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A BU THESIS LATEX TEMPLATE

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*Facilis descensus Averni;
Noctes atque dies patet atri janua Ditis;
Sed revocare gradum, superasque evadere ad auras,
Hoc opus, hic labor est.* Virgil (from Don's thesis!)

Acknowledgments

[This is where the acknowledgments go...]

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ABSTRACT

[This is where the text for the abstract will go]

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List of Abbreviations

FPUT	Fermi-Pasta-Ulam-Tsingou
mKdV	modified Korteweg-De Vries

Chapter 1

Long-Time stability of small FPUT solitary waves

1.1 Introduction

As shown in earlier work, there exists a wave solution of the FPUT lattice whose profile is well approximated by that of the kink solution to the (defocusing) mKdV. We are now interested in studying the stability of this wave solution on the FPUT lattice. The equations of motion on the lattice are given by

$$\ddot{x}_n = V'(x_{n+1} - x_n) - V'(x_n - x_{n-1}), \quad n \in \mathbb{Z}. \quad (1.1)$$

where V is the interaction potential between neighboring particles and $\dot{}$ denotes the derivative with respect to the time $t \in \mathbb{R}$. Equation (1.1) can be rewritten in the strain variables $u_n := x_{n+1} - x_n$ as follows

$$\ddot{u}_n = V'(u_{n+1}) - 2V'(u_n) + V'(u_{n-1}), \quad n \in \mathbb{Z} \quad (1.2)$$

The moving wave solution in eq. (1.1) corresponds to a kink solution in eq. (1.2).

For the case where V is of the form $V(u) = \frac{1}{2}u^2 + \frac{\epsilon^2}{p+1}u^{p+1}$ for $p \geq 2$, the generalized KdV equation given by

$$2\partial_T W + \frac{1}{12}\partial_X^3 W + \partial_X(W^p) = 0, \quad X \in \mathbb{R} \quad (1.3)$$

serves as a modulation equation for solutions of eq. (1.2) (Bambusi and Ponno, 2006;

Friesecke and Pego, 1999). That is, for a local solution $W \in C([- \tau_0, \tau_0], H^s(\mathbb{R}))$ of eq. (1.3) there exist positive constants ϵ_0 and C_0 such that, for all $\epsilon \in (0, \epsilon_0)$, when initial data $(u_{\text{in}}, \dot{u}_{\text{in}}) \in \ell^2(\mathbb{R})$ satisfy

$$\|u_{\text{in}} - W(\epsilon \cdot, 0)\|_{\ell^2} + \|\dot{u}_{\text{in}} + \epsilon \partial_X W(\epsilon \cdot, 0)\|_{\ell^2} \leq \epsilon^{3/2}, \quad (1.4)$$

the unique solution to eq. (1.2) with initial data $(u_{\text{in}}, \dot{u}_{\text{in}})$ belongs to $C^1([- \tau_0 \epsilon^{-3}, \tau_0 \epsilon^{-3}]; \ell^2(\mathbb{Z}))$ and satisfies

$$\begin{aligned} \|u(t) - W(\epsilon(\cdot - t), \epsilon^3 t)\|_{\ell^2(\mathbb{Z})} + \|\dot{u}(t) + \epsilon \partial_X W(\epsilon(\cdot - t), \epsilon^3 t)\|_{\ell^2(\mathbb{Z})} &\leq C_0 \epsilon^{3/2}, \\ t &\in [- \tau_0 \epsilon^{-3}, \tau_0 \epsilon^{-3}]. \end{aligned} \quad (1.5)$$

Furthermore, the approximation can also be extended to include counter-propagating solutions of the KdV in the case where $p = 2$ (Schneider and Wayne, 2000).

The KdV approximation was extended to longer time scales on the order of $\epsilon^{-3} |\log(\epsilon)|$ by Khan and Pelinovsky in order to deduce the nonlinear metastability of small FPUT solitary waves from the orbital stability of the corresponding KdV solitary waves (Khan and Pelinovsky, 2017).

We consider the FPUT with potential

$$V(u) = \frac{1}{2} u^2 - \frac{1}{24} u^4. \quad (1.6)$$

We will introduce an ansatz that solutions of the FPUT with this potential can be well-approximated by counter-propagating solutions of mKdV equations.

1.2 Counter-Propagating Waves Ansatz

We make the assumption that solutions of eq. (1.2) can be expressed as a sum of two counter-propagating small-amplitude waves, i.e.,

$$u_n(t) \approx \epsilon f(\epsilon(n+t), \epsilon^3 t) + \epsilon g(\epsilon(n-ct), \epsilon^3 t) + \epsilon^3 \phi(\epsilon n, \epsilon t) \quad (1.7)$$

where we allow f to have a fixed non-zero limit, f_∞ , at positive infinity and ϕ captures the interaction effects between f and g . The wave speed of g is given by

$$c = c(\epsilon, f_\infty) = 1 - \frac{\epsilon^2 f_\infty^2}{4}. \quad (1.8)$$

Plugging in the ansatz in eq. (1.7) back into eq. (1.2) and doing formal calculations gives that the approximation holds up to order ϵ^6 terms if the functions f and g satisfy

$$2\partial_2 f = -\frac{1}{6}\partial_1(f^3) + \frac{1}{12}\partial_1^3 f \quad (1.9)$$

and

$$-2\partial_2 g = -\frac{1}{6}\partial_1(g^3 + 3f_\infty g^2) + \frac{1}{12}\partial_1^3 g, \quad (1.10)$$

and ϕ satisfies

$$\begin{aligned} \partial_2^2 \phi(\xi, \tau) = \partial_1^2 \phi(\xi, \tau) - \frac{1}{6}\partial_1^2 [3(f^2(\xi + \tau, \epsilon^2 \tau) - f_\infty^2)g(\xi - c\tau, \epsilon^2 \tau) \\ + 3(f(\xi + \tau, \epsilon^2 \tau) - f_\infty)g^2(\xi - c\tau, \epsilon^2 \tau)] \end{aligned} \quad (1.11)$$

$$\phi(\xi, 0) = \partial_1 \phi(\xi, 0) = 0.$$

Note that eq. (1.9) is the defocusing mKdV equation and eq. (1.10) is a type of generalized KdV equation.

A natural choice of function space for g is a Sobolev space like $H^k(\mathbb{R})$. However, for f , we want to allow the possibility of the function approaching a non-zero limit at positive and negative infinity while also having sufficient regularity.

Definition 1. For $k \in \mathbb{N}$, let $\mathcal{X}^k(\mathbb{R})$ be the Banach space

$$\mathcal{X}^k(\mathbb{R}) := \{f \in L^\infty(\mathbb{R}) \mid f' \in H^{k-1}(\mathbb{R})\} \quad (1.12)$$

with norm

$$\|f\|_{\mathcal{X}^k(\mathbb{R})} := \|f\|_{L^\infty(\mathbb{R})} + \|f'\|_{H^{k-1}(\mathbb{R})}. \quad (1.13)$$

Then \mathcal{X}^k is the set of L^∞ functions which are k times weakly differentiable and whose derivatives are in L^2 . That this is a Banach space follows from the Banach space isomorphism

$$\mathcal{X}^k(\mathbb{R}) \cong L^\infty(\mathbb{R}) \cap \dot{H}^1(\mathbb{R}) \cap \dot{H}^k(\mathbb{R}), \quad (1.14)$$

where $\dot{H}^k(\mathbb{R})$ denotes the homogeneous Sobolev spaces. For convenience, we let $\mathcal{X}^0(\mathbb{R})$ denote $L^\infty(\mathbb{R})$

The space \mathcal{X}^k is a natural one for f , and allows f to be kink solutions of eq. (1.9). We also have the following inequalities for products of functions in \mathcal{X}^k and H^k that will be useful.

