\infty} \frac{k}{1+k^2\varepsilon} dk
\]
with
\[
\Phi(k) = \frac{1}{1+k^2\varepsilon} e^{-2q(k)} \quad \text{and} \quad q(k) = [1 - (\varepsilon k + n)^2]^2.
\]
Now, let us bound \( q(k) \) on \([0, \pm \frac{1}{2\varepsilon}]\). We consider several cases depending on \( n \) and \( k \).

**First case** \( n = 0 \) and \( k \in [-\frac{1}{2\varepsilon}, \frac{1}{2\varepsilon}] \). In this case as \( |k| \leq \frac{1}{2\varepsilon} \)
\[
q(k) = [1 - \varepsilon^2 k^2]^2 \geq \frac{9}{16}.
\]

**Second case** \( n \geq 2 \) and \( k \in [0, \frac{1}{2\varepsilon}] \) (or \( n \leq -2 \) and \( k \in [\frac{1}{2\varepsilon}, 0] \)). In this case as \( \varepsilon k \geq 0 \)
\[
q(k) = [n+1+\varepsilon k]^2[n-1+\varepsilon k]^2 \geq [n+1]^2[n-1]^2 = (n^2 - 1)^2.
\]

**Third case** \( n \geq 2 \) and \( k \in [-\frac{1}{2\varepsilon}, 0] \), (or \( n \leq -2 \) and \( k \in [0, \frac{1}{2\varepsilon}] \)). In this case as \( k \leq \frac{1}{2\varepsilon} \)
\[
q(k) = [n-1-\varepsilon k]^2[n+1-\varepsilon k]^2 \geq \frac{1}{16}[n+\frac{1}{2}]^2.
\]

We deduce from the previous three cases that
\[
q(k) \geq \frac{1}{2}\epsilon_n > 0.
\]
Thus,
\[
\int_{-\infty}^{\infty} \Phi(k)dk \leq 2\int_{0}^{\frac{1}{2\varepsilon}} \frac{1}{(1+k^2\varepsilon)} \cdot e^{-\epsilon_n t} dk + 2\int_{\frac{1}{2\varepsilon}}^{\infty} \frac{k}{1+k^2\varepsilon} dk
\]
\[
\leq 2e^{-\epsilon_n t} \int_{0}^{\infty} \frac{1}{(1+k^2\varepsilon)} dk + 2\int_{\frac{1}{2\varepsilon}}^{\infty} k^{-2\alpha} dk
\]
\[
\leq Ce^{-\epsilon_n t} + C\varepsilon^{2\alpha-1}.
\]
Plugging (25) into (24), yields (23). \( \square \)

## 5. General Bounds on \( Z_\varepsilon \)

In this section, we prove Lemmas 3.1 and 3.2.

**Proof of Lemma 3.1.** See the first part of the proof of Lemma 14 in [6] with \( \lambda_k = 1 \). \( \square \)

**Proof of Lemma 3.2.** First, we note from Lemma 2.2 and 2.3 that
\[
\|Y(T,s)\|_\infty^p \leq C \sup_{[0,T_n]} \|y\|_\infty^p \leq C \sup_{[0,T_n]} \|y\|_\alpha^p \leq C\varepsilon^{-pr}.
\]
Applying Itô formula to \( YZ_\varepsilon^2 \), yields
\[
d(YZ_\varepsilon^2) = e^{4(T-s)}\sigma Z_\varepsilon^2 G(s) Z_\varepsilon^2 ds - 2\varepsilon^{-2} YZ_\varepsilon^2 ds + 2\varepsilon^{-1} \sigma Z_\varepsilon Yd\beta + \varepsilon^{-2}\sigma^2 Y ds.
\]
Lemma 5.1. If $A$ is a solution of (GL) with $\sup_{[0,T_0]} \|A\|_\alpha \leq C$, then
\begin{equation}
\int_0^T e^{4(T-s)\partial^2_x} A(s) \{Z^2_x(s) - \frac{\alpha^2}{T} \} ds = O(\varepsilon^{1-2\kappa_0}),
\end{equation}
for any $\kappa_0 > 0$.

