Ángel Castro, Diego Córdoba and Fan Zheng

Stability of Traveling Waves for the Burgers–Hilbert Equation
STABILITY OF TRAVELING WAVES FOR THE BURGERS–HILBERT EQUATION

ÁNGEL CASTRO, DIEGO CÓRDOBA AND FAN ZHENG

We consider smooth solutions of the Burgers–Hilbert equation that are a small perturbation \( \delta \) from a global periodic traveling wave with small amplitude \( \epsilon \). We use a modified energy method to prove the existence time of smooth solutions on a time scale of \( 1/(\epsilon \delta) \), with \( 0 < \delta \ll \epsilon \ll 1 \), and on a time scale of \( \epsilon/\delta^2 \), with \( 0 < \delta \ll \epsilon^2 \ll 1 \). Moreover, we show that the traveling wave exists for an amplitude \( \epsilon \) in the range \((0, \epsilon^*)\), with \( \epsilon^* \sim 0.23 \), and fails to exist for \( \epsilon > 2/e \).

1. Introduction

1A. The Burgers–Hilbert equation (BH). We study the size and stability of traveling waves of the Burgers–Hilbert equation (BH),

\[
\begin{align*}
    f_t &= Hf + ff_x \quad \text{for} \ (x, t) \in \Omega \times \mathbb{R}, \\
    f(x, 0) &= f_0(x),
\end{align*}
\]

where \( \Omega \) is the real line \( \mathbb{R} \) or the torus \( \mathbb{T} = \mathbb{R}/2\pi \mathbb{Z} \) and \( Hf \) is the Hilbert transform which is defined for \( f : \mathbb{R} \) (resp. \( \mathbb{T} \)) \( \rightarrow \mathbb{R} \) by

\[
Hf(x) = \frac{1}{\pi} \text{P. V.} \int_{\mathbb{R}} \frac{f(y)}{x - y} \, dy \quad \text{resp.} \quad Hf(x) = \frac{1}{2\pi} \text{P. V.} \int_{0}^{2\pi} f(y) \cot \frac{x - y}{2} \, dy.
\]

Its action in the frequency space is \( \widehat{Hf}(k) = -i \, \text{sgn} \, k \, \hat{f}(k) \) for \( k \neq 0 \), and \( \widehat{Hf}(0) = 0 \).

This equation arose in [Marsden and Weinstein 1983] as a quadratic approximation for the evolution of the boundary of a simply connected vorticity patch in two dimensions. Later, Biello and Hunter [2010] proposed the model as an approximation for describing the dynamics of small slope vorticity fronts in the 2-dimensional incompressible Euler equations. Recently, the validity of this approximation was proved in [Hunter et al. 2022].

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By standard energy estimates the initial value problem for (BH) is locally well-posed in $H^s$ for $s > \frac{3}{2}$. Bressan and Nguyen [2014] established in global existence of weak solutions for initial data $f_0 \in L^2(\mathbb{R})$, with $f(x, t) \in L^\infty(\mathbb{R}) \cap L^2(\mathbb{R})$ for all $t > 0$. Bressan and Zhang [2017] constructed locally in time piecewise continuous solutions to the BH equation with a single discontinuity where the Hilbert transform generates a logarithmic singularity. Uniqueness for general global weak solutions of [Bressan and Nguyen 2014] is open. But piecewise continuous solutions are shown to be unique in [Krupa and Vasseur 2020].

The Burgers–Hilbert equation can indeed form shocks in finite time. Various numerical simulations have been performed in [Biello and Hunter 2010; Hunter 2018; Klein and Saut 2015]. Finite time singularities, in the $C^{1,\delta}$ norm, with $0 < \delta < 1$, were shown to exist in [Castro et al. 2010] for initial data $f_0$ in $L^2(\mathbb{R}) \cap C^{1,\delta}(\mathbb{R})$ that has a point $x_0 \in \mathbb{R}$ such that $H(f_0)(x_0) > 0$ and $f_0(x_0) \geq (\frac{32\pi}{\|f_0\|_{L^2}})^{1/3}$.

Recently, with a different approach, Saut and Wang [2022] proved shock formation in finite time for (BH) and Yang [2021] constructed solutions that develop an asymptotic self-similar shock at one single point with an explicitly computable blowup profile for (BH).

In this paper we are concerned with the dynamics in the small amplitude regime where (BH) can be viewed as a perturbation of the linearized (BH) equation $f_t = H[f]$. Since the nonlinear term in (1-1) is quadratic and the Hilbert transform is orthogonal in $L^2$, standard energy estimates yield a time of existence of smooth solutions $T \sim \frac{1}{\|f_0\|}$. Thanks to the effect of the Hilbert transform and using the normal form method, Hunter, Ifrim, Tataru and Wong (see [Hunter and Ifrim 2012; Hunter et al. 2015]) were able to improve this time of existence. More precisely, if $\epsilon$ is the size of the initial data, they prove a lifespan $T \sim \frac{1}{\epsilon^2}$ for small enough $\epsilon$ (see also [Ehrnström and Wang 2019] for a similar approach with a modified version of the (BH) equation). The proofs are based on the normal form method and on the modified energy method. Furthermore, Hunter [2018] showed for $0 < \epsilon \ll 1$ the existence of $C^\infty$-traveling wave solutions of the form

$$f_\epsilon(x, t) = u_\epsilon(x + v_\epsilon t),$$

with

$$u_\epsilon(x) = \epsilon \cos(x) + O(\epsilon^2), \quad (1-3)$$

$$v_\epsilon = -1 + O(\epsilon^2). \quad (1-4)$$

Notice that, $(u_\epsilon(nx)/n, v_\epsilon/n)$ is also a $C^\infty$-traveling wave solution.

Throughout the paper we will assume that the initial data $f_0$ has zero mean. Since (1-1) preserves the mean,

$$\int_0^{2\pi} f(x, t) \, dx = 0 \quad \text{for all } t.$$

Since in the construction above $u_\epsilon$ also has zero mean,

$$\int_0^{2\pi} f(x, t) \, dx = 0 \quad \text{for all } t.$$

1B. **The main theorem.** In the present work we extend the results in the small amplitude regime in the following way:

1. **Size of the traveling waves:** We show that the traveling waves exist for an amplitude $\epsilon$ in the range $(0, \epsilon^*)$, with $\epsilon^* \sim 0.23$, and fail to exist for $\epsilon > 2/e$. 


Extended lifespan from a traveling wave: We prove that a \( \delta \)-perturbation of \( u_\epsilon \) lives, at least, for a time \( T \sim 1/(\delta \epsilon) \) for \( 0 < \delta \ll \epsilon \ll 1 \), and for a time \( T \sim \epsilon/\delta^2 \) for \( 0 < \delta \ll \epsilon^2 \ll 1 \). This is an improvement compared with the time \( T \sim 1/\epsilon^2 \) provided by the results in [Hunter and Ifrim 2012; Hunter et al. 2015]. Indeed, our main theorem reads:

**Theorem 1.1.** For \( 0 < |\epsilon|, \delta \ll 1 \) let \((u_\epsilon, v_\epsilon) \in C^\infty(\mathbb{T}) \times \mathbb{R}\) be a traveling wave solution of (1-1) as in (1-3) and (1-4) and \( \|f_0 - u_\epsilon\|_{H^4(\mathbb{T})} < \delta \).