Lemma 1. For non-negative integers k , there is a $C > 0$ such that

$$\|fg\|_{H^k} \leq C\|f\|_{\mathcal{X}^k}\|g\|_{H^k} \quad (1.15)$$

for any $f \in \mathcal{X}^k(\mathbb{R})$ and $g \in H^k(\mathbb{R})$.

Lemma 2. For non-negative integers k , there is a $C > 0$ such that

$$\|fg\|_{\mathcal{X}^k} \leq C\|f\|_{\mathcal{X}^k}\|g\|_{\mathcal{X}^k} \quad (1.16)$$

for any $f, g \in \mathcal{X}^k(\mathbb{R})$.

See appendix A for proofs.

However, for our main result, we require that ϕ , the term which captures the interaction effects, remains uniformly bounded for all time. Intuitively, if f and g localized, the inhomogeneous term in eq. (1.11) will quickly go to zero and ϕ will no

longer experience growth in time. Thus we require that f and g quickly decay to their respective limits at infinity. This is enforced by assuming the functions belong to appropriate weighted Banach spaces.

A suitable choice of space for g is the weighted Sobolev spaces $H_n^k(\mathbb{R})$. Here, H_n^k for $k, n \in \mathbb{N} \cup \{0\}$

$$H_n^k(\mathbb{R}) := \{g \in H^k(\mathbb{R}) \mid g\langle \cdot \rangle^n \in H^k\} \quad (1.17)$$

where $\langle x \rangle = \sqrt{1 + x^2}$. The norm on this space is

$$\|g\|_{H_n^k(\mathbb{R})} := \|g\langle \cdot \rangle^n\|_{H^k(\mathbb{R})}. \quad (1.18)$$

This space has the useful property that if $g \in H_n^k$, then its Fourier transform, \hat{g} , is in H_k^n and

$$c\|\hat{g}\|_{H_k^n} \leq \|g\|_{H_n^k} \leq C\|\hat{g}\|_{H_k^n} \quad (1.19)$$

for $c, C > 0$ and independent on g .

We want an analogous space for f , but allowing for non-zero limits at infinity. Let $\langle \cdot \rangle_+ : \mathbb{R} \rightarrow \mathbb{R}$ be a smooth function such that

$$\langle x \rangle_+ = \begin{cases} \langle x \rangle, & x > 1 \\ 1, & x < 0 \end{cases} \quad (1.20)$$

and $\langle \cdot \rangle_+$ continued smoothly between 0 and 1 such that it is always greater than or equal to 1. Thus $\langle \cdot \rangle_+$ is a function that only acts like $\langle \cdot \rangle$ for positive numbers. The function $\langle \cdot \rangle_-$ is similarly defined but for the negative numbers.

Definition 2. Define $\mathcal{X}_{n+}^k(\mathbb{R})$ to be the Banach space of functions where

$$\mathcal{X}_{n+}^k(\mathbb{R}) := \{f \in \mathcal{X}^k(\mathbb{R}) \mid \lim_{x \rightarrow \infty} f(x) = f_\infty \text{ and } (f - f_\infty)\langle \cdot \rangle_+^n \in \mathcal{X}^k(\mathbb{R})\} \quad (1.21)$$

with norm given by

$$\|f\|_{\mathcal{X}_{n+}^k(\mathbb{R})} := |f_\infty| + \|(f - f_\infty)\langle \cdot \rangle_+^n\|_{\mathcal{X}^k(\mathbb{R})} \quad (1.22)$$

Similarly,

$$\mathcal{X}_{n-}^k(\mathbb{R}) := \{f \in \mathcal{X}^k(\mathbb{R}) \mid \lim_{x \rightarrow -\infty} f(x) = f_{-\infty} \text{ and } (f - f_{-\infty})\langle \cdot \rangle_-^n \in \mathcal{X}^k(\mathbb{R})\} \quad (1.23)$$

and

$$\|f\|_{\mathcal{X}_{n-}^k(\mathbb{R})} := |f_{-\infty}| + \|(f - f_{-\infty})\langle \cdot \rangle_-^n\|_{\mathcal{X}^k(\mathbb{R})} \quad (1.24)$$

Define $\mathcal{X}_n^k(\mathbb{R})$ to be the intersection of these Banach spaces. That is,

$$\mathcal{X}_n^k(\mathbb{R}) := \mathcal{X}_{n+}^k(\mathbb{R}) \cap \mathcal{X}_{n-}^k(\mathbb{R}), \quad \|f\|_{\mathcal{X}_n^k(\mathbb{R})} := \|f\|_{\mathcal{X}_{n+}^k(\mathbb{R})} + \|f\|_{\mathcal{X}_{n-}^k(\mathbb{R})}. \quad (1.25)$$

That $\mathcal{X}_{n\pm}^k$ are Banach spaces follows from the fact that there exists a linear isomorphism between the Banach space $\mathbb{R} \times \mathcal{X}^k$ and these spaces, which is given by

$$(\alpha, f) \mapsto \alpha + f\langle \cdot \rangle_{\pm}^{-n}. \quad (1.26)$$

The definitions above are used to prove that ϕ remains bounded for all time. The idea behind the proof is similar to that of (Schneider and Wayne, 2000, Lemma 3.1); if f and g are localized solutions, then the interaction terms of eq. (1.11) will decay quickly and so ϕ will remain bounded. This decay can be quantified by the following lemma.

Lemma 3. *For each $k \geq 0$ and $c \geq c_0 > 0$, there exists $C > 0$ depending only on k such that*

$$\left\| \frac{1}{\langle \cdot + \tau \rangle_+^2 \langle \cdot - c\tau \rangle^2} \right\|_{C^k} \leq C \sup_{x \in \mathbb{R}} \frac{1}{\langle x + \tau \rangle_+^2 \langle x - c\tau \rangle^2}. \quad (1.27)$$

Furthermore,

$$\int_0^\infty \sup_{x \in \mathbb{R}} \frac{1}{\langle x + \tau \rangle_+^2 \langle x - c\tau \rangle^2} d\tau < \infty. \quad (1.28)$$

See appendix A for proof.