Proof. Define for $s \in [0,T]$
\begin{equation}
Y(T,s) = e^{4(T-s)\partial^2_x} A(s),
\end{equation}
with
\begin{equation}
dY = (-4\partial^2_x) e^{4(T-s)\partial^2_x} A(s) ds + e^{4(T-s)\partial^2_x} A(s) ds.
\end{equation}
Using (GL), we obtain
\begin{equation}
dY = e^{4(T-s)\partial^2_x} \left[ (\nu - \frac{3}{2}\sigma^2) A - 3|A|^2 A \right] ds = e^{4(T-s)\partial^2_x} G(s) ds.
\end{equation}
Using Lemmas 2.3, 2.2 and 2.4, we derive
\begin{equation}
\|G\|_\infty \leq C \|G\|_\alpha \leq C\|A\|_\alpha + C\|A\|_\alpha^3.
\end{equation}
Thus
\[ \sup_{[0,T_0]} \|G\|_\infty \leq C. \]

Now applying Lemma 3.2, yields (27). \(\square\)

6. MAIN RESULTS

In this section, we give the proof of the main result.

**Definition 6.1.** Define the residual \( \rho(T) \) as

\[
\rho(T) = w_A(T) - e^{T \mathcal{L}_c} w_A(0) - \int_0^T e^{(T-s) \mathcal{L}_c} \left[ \nu(w_A + \mathcal{Z}_c) - (w_A + \mathcal{Z}_c)^3 \right] ds,
\]

where \( w_A \) is defined in (12).

**Lemma 6.2.** If \( \sup_{[0,T_0]} \|A\|_\alpha < \infty \) for \( \alpha > \frac{1}{2} \), then for all \( p > 1 \) there is a constant \( C > 0 \) such that

\[
E \sup_{T \in [0,T_0]} \|\rho(T)\|_\infty^p \leq C e^{-3p\epsilon^0} \phi^p_\epsilon,
\]

where \( \phi_\epsilon \) is defined in (14).

**Proof.** From (12), we obtain

\[
\rho(T) = A(T)e^{ix} - e^{T \mathcal{L}_c} A(0)e^{ix} - \int_0^T e^{(T-s) \mathcal{L}_c} (\nu A - 3A \mathcal{Z}_c^2 - 3|A|^2 A) e^{ix} ds
\]

\[+ \int_0^T e^{(T-s) \mathcal{L}_c} A^3 e^{3ix} ds + 3 \int_0^T e^{(T-s) \mathcal{L}_c} A^2 \mathcal{Z}_c e^{2ix} ds \]

\[+ 3 \int_0^T e^{(T-s) \mathcal{L}_c} |A|^2 \mathcal{Z}_c e^{2ix} ds + c.c. \]

\[- \nu \int_0^T e^{-(T-s) \mathcal{L}_c} \mathcal{Z}_c ds + \int_0^T e^{(T-s) \mathcal{L}_c} \mathcal{Z}_c^3 ds. \]

Using Lemma 4.7, we obtain

\[
\rho(T) = \left[ A(T) - e^{4(T-s) \mathcal{L}_c} A(0) \right] \mathcal{Z}_c^2 (\nu A - 3A \mathcal{Z}_c^2 - 3|A|^2 A) ds \cdot e^{ix}
\]

\[+ \int_0^T e^{(T-s) \mathcal{L}_c} A^3 e^{3ix} ds + 3 \int_0^T e^{(T-s) \mathcal{L}_c} A^2 \mathcal{Z}_c e^{2ix} ds \]

\[+ 3 \int_0^T e^{(T-s) \mathcal{L}_c} |A|^2 \mathcal{Z}_c e^{2ix} ds + c.c. - \nu \int_0^T e^{-(T-s) \mathcal{L}_c} \mathcal{Z}_c ds \]

\[+ \int_0^T e^{-(T-s) \mathcal{L}_c} \mathcal{Z}_c^3 ds + O(e^{-3\epsilon^0} \phi_\epsilon). \]