Then there exist \( 0 < \epsilon_0 \ll 1, T(\epsilon, \delta) > 0 \) and a solution of (1-1) \[ f(x, t) \in C([0, T(\epsilon, \delta)); H^4(\mathbb{T})) \] such that

1. if \( \delta \ll |\epsilon| \) and \( |\epsilon| \leq \epsilon_0 \), then \( T(\epsilon, \delta) \sim 1/(\epsilon \delta) \),
2. if \( \delta \ll \epsilon^2 \) and \( |\epsilon| \leq \epsilon_0 \), then \( T(\epsilon, \delta) \sim \epsilon/\delta^2 \).

Moreover, there are two differentiable functions \( \epsilon(t) \) and \( a(t) \) such that

\[ \|f(x, t) - u_{\epsilon(t)}(x + a(t))\|_{H^4} \lesssim \delta. \]

1C. **Sketch of the proof of Theorem 1.1.** Now we briefly describe the proof of Theorem 1.1. Assume that the solution

\[ f(x, t) = u_\epsilon(x + v_\epsilon t) + g(x + v_\epsilon t, t) \]

is a small perturbation around the traveling wave \( u_\epsilon(x + v_\epsilon t) \). Then the linearization of the Burgers–Hilbert equation (1-1) is

\[ L_\epsilon g := -v_\epsilon g_x + H g + (u_\epsilon(x)g)_x = 0 \]

so to the first order, the perturbation \( g \) solves the equation \( g_t = L_\epsilon g \), with solution

\[ g(x, t) = e^{t L_\epsilon} g(x, 0). \]

Therefore the linear evolution of \( g \) is determined by the eigenvalues of \( L_\epsilon \).

The full nonlinear evolution of \( g \) is

\[ g_t = L_\epsilon g + N(g, g), \]

where \( N(g, g) \) is a nonlinearity that is (at least) quadratic in \( g \). We plug in the linear solution to get

\[ g_t = e^{t L_\epsilon} L_\epsilon g(x, 0) + N(e^{t L_\epsilon} g(x, 0), e^{t L_\epsilon} g(x, 0)) \]

to second order, which integrates to

\[ g(x, t) = e^{t L_\epsilon} g(x, 0) + e^{t L_\epsilon} \int_0^t e^{-s L_\epsilon} N(e^{s L_\epsilon} g(x, 0), e^{s L_\epsilon} g(x, 0)) \, ds. \]
Expand (at least formally) the initial data and the nonlinearity in terms of the eigenvectors of $L_\epsilon$ as
\[
g(x, 0) = \sum_n c_n \varphi_n(x), \quad N(\varphi_1, \varphi_m) = \sum_n c_{lmn} \varphi_n,
\]
where the eigenvalue of $\varphi_n$ is $\lambda_n$. Then
\[
g(x, t) \approx \sum_n c_n e^{\lambda_n t} \varphi_n(x) + \sum_{l,m,n} \frac{e^{(\lambda_l + \lambda_m) t} - e^{\lambda_n t}}{\lambda_l + \lambda_m - \lambda_n} c_{lmn} \varphi_n(x)
\]
(1-5)
to second order, provided that the denominator $\lambda_l + \lambda_m - \lambda_n$ is not equal to 0, i.e., that the eigenvalues are “nonresonant”. Then we can integrate (1-1) up to a cubic error term, yielding the “cubic lifespan”, i.e., initial data of size $\epsilon$ leads to a solution that exists for a time at least comparable to $\epsilon^{-2}$. This is the “normal form transformation”, first proposed by Poincaré in the setting of ordinary differential equations (see [Arnold 1983] for a book reference). Its application to partial differential equations was initiated by Shatah [1985] in the study of the nonlinear Klein–Gordon equation, and then extended to the water wave problem by Germain, Masmoudi and Shatah [Germain et al. 2012; 2015] and Ionescu and Pusateri [2015; 2018], the Burgers–Hilbert equation by Hunter, Ifrim, Tataru and Wang [Hunter et al. 2015], and more recently, the Einstein–Klein–Gordon equation by Ionescu and Pausader [2022].

Unfortunately, nonresonance fails for $L_\epsilon$ because 0 is an eigenvalue, and $0 + \lambda_n - \lambda_n = 0$. The eigenvalue 0 arises from the symmetry of (1-1). Indeed, the initial data $u_\epsilon(x + \delta) \approx u_\epsilon(x) + \delta u_\epsilon'(x)$ produces the solution
\[
f(x, t) = u_\epsilon(x + v_\epsilon t + \delta) \approx u_\epsilon(x + v_\epsilon t) + \delta u_\epsilon'(x + v_\epsilon t).
\]
In this case $g(x, t) = \delta u_\epsilon'(x)$, with $g_t = 0$, so $u_\epsilon' \in \ker L_\epsilon$. Also, the initial data $u_{\epsilon+\delta}(x) \approx u_\epsilon(x) + \delta \partial_x u_\epsilon(x)$ produces the solution
\[
f(x, t) = u_{\epsilon+\delta}(x + v_{\epsilon+\delta} t) \approx u_\epsilon(x + v_\epsilon t + \delta) \partial_x u_\epsilon(x + v_\epsilon t) + \delta v_\epsilon' t u_\epsilon'(x + v_\epsilon t).
\]
In this case $g(x, t) = \delta \partial_x u_\epsilon(x) + \delta v_\epsilon' t u_\epsilon'(x)$, so
\[
L_\epsilon g = \delta L_\epsilon \partial_x u_\epsilon = g_t = \delta v_\epsilon' u_\epsilon' \in \ker L_\epsilon,
\]
and thus $\partial_x u_\epsilon$ is in the generalized eigenspace corresponding to the eigenvalue 0.

These perturbations generate translations and variations along the bifurcation curve. We treat them separately using a more sophisticated ansatz
\[
f(x, t) = u_{\epsilon(t)}(x + a(t)) + g(x + a(t), t).
\]
We will show in Proposition 4.1 that if $|\epsilon_0|$ and $\|f - u_\epsilon_0\|_{H^2}/|\epsilon_0|$ are sufficiently small, then $f$ can always be put in the form above, with $|\epsilon - \epsilon_0|/|\epsilon_0|$ also small and the expansion of $g$ not involving any eigenvector with eigenvalue 0. This way we remove the resonance caused by the eigenvalue 0 from the evolution of $g$.