Proposition 1. Fix $T_0 > 0$ and suppose that $f \in C([-T_0, T_0], \mathcal{X}_2^{k+1}(\mathbb{R}))$ and $g \in C([-T_0, T_0], H_2^{k+1}(\mathbb{R}))$, with $k > 2$ an integer. Also, suppose that $f(X, T) \rightarrow f_\infty$ as $X \rightarrow \infty$ for any $T \in [-T_0, T_0]$. Then there exists a constant $C > 0$ such that

$$\sup_{t \in [-\epsilon^{-3}T_0, \epsilon^{-3}T_0]} \|\phi(\cdot, \epsilon t)\|_{H^k} \leq C \left(\sup_{t \in [-\epsilon^{-3}T_0, \epsilon^{-3}T_0]} \left\{ \|f(\cdot, \epsilon^3 t)\|_{\mathcal{X}_2^{k+1}}, \|g(\cdot, \epsilon^3 t)\|_{H_2^{k+1}} \right\} \right)^3 \quad (1.29)$$

and

$$\sup_{t \in [-\epsilon^{-3}T_0, \epsilon^{-3}T_0]} \|\psi(\cdot, \epsilon t)\|_{H^{k-1}} \leq C \left(\sup_{t \in [-\epsilon^{-3}T_0, \epsilon^{-3}T_0]} \left\{ \|f(\cdot, \epsilon^3 t)\|_{\mathcal{X}_2^{k+1}}, \|g(\cdot, \epsilon^3 t)\|_{H_2^{k+1}} \right\} \right)^3, \quad (1.30)$$

where $\psi = \partial_2 \phi$.

Proof. Set $\partial_2 \phi = \psi$. Taking the Fourier transform \mathcal{F} on both sides of eq. (1.11) and writing the ODE as a first order system, we get that

$$\begin{aligned} \partial_2 \begin{bmatrix} \hat{\phi}(k, \tau) \\ \hat{\psi}(k, \tau) \end{bmatrix} &= \begin{bmatrix} \hat{\psi}(k, \tau) \\ -k^2 \hat{\phi}(k, \tau) \end{bmatrix} \\ &+ \begin{bmatrix} 0 \\ \frac{1}{2} k^2 \mathcal{F}[(f^2(\cdot + \tau), \epsilon^2 \tau) - f_\infty^2)g(\cdot - c\tau, \epsilon^2 \tau) + (f(\cdot + \tau, \epsilon^2 \tau) - f_\infty)g^2(\cdot - c\tau, \epsilon^2 \tau)](k) \end{bmatrix}. \end{aligned} \quad (1.31)$$

The semigroup generated by the linear part can be computed explicitly. Putting the solution into variation of constants form with initial conditions set to zero gives

$$\begin{aligned} \hat{\phi}(k, T) &= \frac{1}{2} \int_0^T k \sin(k(T - \tau)) \times \\ &\mathcal{F}[(f^2(\cdot + \tau), \epsilon^2 \tau) - f_\infty^2)g(\cdot - c\tau, \epsilon^2 \tau) + (f(\cdot + \tau, \epsilon^2 \tau) - f_\infty)g^2(\cdot - c\tau, \epsilon^2 \tau)](k) d\tau \end{aligned} \quad (1.32)$$

and

$$\begin{aligned} \hat{\psi}(k, T) &= \frac{1}{2} \int_0^T k^2 \cos(k(T - \tau)) \times \\ &\mathcal{F}[(f^2(\cdot + \tau), \epsilon^2 \tau) - f_\infty^2)g(\cdot - c\tau, \epsilon^2 \tau) + (f(\cdot + \tau, \epsilon^2 \tau) - f_\infty)g^2(\cdot - c\tau, \epsilon^2 \tau)](k) d\tau \end{aligned} \quad (1.33)$$

Hence we can get that

$$\begin{aligned}
& \|\phi(\cdot, T)\|_{H^k} \\
& \leq C \|\hat{\phi}(\cdot, T)\|_{H_k^0} \\
& \leq C \int_0^T \|\partial_1((f^2(\cdot + \tau) - f_\infty^2)g(\cdot - c\tau))\|_{H^k} + \|\partial_1((f(\cdot + \tau) - f_\infty)g^2(\cdot - c\tau))\|_{H^k} d\tau \\
& \leq C \int_0^T \|f(\cdot + \tau)\partial_1 f(\cdot + \tau)g(\cdot - c\tau)\|_{H^k} + \|(f^2(\cdot + \tau) - f_\infty^2)\partial_1 g(\cdot - c\tau)\|_{H^k} \\
& \quad + \|\partial_1 f(\cdot + \tau)g^2(\cdot - c\tau)\|_{H^k} + \|(f(\cdot + \tau) - f_\infty)\partial_1 g(\cdot - c\tau)\|_{H^k} d\tau \\
& \leq C \int_0^T \sup_{x \in \mathbb{R}} \frac{1}{\langle x + \tau \rangle_+^2 \langle x - c\tau \rangle^2} \times \left(\|f\|_{\mathcal{X}_2^{k+1}}^2 \|g\|_{H_2^{k+1}} + \|f\|_{\mathcal{X}_2^{k+1}} \|g\|_{H_2^{k+1}}^2 \right) d\tau,
\end{aligned}$$

whence eq. (1.29) follows. The proof for eq. (1.30) is analogous. \square

1.3 Setup of Lattice Equations

The scalar second-order differential equation eq. (1.2) with potential V given by eq. (1.6) can be rewritten as the following first-order system:

$$\begin{cases} \dot{u}_n = q_{n+1} - q_n, \\ \dot{q}_n = u_n - u_{n-1} - \frac{1}{6}(u_n^3 - u_{n-1}^3), \end{cases} \quad n \in \mathbb{Z}. \quad (1.34)$$

We will now introduce the traveling wave ansatz for the system in eq. (1.34), but we first must assume certain regularity and decay of f and g .

Assumption 1. *Let f and g be solutions of eqs. (1.9) and (1.10), respectively. Assume that*

$$f \in C_b(\mathbb{R}, \mathcal{X}_2^6(\mathbb{R})) \quad \text{and} \quad g \in C_b(\mathbb{R}, H_2^6(\mathbb{R})).$$

Furthermore, assume that f has fixed limits in its spatial variable at $\pm\infty$ given by $f_{\pm\infty}$.

The traveling wave ansatz for u_n and q_n is then given by

$$u_n(t) = \epsilon f(\epsilon(n+t), \epsilon^3 t) + \epsilon g(\epsilon(n-ct), \epsilon^3 t) + \epsilon^3 \phi(\epsilon n, \epsilon t) + \mathcal{U}_n(t) \quad (1.35)$$

and

$$q_n(t) = \epsilon F(\epsilon(n+t), \epsilon^3 t) + \epsilon G(\epsilon(n-ct), \epsilon^3 t) + \epsilon^3 \Phi(\epsilon n, \epsilon t) - \epsilon F_{-\infty} + \mathcal{Q}_n(t). \quad (1.36)$$