From (GL) we have

\[
\rho(T) = 3 \int_0^T e^{4(T-s) \mathcal{L}_c} A(\mathcal{Z}_c^2 - \frac{1}{2}\sigma^2) ds \cdot e^{ix} + \int_0^T e^{(T-s) \mathcal{L}_c} A^3 e^{3ix} ds
\]

\[+ 3 \int_0^T e^{(T-s) \mathcal{L}_c} A^2 \mathcal{Z}_c e^{2ix} ds + 3 \int_0^T e^{(T-s) \mathcal{L}_c} |A|^2 \mathcal{Z}_c e^{2ix} ds \]

\[+ c.c. + O(e^{-3\epsilon^0} \phi_\epsilon). \]
Taking the norm \(|\cdot|_p^\infty\) on both sides and using Lemma 4.8 in order to obtain
\[
\|\rho\|_\infty^p \leq C \left\| \int_0^T e^{A(T-s)} Z_s^2 \right\|_\infty^p + C \left( \varepsilon^{2p} + \varepsilon^{p\kappa - p} \right) \left( \|A\|_\infty^p + |Z|_p^p \|A\|_\alpha^2 + |Z|_p^p \|A\|_\alpha^2 \right).
\]
Taking expectation after supremum and using the bound on \(Z\) from Lemma 3.1, the fact \(H^\alpha\) is a Banach algebra from Lemma 2.4 and averaging result for a mild formulation from Lemma 5.1, yields (29).

**Definition 6.3.** Define the set \(\Omega_0 \subset \Omega\) such that all these estimates
\[
\sup_{T \in [0,T_0]} |Z_{\varepsilon}(T)| < e^{-\kappa_0},
\]
\[
\left| \int_0^{T_0} \{ |Z_{\varepsilon}|^2 - \frac{\sigma^2}{2} \} d\tau \right| < e^{1-3\kappa_0},
\]
and
\[
\sup_{T \in [0,T_0]} \|\rho(T)\|_\infty < e^{-4\kappa_0 \phi_{\varepsilon}},
\]
hold on \(\Omega_0\) for all \(\varepsilon \in (0,1)\).

**Corollary 6.4.** For all \(p > 0\) there exist a constant \(C_p\) such that on \(\Omega_0\)
\[
P(\Omega_0) \geq 1 - C_p \varepsilon^p \text{ for all } \varepsilon \in (0,1).
\]

**Proof.** We note that
\[
P(\Omega_0) \geq 1 - P \left( \sup_{[0,T_0]} |Z_{\varepsilon}(T)| \geq e^{-\kappa_0} \right) - P \left( \int_0^{T_0} \{ |Z_{\varepsilon}|^2 - \frac{\sigma^2}{2} \} d\tau \geq e^{1-3\kappa_0} \right)
\]
\[-P \left( \sup_{[0,T_0]} |\rho(T)| \geq e^{-4\kappa_0 \phi_{\varepsilon}} \right).
\]
Using Chebychev’s inequality
\[
P(\Omega_0) \geq 1 - e^{q\kappa_0} E \sup_{[0,T_0]} |Z_{\varepsilon}|^q - e^{4q\kappa_0 \phi_{\varepsilon}} E \sup_{[0,T_0]} \|\rho\|_\infty^q
\]
\[-e^{-q + 3q\kappa_0} E \left( \int_0^{T_0} \{ |Z_{\varepsilon}|^2 - \frac{\sigma^2}{2} \} d\tau \right)^q.
\]
From Lemmas 3.1,3.2 and 6.2, we obtain
\[
P(\Omega_0) \geq 1 - C_q e^{q\kappa_0 - \kappa_0} - C_q e^{q\kappa_0}.
\]
Thus for sufficiently large \(q\)
\[
P(\Omega_0) \geq 1 - C_p \varepsilon^p \text{ for all } p > 0.
\]