We also need to analyze the other eigenvalues of $L_\epsilon$, a first-order differential operator with variable coefficients, and a quasilinear perturbation from $L_0 = \partial_x + H$, whose eigenvectors are the Fourier modes $e^{inx}$. Just like the Schrödinger operator with potential $-\Delta + V$, with a basis of eigenvectors known as the “Jost
functions”, giving rise to the “distorted Fourier transform” (see [Agmon 1975]), $L_\epsilon$ can also be diagonalized using a combination of conjugation and perturbative analysis. More precisely, let $g = h_x$. Then

$$L_\epsilon g = ((u_\epsilon(x) - v_\epsilon)g)_x + Hg = ((u_\epsilon(x) - v_\epsilon)h_x + Hh)_x,$$

so $L_\epsilon$ is conjugate to the operator $h \mapsto (u_\epsilon(x) - v_\epsilon)h_x + Hh$. Let $h = \tilde{h} \circ \phi_\epsilon$, where $\phi'_\epsilon(x)$ is proportional to $(u_\epsilon(x) - v_\epsilon)^{-1}$. Then

$$L_\epsilon g = ((c_\epsilon \partial_x + H + R_\epsilon)\tilde{h} \circ \phi_\epsilon)_x,$$

where $c_\epsilon \to 1$ as $\epsilon \to 0$, and $R_\epsilon$ is a small smoothing remainder (i.e., it gains derivatives of arbitrarily high orders). Thus $L_\epsilon$ is conjugate to $c_\epsilon \partial_x + H + R_\epsilon$, whose eigenvalues can be approximated by those of $c_\epsilon \partial_x + H$, which are $\pm (nc_\epsilon i - i)$, $n = 1, 2, \ldots$. The general theory of unbounded analytic operators developed in [Kato 1976] allows us to justify this approximation up to $O(\epsilon^2)$ (see Corollary 3.10), and to relate the eigenvectors of $L_\epsilon$ to the Fourier modes (see Lemma 3.7), in the sense that another linear map $\tilde{h} \mapsto h$ conjugates $L_\epsilon$ into a Fourier multiplier whose action on $e^{i(n+\text{sgn} n)x}$ is multiplication by $\lambda_n$ ($n \neq 0$).

At the end of the day we have the following estimate for small $\epsilon$:

$$|\lambda_l + \lambda_m - \lambda_n| > \begin{cases} \frac{1}{2}, & l + m \neq n, \\ \frac{1}{5\epsilon^2}, & l + m = n; \end{cases}$$

see Proposition 3.11. Because this value appears in the denominator in (1-5), if $g$ has size $\delta$, a direct application of the normal form transformation yields a lifespan comparable to $\epsilon^2/\delta^2$. To improve on this, we will make use of the structure of the nonlinearity:

$$N(h, h) = \frac{1}{2}h^2 + O(|\epsilon|).$$

The first term is the usual product-style nonlinearity, which imposes the restriction $l + \text{sgn} l + m + \text{sgn} m = n + \text{sgn} n$, and implies $l + m - n = \pm 1 \neq 0$, so the normal form transformation can be carried out as before. The second term is of size $|\epsilon|$ and gains a factor of $1/|\epsilon|$ in the lifespan. Thus the usual energy estimate can show a lifespan comparable to $1/|\epsilon \delta|$, and the normal form transformation can show a lifespan comparable to $|\epsilon|/\delta^2$. This decomposition of the nonlinearity into one part satisfying classical additive frequency restrictions and another part enjoying better estimates analytically was first used by Germain, Pusateri and Rousset [Germain et al. 2018] to show global well-posedness of the 1-dimensional Schrödinger equation with potential (see also [Chen and Pusateri 2022]). Our result shows that this approach can be adapted to quasilinear equations and to the case of discrete spectrum.

1D. Outline of the paper. In Section 2 we study the traveling waves solutions for (1-1). For sake of completeness we sketch the proof of existence which follows from bifurcation theory. In addition we analyze the size of the traveling waves. In Section 3 we study the linearization of (1-1) around the traveling waves. In Section 4, we introduce a new frame of reference which will help us to avoid the resonances found in Section 3. Finally, in Section 5 we prove Theorem 1.1.
2. Traveling waves

The existence of traveling waves for (1-1) was shown in [Hunter 2018]. Here we will study their size after we give some details about the existence proof. We look for solutions of (1-1) of the form

\[ f(\epsilon, x, t) = u(\epsilon, x + \epsilon t); \]

thus we have to find \((u_\epsilon, v_\epsilon)\) solving

\[ Hu_\epsilon - v_\epsilon u_\epsilon' + u_\epsilon u_\epsilon''' = 0. \tag{2-1} \]

If \((u_\epsilon, v_\epsilon)\) is a solution, so is \((u_{n\epsilon}(x), v_{n\epsilon}(x)) = (u_\epsilon(nx)/n, v_\epsilon/n)\). Thus from one solution we can get \(n\)-fold symmetric solutions for all \(n \geq 1\).

To solve (2-1) we can apply the Crandall–Rabinowitz theorem [1971] to \(F: H^k_r(\mathbb{T}) \times \mathbb{C} \rightarrow H^{k-1}_r(\mathbb{T}), \quad (u, \mu) \mapsto Hu + uu' - (-1 + \mu)u', \)

where

\[ H^k_r(\mathbb{T}) = \{2\pi\text{-periodic, mean zero, even functions analytic in the strip } \{||\text{Im}(z)|| < r\}\}, \]

endowed with the norm

\[ \|f\|_{H^k_r(\mathbb{T})} = \sum_{\pm} \|f(\cdot \pm ir)\|_{H^k(\mathbb{T})}, \]

and

\[ H^{k,-}_r(\mathbb{T}) = \{2\pi\text{-periodic, odd functions analytic in the strip } \{||\text{Im}(z)|| < r\}\}, \]

endowed with the norm

\[ \|f\|_{H^{k,-}_r(\mathbb{T})} = \sum_{\pm} \|f(\cdot \pm ir)\|_{H^k(\mathbb{T})}. \]

Here \(\|\cdot\|_{H^k(\mathbb{T})}\) is the usual Sobolev norm, and it is enough to take \(k \geq 1\) and \(r = 1\).

We notice that \(F(0, 0) = 0\) and the derivative of \(F\) at \(u = 0, \mu = 0,\)

\[ D_u F(0, 0)h = Hh + h' \]

has a nontrivial element in its kernel belonging to \(H^{k,+}_r(\mathbb{T})\), namely, \(h = \cos(x)\).

Thus, the application of the Crandall–Rabinowitz theorem allows to show the existence of a branch of solutions \((u_\epsilon, v_\epsilon) \in (H^{1,+}_1, \mathbb{R})\), bifurcating from \((0, -1)\) for (2-1) with the leading-order term

\[ u_\epsilon(x) = \epsilon \cos(x) + O(\epsilon^2), \quad v_\epsilon = -1 + O(\epsilon). \]

We remark that we obtain a bifurcation curve

\[ \epsilon \rightarrow (u_\epsilon, v_\epsilon), \quad B_\delta = \{z \in \mathbb{C} : |z| < \delta\} \rightarrow (H^{k-1,-}_r, \mathbb{R}), \tag{2-2} \]

which is differentiable and hence analytic on \(B_\delta\) for \(\delta\) small enough.