The wave speed c is again given by eq. (1.8). The functions F , G , and Φ are chosen to minimize the remainder terms from plugging in the ansatz back into eq. (1.34) and are given explicitly below:

$$F := f - \frac{\epsilon}{2} \partial_1 f + \frac{\epsilon^2}{8} \partial_1^2 f - \frac{\epsilon^2}{12} f^3 - \frac{\epsilon^3}{48} \partial_1^3 f + \frac{\epsilon^3}{8} f^2 \partial_1 f \quad (1.37)$$

$$G := -g + \frac{\epsilon}{2} \partial_1 g + \frac{\epsilon^2 L^2}{4} g + \frac{\epsilon^2}{12} (g^3 + 3Lg^2) - \frac{\epsilon^2}{8} \partial_1^2 g + \frac{\epsilon^3}{48} \partial_1^3 g - \frac{\epsilon^3}{24} \partial_1 (g^3 + 3Lg^2) - \frac{\epsilon^3 L^2}{8} \partial_1 g \quad (1.38)$$

$$\Phi := \partial_1^{-1} \psi - \frac{\epsilon}{2} \psi. \quad (1.39)$$

Here $\psi = \partial_2 \phi$ and ∂_1^{-1} is defined as a Fourier multiplier. That $\partial_1^{-1} \psi$ is well-defined and in $H^5(\mathbb{R})$ follows from eq. (1.33). Assumption 1 implies that F has fixed limits in its spatial variable at $\pm\infty$ given by $F_{\pm\infty} = f_{\pm\infty} - \frac{\epsilon^2}{12} f_{\pm\infty}^3$.

We want $\mathcal{U}(t)$ and $\mathcal{Q}(t)$ to be elements of $\ell^2(\mathbb{Z})$ (at least locally in time). However, to satisfy $\mathcal{Q}(0) \in \ell^2(\mathbb{Z})$ and $\dot{u}_n(0) = q_{n+1}(0) - q_n(0)$, a compatibility condition must hold.

Assumption 2. *Assume that*

$$\sum_{n=-\infty}^{\infty} \dot{u}_n(0) = \epsilon F_{+\infty} - \epsilon F_{-\infty}.$$

Note that if this did not hold, then $\mathcal{Q}_n(0) \not\rightarrow 0$ as $n \rightarrow \infty$ and $\mathcal{Q}(0) \notin \ell^2(\mathbb{Z})$. That $\mathcal{Q}(0_n \rightarrow 0)$ as $n \rightarrow -\infty$ follows directly from the ansatz. The introduction of the

constant $\epsilon F_{-\infty}$ in eq. (1.36) does not affect the dynamics of q in eq. (1.34)

An equivalent set of equations to eq. (1.34) are given by

$$\left\{ \begin{array}{l} \dot{\mathcal{U}}_n(t) = \mathcal{Q}_{n+1}(t) - \mathcal{Q}_n(t) + \text{Res}_n^{(1)}(t) \\ \dot{\mathcal{Q}}_n(t) = \mathcal{U}_n(t) - \mathcal{U}_{n-1}(t) \\ \quad - \frac{1}{2}(\epsilon f(\epsilon(n+t)) + \epsilon g(\epsilon(n-ct)) + \epsilon^3 \phi(\epsilon n))^2 \mathcal{U}_n(t) \\ \quad + \frac{1}{2}(\epsilon f(\epsilon(n-1+t)) + \epsilon g(\epsilon(n-1-ct)) + \epsilon^3 \phi(\epsilon(n-1)))^2 \mathcal{U}_{n-1}(t) \\ \quad + \text{Res}_n^{(2)}(t) + \mathcal{B}_n(\epsilon f + \epsilon g + \epsilon^3 \phi, \mathcal{U}) \end{array} \right. \quad n \in \mathbb{Z} \quad (1.40)$$

where

$$\begin{aligned} \text{Res}_n^{(1)}(t) &= \epsilon F(\epsilon(n+1+t)) - \epsilon F(\epsilon(n+t)) \\ &\quad + \epsilon G(\epsilon(n+1-ct)) - \epsilon G(\epsilon(n-ct)) + \epsilon^3 \Phi(\epsilon(n+1)) - \epsilon^3 \Phi(\epsilon n) \\ &\quad - \epsilon^2 \partial_1 f(\epsilon(n+t)) - \epsilon^4 \partial_2 f(\epsilon(n+t)) \\ &\quad + \epsilon^2 c \partial_1 g(\epsilon(n-ct)) - \epsilon^4 \partial_2 g(\epsilon(n-ct)) - \epsilon^4 \partial_2 \phi(\epsilon n) \\ \text{Res}_n^{(2)}(t) &= \epsilon f(\epsilon(n+t)) - \epsilon f(\epsilon(n-1+t)) \\ &\quad + \epsilon g(\epsilon(n-ct)) - \epsilon g(\epsilon(n-1-ct)) + \epsilon^3 \phi(\epsilon n) - \epsilon^3 \phi(\epsilon(n-1)) \\ &\quad - \epsilon^2 \partial_1 F(\epsilon(n+t)) - \epsilon^4 \partial_2 F(\epsilon(n+t)) \\ &\quad + \epsilon^2 c \partial_1 G(\epsilon(n-ct)) - \epsilon^4 \partial_2 G(\epsilon(n-ct)) - \epsilon^4 \partial_2 \Phi(\epsilon n) \\ &\quad - \frac{1}{6} \left((\epsilon f(\epsilon(n+t)) + \epsilon g(\epsilon(n-ct)) + \epsilon^3 \phi(\epsilon n))^3 \right. \\ &\quad \left. - (\epsilon f(\epsilon(n-1+t)) + \epsilon g(\epsilon(n-1-ct)) + \epsilon^3 \phi(\epsilon(n-1)))^3 \right) \end{aligned}$$

and

$$\begin{aligned} \mathcal{B}_n(\epsilon f + \epsilon g + \epsilon^3 \phi, \mathcal{U}) = & -\frac{1}{6} \left(3(\epsilon f(\epsilon(n+t)) + \epsilon g(\epsilon(n-ct)) + \epsilon^3 \phi(\epsilon n)) \mathcal{U}_n^2(t) \right. \\ & - 3(\epsilon f(\epsilon(n-1+t)) + \epsilon g(\epsilon(n-1-ct)) + \epsilon^3 \phi(\epsilon(n-1))) \mathcal{U}_{n-1}^2(t) \\ & \left. + \mathcal{U}_n^3(t) - \mathcal{U}_{n-1}^3(t) \right). \end{aligned}$$

The terms \mathcal{U} and \mathcal{Q} control the error associated with the ansatz in eqs. (1.35) and (1.36). Thus if these terms remain small in the $\ell^2(\mathbb{Z})$ norm, then the traveling wave ansatz will remain valid.

1.4 Preparatory Estimates

To control the dynamics of \mathcal{U} and \mathcal{Q} , we need estimates of the residuals and the nonlinearity. It will frequently normal to bound the $\ell^2(\mathbb{Z})$ of a term by the $H^1(\mathbb{R})$ norm of a function. To this end the following lemma proved in (Dumas and Pelinovsky, 2014) is useful.

Lemma 4. *There exists $C > 0$ such that for all $X \in H^1(\mathbb{R})$ and $\epsilon \in (0, 1)$,*

$$\|x\|_{\ell^2} \leq C\epsilon^{-1/2}\|X\|_{H^1},$$

where $x_n := X(\epsilon n)$, $n \in \mathbb{Z}$.