Finally, we use the previously obtained results to prove the main assertion of Theorem 3.3 for the approximation of the solution of the SPDE \((SH_{\varepsilon})\).
Proof of Theorem 3.3. Define

\begin{equation}
R(T) = u(T) - w_A(T) - Z_\varepsilon(T).
\end{equation}

Considering the mild formulation for (SH), we obtain

\begin{equation}
u(T) = e^{T \mathcal{L}_\varepsilon} u(0) + \nu \int_0^T e^{(T-s) \mathcal{L}_\varepsilon} u(s) ds - \int_0^T e^{(T-s) \mathcal{L}_\varepsilon} u(s)^3 ds + Z_\varepsilon(T).
\end{equation}

Substituting (33) into (34), we obtain

\begin{align*}
R(T) &= e^{T \mathcal{L}_\varepsilon} R(0) + \nu \int_0^T e^{(T-s) \mathcal{L}_\varepsilon} R ds - 3 \int_0^T e^{(T-s) \mathcal{L}_\varepsilon} Z_\varepsilon R^2 ds \\
&\quad - 3 \int_0^T e^{(T-s) \mathcal{L}_\varepsilon} Z_\varepsilon^2 R ds - \int_0^T e^{(T-s) \mathcal{L}_\varepsilon} R^3 ds - 3 \int_0^T e^{(T-s) \mathcal{L}_\varepsilon} w_A^2 R ds \\
&\quad - 6 \int_0^T e^{(T-s) \mathcal{L}_\varepsilon} w_A Z_\varepsilon R ds - 3 \int_0^T e^{(T-s) \mathcal{L}_\varepsilon} w_A R^2 ds + \rho(T),
\end{align*}

where the residual \( \rho(T) \) is defined in (28). Taking the norm \( \| \cdot \|_\infty \) on both sides and using Corollary 4.6, yields on \( \Omega_0 \)

\begin{align*}
\| R(T) \|_\infty &\leq C\| R(0) \|_\infty + C \int_0^T \| R \|_\infty ds + C \int_0^T | Z_\varepsilon \| | R \|_\infty^2 ds \\
&\quad + C \int_0^T | Z_\varepsilon^2 \| | R \|_\infty ds + C \int_0^T \| R \|_\infty^3 ds + C \int_0^T | Z_\varepsilon \| | R \|_\infty ds \\
&\quad + C \int_0^T \| R \|_\infty^2 ds + C e^{-4\kappa_0 \phi_\varepsilon},
\end{align*}

where we used \( \| w_A \|_\infty \leq C \). Define for some \( D \) fixed later the stopping time \( T_* \) as the largest time, such that \( T_* \leq T_0 \) and \( \| R(T) \|_\infty \leq D e^{-4\kappa_0 \phi_\varepsilon} \) for all \( T \leq T_* \). We obtain for \( T \leq T_* \) that

\begin{align*}
\| R(T) \|_\infty &\leq (C e^{\kappa_0 d} + C) e^{-4\kappa_0 \phi_\varepsilon} \\
&\quad + C [1 + D e^{-4\kappa_0 \phi_\varepsilon} + | Z_\varepsilon^2 | + D^2 e^{-8\kappa_0 \phi_\varepsilon^2} + | Z_\varepsilon |] \int_0^T \| R \|_\infty ds \\
&\leq C_1 e^{-4\kappa_0 \phi_\varepsilon} + C [1 + D e^{-4\kappa_0 \phi_\varepsilon} + | Z_\varepsilon | + D^2 e^{-8\kappa_0 \phi_\varepsilon^2}] \int_0^T \| R \|_\infty ds \\
&\leq C_1 e^{-4\kappa_0 \phi_\varepsilon} + \int_0^T | C_2 + \frac{1}{2} C | Z_\varepsilon |^2 \| R \|_\infty ds,
\end{align*}

where \( C_1 = C d + C \) and

\begin{align*}
C_1 [1 + D e^{-4\kappa_0 \phi_\varepsilon} + D^2 e^{-8\kappa_0 \phi_\varepsilon^2}] &\leq C [2 + \frac{1}{2} D^2 e^{-8\kappa_0 \phi_\varepsilon^2}] \\
&\leq C_2
\end{align*}