The rest of this section is devoted to proving further properties of these solutions.
Introducing the asymptotic expansion
\[ u_\varepsilon(x) = \sum_{n=1}^{\infty} u_n(x) \varepsilon^n, \quad v_\varepsilon = \sum_{n=0}^{\infty} v_n \varepsilon^n, \quad (2-3) \]
taking \( u_1 = \cos(x), \lambda_0 = -1 \) and comparing the coefficient in \( \varepsilon^n \) we obtain that
\[ u_n' + H u_n = -v_{n-1} \sin(x) + \sum_{m=1}^{n-2} v_m u_{n-m} - \frac{1}{2} \partial_x \sum_{m=1}^{n-1} u_{n-m} u_m = -v_{n-1} \sin(x) + f_n \]
for \( n = 2, 3, \ldots \).

We notice that in order to solve the equation \( H u + u' = f \) we need \( (f, \sin(x)) = 0 \). Therefore we have to choose \( v_{n-1} = \frac{1}{\pi} (\sin(x), f_n) \). This gives us a recurrence for \( (u_n, v_{n-1}), n \geq 2, \) in terms of \( \{(u_m, v_{m-1})\}_{m=1}^{n-1} \). In order to study this recurrence we will introduce the ansatz
\[ u_n = \sum_{k=2}^{n} u_{n,k} \cos(kx). \quad (2-4) \]

By induction, one can check that the rest of coefficients in the expansion on cosines of \( u_n \) must be zero. In addition, if \( u_\varepsilon(x) \) solves \( (2-1) \), \( u_\varepsilon(x + \pi) \) is also a bifurcation curve in the direction of \( \cos(x) \), and then by uniqueness, \( u_\varepsilon(x) = u_\varepsilon(x + \pi) \), which yields \( u_{n,k} = 0 \) if \( n - k = 1 \) (mod 2).

Comparing the coefficient of \( \sin(kx) \), with \( k = n \) (mod 2), and \( 2 \leq k \leq n \), we have
\[ (1 - k) u_{n,k} + k \sum_{m=1}^{n-k} v_m u_{n-m,k} - \frac{k}{4} \sum_{m=1}^{n-1} \min(m,k-1) \sum_{l=\max(1,k-n+m)}^{n-m-k} u_{m,l} u_{n-m-k-l} - \frac{k}{2} \sum_{m=1}^{n-1} \min(m,n-m-k) \sum_{l=1}^{n-m-k} u_{m,l} u_{n-m-k+l} = 0. \quad (2-5) \]

And comparing with \( \sin(x) \) we have
\[ v_{n-1} = \frac{1}{2} \sum_{m=1}^{n-1} \min(m,n-m-1) \sum_{l=1}^{n-m-1} u_{m,l} u_{n-m-1+l}. \quad (2-6) \]

Up to order \( O(\varepsilon^4) \) we find
\[ u_\varepsilon(x) = \varepsilon \cos x - \frac{1}{2} \varepsilon^2 \cos 2x + \frac{3}{8} \varepsilon^3 \cos 3x + O(\varepsilon^4), \]
\[ v_\varepsilon = -1 - \frac{1}{4} \varepsilon^2 + O(\varepsilon^4). \quad (2-7) \]

The recurrence \( (2-5)–(2-6) \) allows us to prove the following result.

**Theorem 2.1.** The radius of convergence of the series \( (2-3) \), with the coefficients given by \( (2-4)–(2-6) \), is not bigger than \( 2/\varepsilon \).

**Proof.** From \( (2-5) \) and \( (2-6) \) we have
\[ (1 - n) u_{n,n} = \frac{1}{2} \sum_{k=1}^{n-1} (n - k) u_{k,k} u_{n-k,n-k}. \]
Let
\[ y = y(x) = x + \sum_{n=2}^{\infty} u_{n,n} x^n. \]
Then \( y - xy' = xyy'/2 \), which, together with \( y \sim x \) for small \( x \), yields \( y = 2W(x/2) \), where \( W \) is the Lambert \( W \)-function. Since the radius of convergence of \( W \) at 0 is \( 1/e \), the radius of convergence of \( y \) at 0 is \( 2/e \), so the radius of convergence of (2-5) and (2-6) is at most \( 2/e \).

In addition we can get a bound for how large the traveling wave can be.

**Theorem 2.2.** The series (2-3), with the coefficients given by (2-4)–(2-6), converges for any \( \epsilon < x^* \sim 0.23 \).

**Proof.** This proof is based on the implicit function theorem.

First we introduce the spaces

\[
L^{2,-} = \{ \text{odd functions } f \in L^2(\mathbb{T}) \},
\]

\[
H^{1,+} = \{ \text{even functions } f \in H^1(\mathbb{T}) \}.
\]

The space \( X \) is the orthogonal complement of the span of \( \cos(x) \) in \( H^{1,+} \). We will equip \( L^{2,-} \) with the norm

\[
\| u \|_{L^{2,-}}^2 = \frac{1}{\pi} \int_{-\pi}^{\pi} |u(x)|^2 \, dx
\]

in such a way that \( \| \sin(nx) \|_{L^{2,-}} = 1 \) for \( n \geq 1 \). We also define

\[
\| u \|_X^2 = \frac{1}{\pi} \int_{-\pi}^{\pi} (|u'(x)|^2 + |u(x)|^2 - 2u(x)\Lambda u(x)) \, dx.
\]

Thus \( \| \cos(nx) \|_X = n - 1 \) for \( n \geq 2 \). The reason why we take these norms is technical and it will arise below. Finally we define

\[
\mathcal{X} = X \times \mathbb{R}
\]

equipped with the norm

\[
\| (\tilde{u}, \nu) \|_\mathcal{X} = \sqrt{\| \tilde{u} \|_X^2 + |\nu|^2}.
\]

Since \( u_{\epsilon} = \epsilon \cos x - \frac{1}{2} \epsilon^2 \cos 2x + O(\epsilon^3) \) and \( v_{\epsilon} = -1 + O(\epsilon^2) \), we can let \( G(\epsilon, \tilde{u}, \mu) \)

\[
= \frac{1}{\epsilon^2} F(\epsilon \cos x - \frac{1}{2} \epsilon^2 \cos 2x + \epsilon^2 \tilde{u}, \epsilon \mu)
\]

\[
= H \tilde{u} + \epsilon \left( \cos x (\sin 2x + \tilde{u}') + \frac{1}{2} \cos 2x - \tilde{u}' \right) (\sin x - \epsilon \sin 2x - \epsilon \tilde{u}') + \tilde{u}' - \mu (\sin x - \epsilon \sin 2x - \epsilon \tilde{u}')
\]

map \( \mathbb{R} \times \mathcal{X} \) to \( L^{2,-} \).