Lemma 5. *Let f and g be solutions of eqs. (1.9) and (1.10), respectively, such that $f \in C([- \tau_0, \tau_0], \mathcal{X}_2^6)$ and $g \in C([- \tau_0, \tau_0], H_2^6)$. Let $\tau_0 > 0$ be fixed and $\delta > 0$ be as*

$$\delta := \max \left\{ \sup_{\tau \in [-\tau_0, \tau_0]} \|f(\cdot, \tau)\|_{\mathcal{X}_2^6}, \sup_{\tau \in [-\tau_0, \tau_0]} \|g(\cdot, \tau)\|_{H_2^6} \right\} \quad (1.41)$$

Then there exists a δ -independent constant $C > 0$ such that the residual and nonlinear terms satisfy

$$\|\text{Res}^{(1)}(t)\|_{\ell^2} + \|\text{Res}^{(2)}(t)\|_{\ell^2} \leq C\epsilon^{11/2}(\delta + \delta^5) \quad (1.42)$$

and

$$\|\mathcal{B}_n(\epsilon f + \epsilon g + \epsilon^3 \phi, \mathcal{U})\|_{\ell^2} \leq C\epsilon[(\delta + \epsilon^2 \delta^3)\|\mathcal{U}\|_{\ell^2}^2 + \|\mathcal{U}\|_{\ell^2}^3] \quad (1.43)$$

for every $t \in [-\epsilon^{-3}\tau_0, \epsilon^{-3}\tau_0]$ and $\epsilon \in (0, 1)$.

Proof. We first focus on bounding $\text{Res}^{(1)}(t)$. Looking first at the terms in $\text{Res}^{(1)}(t)$ involving f and F and using Taylor expansions and eq. (1.9), we get the following:

$$\begin{aligned}
& \epsilon F(\cdot + \epsilon) - \epsilon F - \epsilon^2 \partial_1 f - \epsilon^4 \partial_2 f = \\
& \epsilon^2 \partial_1 f + \frac{\epsilon^3}{2} \partial_1^2 f + \frac{\epsilon^4}{6} \partial_1^3 f + \frac{\epsilon^5}{24} \partial_1^4 f + \frac{\epsilon^6}{24} \int_0^1 \partial_1^5 f(\epsilon(n+t+s))(1-s)^4 ds \\
& - \frac{\epsilon^3}{2} \partial_1^2 f - \frac{\epsilon^4}{4} \partial_1^3 f - \frac{\epsilon^5}{12} \partial_1^4 f - \frac{\epsilon^6}{12} \int_0^1 \partial_1^5 f(\epsilon(n+t+s))(1-s)^3 ds \\
& + \frac{\epsilon^4}{8} \partial_1^3 f + \frac{\epsilon^5}{16} \partial_1^4 f + \frac{\epsilon^6}{16} \int_0^1 \partial_1^5 f(\epsilon(n+t+s))(1-s)^2 ds \\
& - \frac{\epsilon^4}{12} \partial_1(f^3) - \frac{\epsilon^5}{24} \partial_1^2(f^3) - \frac{\epsilon^6}{24} \int_0^1 \partial_1^3(f^3)(\epsilon(n+t+s))(1-s)^2 ds \\
& - \frac{\epsilon^5}{48} \partial_1^4 f - \frac{\epsilon^6}{48} \int_0^1 \partial_1^5 f(\epsilon(n+t+s))(1-s) ds \\
& + \frac{\epsilon^5}{24} \partial_1^2(f^3) + \frac{\epsilon^6}{24} \int_0^1 \partial_1^3(f^3)(\epsilon(n+t+s))(1-s) ds \\
& - \epsilon^2 \partial_1 f \\
& + \frac{\epsilon^4}{12} \partial_1(f^3) \\
& - \frac{\epsilon^4}{24} \partial^3 f.
\end{aligned} \tag{1.44}$$

Note that the terms involving lower orders of ϵ cancel, and so we are only left with the integral terms of order ϵ^6 . Applying lemma 4 (and lemmas 1 and 2 when needed) to the remaining terms gives that the ℓ^2 norm on the left-hand side of the above inequality can be bounded by

$$C(\epsilon^{11/2}(\delta + \delta^3))$$

for some choice of constant $C > 0$.

Doing the same Taylor expansion for the g and G terms in $\text{Res}^{(1)}(t)$ along with eq. (1.10) gives similar results. In particular, the terms of order ϵ^5 cancel out, and we

are left terms of order ϵ^6 like

$$\int_0^1 \partial_1^3(g^3)(\epsilon(n-ct+s))(1-s)^2 ds \quad \text{and} \quad \int_0^1 \partial_1^3(3f_\infty g^2)(\epsilon(n-ct+s))(1-s)^2 ds \quad (1.45)$$

that can be controled with lemma 4.

Similarly we have

$$\epsilon^3 \Phi(\epsilon(n+1), \epsilon t) - \epsilon^3 \Phi(\epsilon n, \epsilon t) - \epsilon^4 \partial_2 \phi_2(\epsilon n, \epsilon t) = \frac{\epsilon^6}{2} \int_0^1 \partial_1^2 \psi(\epsilon(n+s), \epsilon t) (1-s)^2 ds, \quad (1.46)$$

whose ℓ^2 norm can also be controlled.

Therefore we have

$$\|\text{Res}^{(1)}(t)\|_{\ell^2} \leq C \epsilon^{11/2} (\delta + \delta^3) \quad (1.47)$$

The bound on $\text{Res}^{(2)}(t)$ can be approached similarly. Focusing first on the terms with f and F in $\text{Res}^{(2)}(t)$, we have that all terms of order ϵ^5 or lower cancel. We are again left with ϵ^6 order terms that are integral remainders from Taylor expansion that are controlled and a term of the form

$$\partial_2 \left(\frac{1}{8} \partial_1^2 f - \frac{1}{12} f^3 - \frac{\epsilon}{48} \partial_1^3 f + \frac{\epsilon}{8} f^2 \partial_1 f \right), \quad (1.48)$$

which can also be controlled by lemma 4.

For the remaining terms, we have that terms of order ϵ^3 or lower cancel out. The terms of order ϵ^4 are equal to

$$-\partial_2 \partial_1^{-1} \psi + \partial_1 \phi - \frac{1}{6} \partial_1 (3(f^2 - L^2)g + 3(f - L)g^2). \quad (1.49)$$

Formally applying ∂_1 implies that the above terms should be constant in space (taking a derivative with respect to the rescaled $\epsilon x = \epsilon n$ shows that this is the case). Since all the terms decay to zero at spatial infinity, they are exactly zero.

The terms of order ϵ^5 can be rewritten as

$$\frac{1}{4} \partial_1 (-2\partial_2 g - \frac{1}{12} \partial_1^3 g + \frac{1}{6} (g^3 + 3f_\infty g^2)) + \frac{1}{2} (\partial_2^2 \phi - \partial_1^2 \phi + \frac{1}{6} \partial_1^2 (3(f - f_\infty)g^2 + 3(f^2 - f_\infty^2)g)) \quad (1.50)$$

which is equal to zero. The remaining terms are all of order of ϵ^6 or above are integral

remainders from Taylor expansion and terms of the form

$$\partial_2(G_2 + \epsilon G_3) \quad \text{and} \quad f_\infty^2 \partial_1(G_2 + \epsilon G_3). \quad (1.51)$$

We can then get the following bound:

$$\|\text{Res}^{(2)}(t)\|_{\ell^2} \leq C\epsilon^{11/2}(\delta + \delta^5).$$

Interpolating between powers of δ gives the desired inequality eq. (1.42).