Note that by Assumption on \( \kappa_0 \), we can choose \( C_2 \) independent of \( D \), provided \( \varepsilon > 0 \) is sufficiently small. Using Gronwall’s inequality, we obtain

\begin{align*}
\| R(T) \|_\infty &\leq C_1 e^{-4\kappa_0 \phi_\varepsilon} [1 + \int_0^T | C_2 + \frac{1}{2} C | Z_\varepsilon |^2 \| R \|_\infty ds] \\
&\leq C_1 e^{-4\kappa_0 \phi_\varepsilon} [1 + \int_0^{T_0} | C_2 + \frac{1}{2} C | Z_\varepsilon |^2 \| R \|_\infty ds] \\
&\quad \cdot \exp [\int_0^{T_0} | C_2 + \frac{1}{2} C | Z_\varepsilon |^2 \| R \|_\infty ds].
\end{align*}
Taking the supremum over \([0, T^\star]\) yields
\[
\sup_{T \in [0, T^\star]} \|R(T)\|_\infty \leq C_1 \varepsilon^{-4\kappa_0} \phi_\varepsilon [1 + \tilde{C}_2] \quad \text{on } \Omega_0,
\]
where we used (see (31))
\[
\int_0^{T^\star} |Z_\varepsilon|^2 \mathrm{d}t \leq \varepsilon^{1-3\kappa_0} + \frac{\sigma^2}{\varepsilon^2} T_0 \leq \tilde{C} \quad \text{on } \Omega_0
\]
and defined
\[
\tilde{C}_2 = (C_2 T_0 + \frac{1}{2} C \tilde{C}) e^{(C_2 T_0 + \frac{1}{2} C \tilde{C})}.
\]
Now fix \(D > C_1[1 + \tilde{C}_2]\). Hence, (35) shows that
\[
\sup_{T \in [0, T^\star]} \|R(T)\|_\infty < D \varepsilon^{-4\kappa_0} \phi_\varepsilon.
\]
Hence, \(T^\star = T_0\) and finally
\[
\sup_{t \in [0, \varepsilon^{-2} T_0]} \left\| U(t, x) - \varepsilon w_\Lambda(\varepsilon^2 t, \varepsilon x) - \varepsilon Z_\varepsilon(\varepsilon^2 t) \right\|_\infty \leq \varepsilon \sup_{T \in [0, T_0]} \|R(T)\|_\infty \leq C \varepsilon^{1-4\kappa_0} \phi_\varepsilon.
\]
Thus,
\[
\mathbb{P}\left\{ \sup_{t \in [0, \varepsilon^{-2} T_0]} \left\| U(t, x) - \varepsilon w_\Lambda(\varepsilon^2 t, \varepsilon x) - \varepsilon Z_\varepsilon(\varepsilon^2 t) \right\|_\infty > C \varepsilon^{1-4\kappa_0} \phi_\varepsilon \right\} \leq 1 - \mathbb{P}(\Omega_0).
\]
Using (32), yields (13).

Acknowledgements

This work is supported by the Deutsche Forschungsgemeinschaft (DFG BL535/9-1), and Wael Mohammed is supported by a fellowship from the Egyptian government in the Long Term Mission system.

References


Institut für Mathematik, Universität Augsburg, Germany
E-mail address: dirk.bloemker@math.uni-augsburg.de

Institut für Mathematik, Universität Augsburg, Germany
E-mail address: wael.mohammed@math.uni-augsburg.de