Because of the existence of traveling waves, we already know that there exists \( \epsilon^* \) such that, for every \( \epsilon \in [0, \epsilon^*) \), there exist \( \tilde{u}_{\epsilon} \) and \( \mu_{\epsilon} \) satisfying

\[
G(\epsilon, \tilde{u}_{\epsilon}, \mu_{\epsilon}) = 0.
\]

In addition we have

\[
\frac{dG(\epsilon, \tilde{u}_{\epsilon} + s\tilde{v}, \mu + s\nu)}{ds} \bigg|_{s=0} = dG_{\epsilon, \tilde{u}_{\epsilon}, \mu}(\tilde{v}, \nu)
\]

\[
= H \tilde{v} + \epsilon \left( \tilde{v}' \cos x - \tilde{v} (\sin x - \epsilon \sin 2x - \epsilon \tilde{u}') - \epsilon \left( \frac{1}{2} \cos 2x - \tilde{u}' \right) \tilde{v}' \right)
\]

\[
+ \tilde{v}' - \nu (\sin x - \epsilon \sin 2x - \epsilon \tilde{u}') + \epsilon \mu \tilde{v}'
\]

maps \( (\tilde{v}, \nu) \in \mathcal{X} \) linearly to \( L^{2,-} \).
Thus as far as $dG_{\epsilon, \bar{u}_\epsilon, \mu_\epsilon}(\bar{u}, \mu)$ is invertible from $\mathcal{X}$ to $L^{2,-}$ for $\epsilon \in [0, x^*)$ we will be able to extend the solution $(u_\epsilon, \mu_\epsilon)$ from $[0, \epsilon^*)$ to $[0, x^*)$ by the implicit function theorem.

Note that

$$dG_{0,0,0,0}(\bar{v}, \nu) = H \bar{v} + \bar{v}' - \nu \sin x$$

is an isometry from $\mathcal{X}$ to $L^{2,-}$ under the norms given by (2-8) and (2-9). Therefore one can compute

$$dG_{\epsilon, \bar{u}_\epsilon, \mu_\epsilon} = dG_{0,0,0,0}^{-1}(\bar{v} + dG_{0,0,0,0}^{-1}(dG_{\epsilon, \bar{u}_\epsilon, \mu_\epsilon} - dG_{0,0,0,0})).$$

By the Neumann series and the fact that $dG_{0,0,0,0}$ is an isometry, $dG_{\epsilon, \bar{u}_\epsilon, \mu_\epsilon}$ will be invertible, as long as $\|dG_{\epsilon, \bar{u}_\epsilon, \mu_\epsilon} - dG_{0,0,0,0}\|_{\mathcal{X} \to L^{2,-}} < 1$. In order to show this last inequality we will bound

$$A_\epsilon := \|dG_{\epsilon, \bar{u}_\epsilon, \mu_\epsilon} - dG_{0,0,0,0}\|_{\mathcal{X} \to L^{2,-}}$$

in terms of $\|\bar{u}_\epsilon\|_{\mathcal{X}}$ and $\mu_\epsilon$. After that we will bound $\|\bar{u}_\epsilon\|_{\mathcal{X}}$ and $\mu_\epsilon$. To do it we will use the information we have about $\partial_\epsilon \bar{u}_\epsilon$ and $\partial_\epsilon \mu_\epsilon$.

Along the bifurcation curve,

$$dG_{\epsilon, \bar{u}_\epsilon, \mu_\epsilon}(\partial_\epsilon \bar{u}_\epsilon, \mu'_\epsilon)$$

$$= -\partial_\epsilon G(\epsilon, \bar{u}_\epsilon, \mu_\epsilon)$$

$$= \cos x (\sin 2x + \bar{u}_\epsilon') + \frac{1}{2} \sin x (\cos 2x - 2\bar{u}_\epsilon) - \epsilon (\cos 2x - 2\bar{u}_\epsilon) (\sin 2x + \bar{u}_\epsilon') + \mu_\epsilon (\sin 2x + \bar{u}_\epsilon').$$

(2-10)

Thus

$$(\partial_\epsilon \bar{u}_\epsilon, \mu'_\epsilon) = dG_{\epsilon, \bar{u}_\epsilon, \mu_\epsilon}^{-1} (-\partial_\epsilon G(\epsilon, \bar{u}_\epsilon, \mu_\epsilon)).$$

Therefore

$$\sqrt{\|\partial_\epsilon \bar{u}_\epsilon\|_{\mathcal{X}}^2 + \|\mu'_\epsilon\|^2} \leq \frac{1}{1 - A_\epsilon} \|\partial_\epsilon G(\epsilon, \bar{u}_\epsilon, \mu_\epsilon)\|_{L^{2,-}}.$$ (2-11)

In addition we have, for $r_\epsilon = \sqrt{\|\bar{u}_\epsilon\|_{\mathcal{X}}^2 + \|\mu_\epsilon\|^2}$, $\partial_\epsilon r_\epsilon \leq \sqrt{\|\partial_\epsilon \bar{u}_\epsilon\|_{\mathcal{X}}^2 + \|\mu'_\epsilon\|^2} \leq \frac{1}{1 - A_\epsilon} \|\partial_\epsilon G(\epsilon, \bar{u}_\epsilon, \mu_\epsilon)\|_{L^{2,-}}.$

Thus, explicit estimates for $A_\epsilon$ and $\|\partial_\epsilon G(\epsilon, \bar{u}_\epsilon, \mu_\epsilon)\|_{L^{2,-}}$ in terms of $r_\epsilon$ and $\epsilon$ give a differential inequality for $r_\epsilon$ which can be used to bound $A_\epsilon$.

We will need the following lemmas to bound $A_\epsilon$ and the norm $\|\partial_\epsilon G(\epsilon, \bar{u}_\epsilon, \mu_\epsilon)\|_{L^{2,-}}$, where $\partial_\epsilon G(\epsilon, \bar{u}_\epsilon, \mu_\epsilon)$ is given by the right-hand side of (2-10).

**Lemma 2.3.** If $f \in \mathcal{X}$ then $\|f \sin x - f' \cos x\|_{L^2} \leq \sqrt{3} \|f\|_{\mathcal{X}}$.

**Lemma 2.4.** If $f \in \mathcal{X}$ then $\|2f \sin 2x - f' \cos 2x\|_{L^2} \leq \frac{1}{2} \sqrt{17} \|f\|_{\mathcal{X}}$.

**Proof.** We only show **Lemma 2.3.** The proof of **Lemma 2.4** is similar.

Let $f = \sum_{n=2}^{\infty} f_n \cos nx$. Then

$$2(f \sin x - f' \cos x) = f_2 \sin x + 2f_3 \sin 2x + \sum_{n=3}^{\infty} n(f_{n-1} + f_{n+1}) \sin nx,$$
By Lemmas 2.3, 2.5 and 2.4 we find
\[
4\| f \sin(x) - f' \cos(x) \|^2_{L^2} = f_2^2 + 4 f_3^2 + \sum_{n=3}^{\infty} n^2 (f_{n-1} + f_{n+1})^2
\]
\[
\leq 10 f_2^2 + 20 f_3^2 + 59 f_4^2 + 88 f_5^2 + 18 f_2 f_4 + 32 f_3 f_5 + 4 \sum_{n=6}^{\infty} (n^2 + 1) f_n^2.
\]
The infinite sum is bounded by \(1.48 \sum_{n=6}^{\infty} (n-1)^2 f_n^2\), and it remains a finite-dimensional problem to show that the remaining terms are bounded by \(12 \sum_{n=2}^{5} (n-1)^2 f_n^2\).