The proof of eq. (1.43) follows immediately. \square

Define

$$\mathcal{E}(t) = \frac{1}{2} \sum_{n \in \mathbb{Z}} \mathcal{Q}_n^2(t) + \mathcal{U}_n^2(t) - \frac{1}{2} \left(\epsilon f(\epsilon(n+t), \epsilon^3 t) + \epsilon g(\epsilon(n-ct), \epsilon^3 t) + \epsilon^3 \phi(\epsilon n, \epsilon t) \right)^2 \mathcal{U}_n^2(t) \quad (1.52)$$

Lemma 6. Fix $\tau_0 > 0$ and let δ be given by eq. (1.41). There exists $\epsilon_0 = \epsilon_0(\delta) > 0$ sufficiently small such that for every $\epsilon \in (0, \epsilon_0)$ and for every local solution $(\mathcal{U}, \mathcal{Q}) \in C^1([- \tau_0 \epsilon^{-3}, \tau_0 \epsilon^{-3}], \ell^2(\mathbb{Z}))$ of eq. (1.40), the energy-type quantity given in eq. (1.52) is coercive with the bound

$$\|\mathcal{Q}(t)\|_{\ell^2}^2 + \|\mathcal{U}(t)\|_{\ell^2}^2 \leq 4\mathcal{E}(t), \quad \text{for } t \in (-\tau_0 \epsilon^{-3}, \tau_0 \epsilon^{-3}). \quad (1.53)$$

Moreover, there exists $C > 0$ independent of ϵ and δ such that

$$\left| \frac{d\mathcal{E}}{dt} \right| \leq C\mathcal{E}^{1/2} [\epsilon^{11/2}(\delta + \delta^5) + \epsilon^3 \delta^2 \mathcal{E}^{1/2} + \epsilon(\delta + \mathcal{E}^{1/2})\mathcal{E}] \quad (1.54)$$

for every $t \in [-\tau_0 \epsilon^{-3}, \tau_0 \epsilon^{-3}]$ and $\epsilon \in (0, \epsilon_0)$.

Proof. Note that $\delta > 0$ can be used to control the $L^\infty(\mathbb{R})$ norms of f , g , and ψ . Thus we can choose ϵ_0 small enough so that for $\epsilon \in (0, \epsilon_0)$ we have

$$1 - \frac{1}{2} (\epsilon \|f\|_{L^\infty} + \epsilon \|g\|_{L^\infty} + \epsilon^3 \|\phi\|_{L^\infty})^2 \geq \frac{1}{2}, \quad (1.55)$$

independent on the particular choices of f and g . Hence

$$\mathcal{E}(t) \geq \frac{1}{2} \|\mathcal{Q}\|_{\ell^2}^2 + \frac{1}{4} \|\mathcal{U}\|_{\ell^2}^2 \geq \frac{1}{4} \|\mathcal{Q}\|_{\ell^2}^2 + \frac{1}{4} \|\mathcal{U}\|_{\ell^2}^2 \quad (1.56)$$

and eq. (1.53) follows.

Now we take the time derivative of \mathcal{E} to get that

$$\begin{aligned} \frac{d\mathcal{E}}{dt} = & \sum_{n \in \mathbb{Z}} \mathcal{Q}_n(t) \text{Res}_n^{(2)}(t) + \mathcal{Q}_n(t) \mathcal{B}_n(\epsilon f + \epsilon g + \epsilon^3 \phi, \mathcal{U}(t) \\ & + \mathcal{U}_n(t) \text{Res}_n^{(1)}(t) \left(1 - \frac{1}{2}(\epsilon f + \epsilon g + \epsilon^3 \phi)^2 \right) \\ & + \mathcal{U}_n^2(t)(\epsilon f + \epsilon g + \epsilon^3 \phi) \times (\epsilon^2 \partial_1 f + \epsilon^4 \partial_2 f - \epsilon^2 c \partial_1 g + \epsilon^4 \partial_2 g + \epsilon^4 \partial_2 \phi). \end{aligned}$$

Then using the Cauchy inequality, taking ℓ^∞ norms, and applying eqs. (1.42) and (1.43), we get that

$$\begin{aligned} \left| \frac{d\mathcal{E}}{dt} \right| \leq & \|\mathcal{Q}\|_\ell^2 \times \|\text{Res}^{(2)}(t)\|_{\ell^2} + \|\mathcal{Q}\|_{\ell^2} \times \|\mathcal{B}\|_{\ell^2} + \|\mathcal{U}\|_{\ell^2} \times \|\text{Res}_n^{(1)}(t)\|_{\ell^2} \\ & + \|\mathcal{U}\|_{\ell^2}^2 (\epsilon \delta + \epsilon \delta + \epsilon^3 \delta^3) \times (\epsilon^2 \delta + \epsilon^4 \delta + \epsilon^2 c \delta + \epsilon^4 \delta + \epsilon^4 \delta^3) \\ \leq & C \left[\mathcal{E}^{1/2} \epsilon^{11/2} (\delta + \delta^5) + \mathcal{E}^{1/2} \epsilon [(\delta + \epsilon^2 \delta^3) \mathcal{E} + \mathcal{E}^{3/2}] + \mathcal{E} (\epsilon^3 \delta^2 + \epsilon^5 \delta^2 + \epsilon^5 \delta^4 + \epsilon^7 \delta^4 + \epsilon^7 \delta^6) \right], \end{aligned}$$

with $C > 0$ independent of ϵ and δ . The right-hand side of the above inequality can be simplified by taking ϵ_0 smaller; taking ϵ_0 sufficiently small (dependent on δ), we can absorb higher orders of ϵ into lower orders. For example, $\epsilon^3 \delta^2 + \epsilon^5 \delta^2 \leq 2\epsilon^3 \delta^2$ for ϵ small enough. Thus we arrive at

$$\left| \frac{d\mathcal{E}}{dt} \right| \leq C \mathcal{E}^{1/2} \left[\epsilon^{11/2} (\delta + \delta^5) + \epsilon^3 \delta^2 \mathcal{E}^{1/2} + \epsilon (\delta + \mathcal{E}^{1/2}) \mathcal{E} \right]$$

as desired. □

Lastly, before we can prove our main result, we must show that for appropriate initial conditions that $\mathcal{U}(0)$ and $\mathcal{Q}(0)$ are suitably small. In particular, we want our initial conditions to be “close to” the traveling wave ansatz in the sense that

$$u_n(0) \approx \epsilon f(\epsilon n, 0) + \epsilon g(\epsilon n, 0) \tag{1.57}$$

and

$$\dot{u}_n(0) \approx \epsilon \partial_1 f(\epsilon n, 0) - \epsilon^2 g(\epsilon n, 0) \tag{1.58}$$

where the higher-order ϵ terms are dropped. Recall that we assume $\phi, \partial_1 \phi$ to have initial conditions exactly equal to zero, so those terms drop. A seemingly appropriate notion of “closeness” would be in the ℓ^2 norm, as used in (Khan and Pelinovsky, 2017; Schneider and Wayne, 2000). However, since $q_n(0) = \sum_{k=-\infty}^{n-1} \dot{u}_k(0)$, we may lose some decay due to the summation and $\mathcal{Q}(0)$ will not be in ℓ^2 . To counter this, we need some extra localization assumptions on $\dot{u}_n(0)$.

Assumption 3. *Suppose that the initial conditions for u satisfy*

$$\|u(0) - \epsilon f(\epsilon \cdot, 0) - \epsilon g(\epsilon \cdot, 0)\|_{\ell^2} + \|\dot{u}(0) - \epsilon^2 \partial_1 f(\epsilon \cdot, 0) + \epsilon^2 \partial g(\epsilon \cdot, 0)\|_{\ell_2^2} \leq \epsilon^{5/2} \quad (1.59)$$

and that $f(\cdot, 0) \in \mathcal{X}_2^6$ and $g(\cdot, 0) \in H_2^6$

The ℓ_2^2 norm will be sufficient to get that the partial summation is in ℓ^2 based on the following lemma.

Lemma 7. *If $a \in \ell_2^2(\mathbb{Z})$ and*

$$\sum_{k=-\infty}^n a_k = 0, \quad (1.60)$$

then $b_n = \sum_{k=-\infty}^n a_k$ is in $\ell^2(\mathbb{Z})$ and

$$\|b\|_{\ell^2} \leq C \|a\|_{\ell_2^2} \quad (1.61)$$

for some $C > 0$ independent of a .

Proof. See appendix A for proof. □

We can now show the following.

Lemma 8. *Let assumptions 2 and 3 hold. Then $\mathcal{U}(0), \mathcal{Q}(0) \in \ell^2(\mathbb{Z})$ satisfy*

$$\dot{u}_n(0) = q_{n+1}(0) - q_n(0) \quad (1.62)$$

and

$$\|\mathcal{U}(0)\|_{\ell^2} + \|\mathcal{Q}(0)\|_{\ell^2} \leq C \epsilon^{5/2} \quad (1.63)$$

with $C > 0$ independent of ϵ .

Proof. That $\|\mathcal{U}(0)\|_{\ell^2} \leq C\epsilon^{5/2}$ follows immediately from applying assumption 3 to eq. (1.35).

For $q_n(0)$ to satisfy eq. (1.62), it must equal $\sum_{k=-\infty}^{n-1} \dot{u}_k(0)$ (modulo a constant which we assume without loss of generality to be zero). Thus we have

$$\begin{aligned}
q_n(0) &= \sum_{k=-\infty}^{n-1} \dot{u}_k(0) \\
&= \sum_{k=-\infty}^{n-1} [\dot{u}_k(0) - \epsilon^2 \partial_1 f(\epsilon k, 0) - \epsilon^4 \partial_1 f(\epsilon k, 0) + \epsilon^2 c \partial_1 g(\epsilon k, 0) - \epsilon^4 \partial_2 g(\epsilon k, 0)] \\
&\quad + \sum_{k=-\infty}^{n-1} [\epsilon^2 \partial_1 f(\epsilon k, 0) + \epsilon^4 \partial_1 f(\epsilon k, 0) - \epsilon F(\epsilon(k+1), 0) + \epsilon F(\epsilon k, 0)] \\
&\quad + \sum_{k=-\infty}^{n-1} [-\epsilon^2 c \partial_1 g(\epsilon k, 0) + \epsilon^4 \partial_1 g(\epsilon k, 0) - \epsilon G(\epsilon(k+1), 0) + \epsilon G(\epsilon k, 0)] \\
&\quad + \epsilon F(\epsilon n, 0) - \epsilon F_{-\infty} + \epsilon G(\epsilon n, 0).
\end{aligned} \tag{1.64}$$

Comparing eq. (1.64) to eq. (1.36), we have that

$$\begin{aligned}
\mathcal{Q}_n(0) &= \sum_{k=-\infty}^{n-1} [\dot{u}_k(0) - \epsilon^2 \partial_1 f(\epsilon k, 0) - \epsilon^4 \partial_1 f(\epsilon k, 0) + \epsilon^2 c \partial_1 g(\epsilon k, 0) - \epsilon^4 \partial_2 g(\epsilon k, 0)] \\
&\quad + \sum_{k=-\infty}^{n-1} [\epsilon^2 \partial_1 f(\epsilon k, 0) + \epsilon^4 \partial_1 f(\epsilon k, 0) - \epsilon F(\epsilon(k+1), 0) + \epsilon F(\epsilon k, 0)] \\
&\quad + \sum_{k=-\infty}^{n-1} [-\epsilon^2 c \partial_1 g(\epsilon k, 0) + \epsilon^4 \partial_1 g(\epsilon k, 0) - \epsilon G(\epsilon(k+1), 0) + \epsilon G(\epsilon k, 0)].
\end{aligned} \tag{1.65}$$

That $\mathcal{Q}_n(0) \rightarrow 0$ as $n \rightarrow \infty$ is guaranteed by assumption 2. Now lemma 7 can be applied to get the result if the summands are in ℓ_2^2 and of order $\epsilon^{5/2}$. The first summand satisfies this condition because of assumption 3. The latter summands also satisfy this condition based on earlier calculations on the residuals. For example, referencing eq. (1.44), the second summand is equal to a sum of integral terms of the form

$$\frac{\epsilon^6}{24} \int_0^1 \partial_1^5 f(\epsilon(n+s), 0) (1-s)^4 ds \tag{1.66}$$

which are elements of ℓ_2^2 since $f(\cdot, 0) \in \mathcal{X}_2^6$ and are of order $\epsilon^{5/2}$. A similar conclusion

holds for the third summand relying on $g \in H_2^6$.

Thus we have eq. (1.63) where the $C > 0$ can be chosen based on the norms of f and g . \square

1.5 Proof of Long-Time Stability

Now with the setup complete, the main result of this section can be shown. The result and proof are analogous to those of (Khan and Pelinovsky, 2017, Thm. 1).