**Lemma 2.5.** If \(f, g \in X\) then \(\|(fg)\|_{L^2} \leq B \|f\|_X \|g\|_X\), where
\[
B = \sqrt{\frac{\pi^2}{3} + \frac{869}{144}} \approx 3.05.
\]

**Proof.** Let \(f = \sum_{n=2}^{\infty} f_n \cos nx, \ g = \sum_{n=2}^{\infty} g_n \cos nx \in X\). Then
\[
(fg)' = -\frac{1}{2} \sum_{n \geq 1} n \sum_{|m| \geq 2, |n-m| \geq 2} f_{|m|} g_{|n-m|} \sin nx,
\]
so by Cauchy–Schwarz,
\[
\|(fg)\|^2_{L^2} = \frac{1}{8} \sum_{|n| \geq 1} n^2 \left( \sum_{|m| \geq 2, |n-m| \geq 2} f_{|m|} g_{|n-m|} \right)^2 \leq C \|f\|^2_X \|g\|^2_X,
\]
where
\[
C = \frac{1}{2} \sup_{n=1}^{\infty} \sum_{|m| \geq 2, |n-m| \geq 2} \frac{n^2}{(|m| - 1)^2 (|n-m| - 1)^2} = \frac{\pi^2}{3} + \frac{869}{144}.
\]

Now, with Lemmas 2.3, 2.5 and 2.4 we are ready to bound the right-hand side of (2-10). Indeed,
\[
\|\text{right-hand side of (2-10)}\|_{L^2} \leq \frac{\sqrt{10 + 4 \epsilon^2}}{4} + 2 \epsilon + \frac{\sqrt{17}}{2} \epsilon \| \tilde{u}_\epsilon \|_X + B \epsilon \| \tilde{u}_\epsilon \|^2_X + \| \tilde{u}_\epsilon \|^2_X + |\mu_\epsilon|^2.
\]
Turning to the other side, we have
\[
(dG(\epsilon, \tilde{u}_\epsilon, \mu_\epsilon) - dG(0,0,0))(\tilde{v}, \nu)
\]
\[
= \epsilon \left( \tilde{v}' \cos x - \tilde{v}(\sin x - \epsilon \sin 2x - \epsilon \tilde{u}_\epsilon') \right) - \epsilon \left( \frac{1}{2} \cos 2x - \tilde{u}_\epsilon \right) \tilde{v}' + \epsilon \nu(\sin 2x + \tilde{u}_\epsilon') + \epsilon \mu_\epsilon \tilde{v}'. \quad (2-12)
\]
Again by Lemmas 2.3, 2.5 and 2.4 we find
\[
\|\text{left-hand side of (2-12)}\|_{L^2} \leq \left( \sqrt{3} \epsilon + \sqrt{\frac{17}{4}} \epsilon^2 + B \epsilon \| \tilde{u}_\epsilon \|_X + 2 \epsilon |\mu_\epsilon| \right) \| \tilde{v} \|_X + \epsilon (1 + 2 \| \tilde{u}_\epsilon \|_X) |\nu|
\]
\[
= \epsilon \left( \sqrt{3} + 2 |\mu_\epsilon|, 1 + 2 \| \tilde{u}_\epsilon \|_X \right) \cdot (\| \tilde{v} \|_X, |\nu|) + \left( \sqrt{\frac{17}{4}} \epsilon^2 + B \epsilon^2 \| \tilde{u}_\epsilon \|_X \right) \| \tilde{v} \|_X,
\]
so
\[
A_\epsilon \leq 2 \epsilon + 2 \epsilon \epsilon + \frac{\sqrt{17}}{4} \epsilon^2 + B \epsilon^2 \epsilon.
\]
Since \(dG(0,0,0)\) is an isometry, the Neumann series \((1 - T)^{-1} = \sum_{n=0}^{\infty} T^n\) shows that if \(A_\epsilon < 1\), then
\[
dG(\epsilon, \tilde{u}_\epsilon, \mu_\epsilon) \) is invertible, and \(\|dG^{-1}(\epsilon, \tilde{u}_\epsilon, \mu_\epsilon)\| \leq (1 - A_\epsilon)^{-1}\), so
\[
\sqrt{\| \partial_\epsilon \tilde{u}_\epsilon \|_X^2 + |\mu_\epsilon'|^2} \leq \frac{1}{1 - A_\epsilon} \left( \frac{\sqrt{10 + 4 \epsilon^2}}{4} + 2 \epsilon + \frac{\sqrt{17}}{2} \epsilon \| \tilde{u}_\epsilon \|_X + B \epsilon \epsilon + \epsilon \right).
Then \( r_0 = 0 \) and
\[
r'_e \leq \frac{1}{2} \sqrt{10 + 4 \epsilon^2} + \left( 2 + \frac{\sqrt{17} \epsilon}{2} \right) r_e + B \epsilon r_e^2 + r_e^2.
\]

By the comparison principle, \( r_e \) is bounded from above by the solution to
\[
\frac{dy}{dx} = y' = \frac{\sqrt{10 + 4x^2} + (8 + 2\sqrt{17}x)y + 4Bxy^2 + 4y^2}{4 - 8x - 8xy - \sqrt{17}x^2 - 4Bx^2y},
\]
with \( y(0) = 0 \), which is
\[
(2Bx^2 + 4x)y^2 + (8x + \sqrt{17}x^2 - 4)y + x\sqrt{x^2 + 2.5 + 2.5 \sinh^{-1}(\sqrt{0.4}x) = 0.
\]
When \( x > 0 \), the quadratic coefficient and the constant are positive, so this equation has a nonnegative root if and only if
\[
8x + \sqrt{17}x^2 - 4 \leq -2\sqrt{(2Bx^2 + 4x)(x\sqrt{x^2 + 2.5 + 2.5 \sinh^{-1}(\sqrt{0.4}x))}
\]
whose solution is \( x \leq x^* \approx 0.23 \) numerically. Hence the solution can be extended to \( \epsilon = x^* \approx 0.23 \). In order to achieve this last conclusion we notice that the solution to (2-13), with \( y(0) = 0 \) can be extended only if \( A_\epsilon < 1 \), since \( 1 - A_\epsilon \) arises in the denominator.