Theorem 1. *Let assumption 1 hold and set*

$$\delta = \max \left\{ \sup_{\tau \in \mathbb{R}} \|f(\cdot, \tau)\|_{\mathcal{X}_2^6}, \sup_{\tau \in \mathbb{R}} \|g(\cdot, \tau)\|_{H_2^6} \right\} \quad (1.67)$$

For fixed $r \in (0, 1/2)$, there exists positive constants ϵ_0 , C , and K such that for all $\epsilon \in (0, \epsilon_0)$, when initial data $(u(0), \dot{u}(0))$ satisfy assumptions 2 and 3, the unique solution (u, q) to the FPU equation eq. (1.34) belongs to

$$C^1([-t_0(\epsilon), t_0(\epsilon)], \ell^\infty(\mathbb{Z})) \quad (1.68)$$

with $t_0(\epsilon) := rK^{-1}\epsilon^{-3}|\log(\epsilon)|$ and satisfies

$$\begin{aligned} & \|u(t) - \epsilon f(\epsilon(\cdot + t), \epsilon^3 t) - \epsilon g(\epsilon(\cdot - ct), \epsilon^3 t)\|_{\ell^2} \\ & + \|\dot{u}(t) - \epsilon \partial_1 f(\epsilon(\cdot + t), \epsilon^3 t) + \epsilon^2 \partial_1 g(\epsilon(\cdot - ct), \epsilon^3 t)\|_{\ell^2} \leq C\epsilon^{5/2-r}, \quad t \in [-t_0(\epsilon), t_0(\epsilon)]. \end{aligned} \quad (1.69)$$

Proof. Set $\mathcal{S} := \mathcal{E}^{1/2}$ where \mathcal{E} is defined in eq. (1.52). From the results in lemma 8, we get that $\mathcal{S}(0) \leq C_0\epsilon^{3/2}$ for some constant $C_0 > 0$ and ϵ_0 as chosen in lemma 6. For fixed constants $r \in (0, 1/2)$, $C > C_0$, and $K > 0$, define the maximal continuation time by

$$T_{C,K,r} := \sup \left\{ T_0 \in (0, rK^{-1}\epsilon^{-3}|\log(\epsilon)|] : \mathcal{S}(t) \leq C\epsilon^{5/2-r}, t \in [-T_0, T_0] \right\}. \quad (1.70)$$

We also define the maximal evolution time of the mKdV equation as $\tau_0(\epsilon) = rK^{-1}|\log(\epsilon)|$. The goal is then to pick C and K so that $T_{C,K,r} = \epsilon^{-3}\tau_0(\epsilon)$.

We have that

$$\begin{aligned} \left| \frac{d}{dt} \mathcal{S}(t) \right| &= \frac{1}{2\mathcal{E}^{1/2}} \left| \frac{d}{dt} \mathcal{E}(t) \right| \\ &\leq C_1(\delta + \delta^5)\epsilon^{11/2} + C_2\epsilon^3 [\delta^2 + \epsilon^{-2}(\delta + \mathcal{S})\mathcal{S}] \mathcal{S} \end{aligned} \quad (1.71)$$

where $C_1, C_2 > 0$ are independent of δ and ϵ . While $|t| \leq T_{C,K,r}$,

$$C_2 [\delta^2 + \epsilon^{-2}(\delta + \mathcal{S})\mathcal{S}] \leq C_2 [\delta^2 + \epsilon^{-2}(\delta + C\epsilon^{11/2-r})C\epsilon^{11/2-r}] , \quad (1.72)$$

where the right-hand side is continuous in ϵ for $\epsilon \in [0, \epsilon_0]$. Thus the right-hand side can be uniformly bounded by a constant independent of ϵ . Choose $K > 0$ (dependent on C) sufficiently large so that

$$C_2 [\delta^2 + \epsilon^{-2}(\delta + C\epsilon^{11/2-r})C\epsilon^{11/2-r}] \leq K. \quad (1.73)$$

Hence, we can get that for $t \in [-T_{C,K,r}, T_{C,K,r}]$

$$\begin{aligned} \frac{d}{dt} e^{-\epsilon^3 K t} \mathcal{S}(t) &= -\epsilon^3 K e^{-\epsilon^3 K t} \mathcal{S} + e^{-\epsilon^3 K t} \frac{d}{dt} \mathcal{S} \\ &\leq -\epsilon^3 K e^{-\epsilon^3 K t} \mathcal{S} + e^{-\epsilon^3 K t} C_1(\delta + \delta^5)\epsilon^{11/2} \\ &\quad + e^{-\epsilon^3 K t} C_2\epsilon^3 [\delta^2 + \epsilon^{-2}(\delta + \mathcal{S})\mathcal{S}] \mathcal{S} \\ &\leq -\epsilon^3 K e^{-\epsilon^3 K t} \mathcal{S} + e^{-\epsilon^3 K t} C_1(\delta + \delta^5)\epsilon^{11/2} + \epsilon^3 K e^{-\epsilon^3 K t} \mathcal{S} \\ &= e^{-\epsilon^3 K t} C_1(\delta + \delta^5)\epsilon^{11/2}. \end{aligned} \quad (1.74)$$

Integrating gives

$$\begin{aligned} \mathcal{S}(t) &\leq (\mathcal{S}(0) + K^{-1}C_1(\delta + \delta^5)\epsilon^{5/2}) e^{\epsilon^3 K t} - \epsilon^{5/2} K^{-1}C_1(\delta + \delta^5) \\ &\leq (\mathcal{S}(0) + K^{-1}C_1(\delta + \delta^5)\epsilon^{5/2}) e^{\epsilon^3 K t} \\ &\leq (\mathcal{S}(0) + K^{-1}C_1(\delta + \delta^5)\epsilon^{5/2}) e^{K\tau_0(\epsilon)} \\ &\leq (C_0 + K^{-1}C_1(\delta + \delta^5)) \epsilon^{5/2-r} \end{aligned} \quad (1.75)$$

for $t \in [-T_{C,K,r}, T_{C,K,r}]$, where the last line follows in part from the definition of $\tau_0(\epsilon)$. Now choose $C > C_0$ sufficiently large so that

$$C_0 + K^{-1}C_1(\delta + \delta^5) \leq C. \quad (1.76)$$

Note that our earlier choice of K can be enlarged so that eq. (1.73) still holds as well as the above inequality. Therefore, with these choices of C and K , the maximal interval can be extended to $T_{C,K,r} = \epsilon^{-3}\tau_0(\epsilon)$. \square

Appendix A

Proofs of lemmas

Proof. The result follows from induction on k .

For $k = 0$, we have

$$\|fg\|_{H^0} \leq \|f\|_{L^\infty} \|g\|_{H^0}. \quad (\text{A.1})$$

Assuming eq. (1.15) holds for $k \geq 0$, we have that

$$\begin{aligned} \|fg\|_{H^{k+1}} &\leq C (\|fg\|_{H^k} + \|\partial^{k+1}(fg)\|_{L^2}) \\ &\leq C (\|f\|_{\mathcal{X}^k} \|g\|_{H^k} + \|\partial^{k+1}(fg)\|_{L^2}), \end{aligned}$$

where the second term can be bounded by

$$\begin{aligned} \|\partial^{k+1}(fg)\|_{L^2} &\leq \|\partial^k(\partial^1 fg)\|_{L^2} + \|\partial^k(f\partial^1 g)\|_{L^2} \\ &\leq \|\partial^1 fg\|_{H^k} + \|f\partial^1 g\|_{H^k} \\ &\leq \|\partial^1 f\|_{H^k} \|g\|_{H^k} + \|f\|_{\mathcal{X}^k} \|\partial^1 g\|_{H^k} \\ &\leq \|f\|_{\mathcal{X}^{k+1}} \|g\|_{H^{k+1}} + \|f\|_{\mathcal{X}^{k+1}} \|g\|_{H^{k+1}} \\ &= 2\|f\|_{\mathcal{X}^{k+1}} \|g\|_{H^{k+1}}. \end{aligned}$$

This completes the induction. □

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