The above argument shows that for \( \epsilon \in (-x^*, x^*) \), the bifurcation curve produces a traveling wave \( u_\epsilon = \epsilon \cos x - \frac{1}{2} \epsilon^2 \cos 2x + \epsilon^2 u_\epsilon \), which travels at speed \( v_\epsilon = -1 - \epsilon \mu_\epsilon \). Since all the operators involved are analytic in all its arguments, the bifurcation curve is analytic in \( \epsilon \) on \(( -x^*, x^*) \). It may be the case, however, that the power series for \( u_\epsilon \) and \( v_\epsilon \) around \( \epsilon = 0 \) has a smaller radius of convergence than \( x^* \) (for example, the function \( f(x) = (x^2 + 1)^{-1} \) is analytic on the whole real line, but the radius of convergence of its power series around 0 is only 1.) We now show that the radius of convergence of the power series for \( u_\epsilon \) and \( v_\epsilon \) are indeed at least \( x^* \).

We note that the above argument also works if \( \epsilon \) is replaced with \( \epsilon e^{i\alpha} (\alpha \in \mathbb{R}) \), so the bifurcation curve \( (u_\epsilon, v_\epsilon) \) is also analytic in a neighborhood of \( \{ \epsilon e^{i\alpha} : \epsilon \in (-x^*, x^*) \} \). Hence the curve is analytic in the disk of radius \( x^* \) centered at 0, so the radius of convergence of its power series around 0 is at least \( x^* \). \( \square \)

### 3. Linearization around traveling waves

In this section we will analyze the spectrum of the operator
\[
L_\epsilon g = -v_\epsilon g_x + H g + (u_\epsilon(x)g)_x
\]
corresponding to the linearization of (1-1) around the traveling wave \((u_\epsilon, v_\epsilon)\) bifurcating from zero in the direction of the cosine studied in the previous section.

Actually, let
\[
f(x, t) = f_\epsilon(x, t) + g(x + v_\epsilon t, t),
\]
with \( f_\epsilon(x, t) = u_\epsilon(x + v_\epsilon t) \). Then
\[
f_t(x, t) = \partial_t f_\epsilon(x, t) + (v_\epsilon g_x + g_t)(x + v_\epsilon t, t)
\]
and
\[(H f + ff')(x, t) = (H f_\epsilon + f_\epsilon \partial_x f_\epsilon)(x, t) + H g(x + \epsilon t, t) + \partial_x (f_\epsilon(x, t)g(x + \epsilon t, t)) + g(x + \epsilon t, t)\partial_x g(x + \epsilon t, t).\]
Putting these in (1-1), we get the equation for \(g(x, t)\)
\[\partial_t g(x, t) = -\epsilon g(x, t) + H g(x, t) + (u_\epsilon(x)g(x, t))_x + g(x, t)g(x, t)_x.
\]
The linearization around \(g = 0\) is
\[\partial_t g = L_\epsilon g,
\]
where
\[L_\epsilon g = -\epsilon g_x + H g + (u_\epsilon g)_x = \frac{H g + g_\epsilon}{L g} + \sum_{n=1}^{\infty} \epsilon^n \left(\frac{(u_\epsilon^{(n)} - v_\epsilon^{(n)})g}{L^{(n)}g}\right).
\] (3-1)

3A. The eigenvalue 0. The action of \(L\) on the Fourier modes is
\[\mathcal{F}(L g)(m) = i(m - \text{sgn} m)\hat{g}(m),\]
with eigenvalues 0 (double), \(\pm i, \pm 2i, \ldots\) (on \(L^2(\mathbb{T})\) with zero mean). We first study the perturbation of the eigenspace corresponding to the double eigenvalue of 0. By translational symmetry, for any \(\delta \in \mathbb{R}\), \(u_\epsilon(x + \delta)\) is also a solution to
\[Hu - \epsilon u + uu' = 0.
\]
Differentiation with respect to \(\delta\) then shows that
\[L_\epsilon u_\epsilon' = Hu_\epsilon' - \epsilon u_\epsilon' + (u_\epsilon u_\epsilon')' = 0.
\]
Also, since \(u_\epsilon\) lies on a bifurcation curve, we can differentiate
\[Hu_\epsilon - \epsilon u_\epsilon' + u_\epsilon u_\epsilon' = 0,
\]
with respect to \(\epsilon\) to get
\[L_\epsilon \partial_\epsilon u_\epsilon = H \partial_\epsilon u_\epsilon - (\partial_\epsilon v_\epsilon)u_\epsilon' + u_\epsilon \partial_\epsilon u_\epsilon' + u_\epsilon' \partial_\epsilon u_\epsilon = (\partial_\epsilon v_\epsilon)u_\epsilon',
\]
so on the span \(V_\epsilon\) of \(u_\epsilon'\) and \(\partial_\epsilon u_\epsilon\), \(L_\epsilon\) acts nilpotently by the matrix
\[
\begin{pmatrix}
0 & \partial_\epsilon v_\epsilon \\
0 & 0
\end{pmatrix}.
\]

3B. Simplifying the linearized operator. We want to solve the eigenvalue problem
\[L_\epsilon g = ((u_\epsilon - v_\epsilon)g)' + H g = \lambda(\epsilon)g.
\]
Let \(g = h'\). Then the antiderivative of the above is
\[(u_\epsilon - v_\epsilon)h' + H h = \lambda(\epsilon)h \pmod{1}.
\] (3-2)
Let \(h = \tilde{h} \circ \phi_\epsilon\), where \(\phi_\epsilon\) satisfies
\[\phi_\epsilon' = \frac{2\pi}{u_\epsilon - v_\epsilon} \left(\int_0^{2\pi} \frac{dy}{u_\epsilon(y) - v_\epsilon}\right)^{-1}.
\] (3-3)
(u_\epsilon - v_\epsilon)\phi_\epsilon'(\tilde{h} \circ \phi_\epsilon) + H(\tilde{h} \circ \phi_\epsilon) = \lambda(\epsilon)\tilde{h} \circ \phi_\epsilon \pmod{1}.

When \epsilon is small enough, \phi_\epsilon is a diffeomorphism of \(\mathbb{R}/2\pi \mathbb{Z}\), so

\[
2\pi \left( \int_0^{2\pi} \frac{dy}{u_\epsilon(y) - v_\epsilon} \right)^{-1} \tilde{h}' + H(\tilde{h} \circ \phi_\epsilon) \circ \phi_\epsilon^{-1} = \lambda(\epsilon)\tilde{h} \pmod{1}.
\]

By the change of variable \(z = \phi_\epsilon(y)\),

\[
H(\tilde{h} \circ \phi_\epsilon) \circ \phi_\epsilon^{-1}(x) = \frac{1}{2\pi} \int_0^{2\pi} \tilde{h}(\phi_\epsilon(y)) \cot\left( \frac{\phi_\epsilon^{-1}(x) - y}{2} \right) dy
= \frac{1}{2\pi} \int_0^{2\pi} \tilde{h}(z) \cot\left( \frac{\phi_\epsilon^{-1}(x) - \phi_\epsilon^{-1}(z)}{2} \right) (\phi_\epsilon^{-1})'(z) dz.
\]

The convolution kernel of the operator

\[
R_\epsilon \tilde{h} = H(\tilde{h} \circ \phi_\epsilon) - H \tilde{h}
\]

is

\[
K_\epsilon(x, z) = \cot\left( \frac{\phi_\epsilon^{-1}(x) - \phi_\epsilon^{-1}(z)}{2} \right) (\phi_\epsilon^{-1})'(z) - \cot\left( \frac{x - z}{2} \right)
\]

(3-4)

and the \(\epsilon\)-derivative of the kernel is

\[
\partial_\epsilon K_\epsilon(x, z) = -\csc^2\left( \frac{\phi_\epsilon^{-1}(x) - \phi_\epsilon^{-1}(z)}{2} \right) \frac{\partial_\epsilon \phi_\epsilon^{-1}(x) - \partial_\epsilon \phi_\epsilon^{-1}(z)}{2} (\phi_\epsilon^{-1})'(z)
+ \cot\left( \frac{\phi_\epsilon^{-1}(x) - \phi_\epsilon^{-1}(z)}{2} \right) \partial_\epsilon (\phi_\epsilon^{-1})'(z).
\]

Near \(x = 0\), \(\csc x - 1/x^2\) and \(\cot x - 1/x\) are smooth, and \((\phi_\epsilon^{-1})'\) is smooth everywhere, so when \(x - z\) is small enough, up to a smooth function in \((x, z)\),

\[
\frac{\partial_\epsilon K_\epsilon(x, z)}{2} = -\frac{(\partial_\epsilon \phi_\epsilon^{-1}(x) - \partial_\epsilon \phi_\epsilon^{-1}(z))(\phi_\epsilon^{-1})'(z)}{(\phi_\epsilon^{-1}(x) - \phi_\epsilon^{-1}(z))^2} + \frac{\partial_\epsilon (\phi_\epsilon^{-1})'(z)}{\phi_\epsilon^{-1}(x) - \phi_\epsilon^{-1}(z)}
= \frac{\partial_\epsilon (\phi_\epsilon^{-1})'(z) (\phi_\epsilon^{-1}(x) - \phi_\epsilon^{-1}(z)) - (\partial_\epsilon \phi_\epsilon^{-1}(x) - \partial_\epsilon \phi_\epsilon^{-1}(z))(\phi_\epsilon^{-1})'(z)}{(\phi_\epsilon^{-1}(x) - \phi_\epsilon^{-1}(z))^2}
= \frac{\partial_\epsilon (\phi_\epsilon^{-1})'(z)(x-z)^2 \int_0^1 (1-t)(\phi_\epsilon^{-1})''((1-t)z + tx) dt}{(\phi_\epsilon^{-1}(x) - \phi_\epsilon^{-1}(z))^2}
= \frac{(\phi_\epsilon^{-1})'(z)(x-z)^2 \int_0^1 (1-t)\partial_\epsilon (\phi_\epsilon^{-1})''((1-t)z + tx) dt}{(\phi_\epsilon^{-1}(x) - \phi_\epsilon^{-1}(z))^2},
\]

which is itself a smooth function of \((x, z)\) when \(x - z\) is small enough (because \(\phi_\epsilon^{-1}\) is smooth). Then

\[
\|\partial_\epsilon R_\epsilon \tilde{h}^{(m)}\|_{\tilde{H}^{k}} \lesssim_{k,m} \|\tilde{h}\|_{L^2(1)}, \quad k, m = 0, 1, \ldots.
\]
where the constant does not depend on \( \epsilon \), for all \( \tilde{h} \in H^m / (1) \), or, equivalently,

\[
\| \partial_\epsilon R_\epsilon \tilde{h} \|_{\dot{H}^k} \lesssim_{k,m} \| \tilde{h} \|_{\dot{H}^{-m}}, \quad k, m = 0, 1, \ldots,
\]

where the dot over \( H \) means that the norm does not measure frequency zero.

**Definition 3.1.** We say an operator is of class \( S \) if it satisfies (3-5). We say a family of operators is of class \( S \) uniformly if for each \( k \) and \( m \) there is an implicit constant that makes (3-5) true for all operators in the family.

Thus \( \partial_\epsilon R_\epsilon \) is of class \( S \) uniformly in \( \epsilon \). Since \( R_0 = 0 \), \( R_\epsilon / \epsilon \) is also of class \( S \) uniformly in \( \epsilon \).

Now the eigenvalue problem for \( \tilde{h} \) is of the form

\[
(c_\epsilon \partial_x + H + R_\epsilon)\tilde{h} = \lambda(\epsilon)\tilde{h} \quad \text{(mod 1)}
\]

or, equivalently,

\[
(\partial_x + c_\epsilon^{-1} H + c_\epsilon^{-1} R_\epsilon)\tilde{h} = c_\epsilon^{-1}\lambda(\epsilon)\tilde{h} \quad \text{(mod 1)}, \tag{3-6}
\]

where

\[
c_\epsilon = 2\pi \left( \int_0^{2\pi} \frac{dy}{u_\epsilon(y) - v_\epsilon} \right)^{-1} \tag{3-7}
\]

and \( R_\epsilon / \epsilon \) is of class \( S \) uniformly in \( \epsilon \). Note that since \( u_\epsilon \) and \( v_\epsilon \) are analytic functions of \( \epsilon \) on a neighborhood of 0, with \( u_0 = 0 \) and \( v_0 = -1 \), so are \( \phi_\epsilon, R_\epsilon \) and \( c_\epsilon \) with \( \phi_0 = I, R_0 = 0 \) and \( c_0 = 1 \).

**3C. Spectral analysis of the linearization.** The eigenvalue problem (3-6) is a perturbation of the eigenvalue problem

\[
\tilde{h}' + H\tilde{h} = \lambda\tilde{h} \quad \text{(mod 1)},
\]

with explicit eigenvalues

\[
0 \quad \text{(double), } \quad ni, \quad n = \pm 1, \pm 2, \ldots,
\]

and eigenfunctions

\[
e^{\pm i x}, \quad e^{i(n+\text{sgn}n)x}, \quad n = \pm 1, \pm 2, \ldots.
\]

They form an orthogonal basis of \( H^k / (1) \) for any nonnegative integer \( k \).

**Definition 3.2.** Let \( T : \dot{H}^k (\mathbb{T}) \to \dot{H}^k (\mathbb{T}) \) for \( k \in \mathbb{N} \) be a linear operator. We will define

\[
\| T \| := \| T \|_{\dot{H}^k (\mathbb{T}) \to \dot{H}^k (\mathbb{T})}.
\]

The resolvent \( (\partial_x + H - z)^{-1} \) is also a Fourier multiplier whose action on Fourier modes is

\[
(\partial_x + H - z)^{-1} e^{\pm i(n+1)x} = (\pm ni - z)^{-1} e^{\pm i(n+1)x}, \quad n = 0, 1, \ldots. \tag{3-8}
\]

The circle

\[
\Gamma_n = \{ z : |z - ni| = \frac{1}{2} \}, \quad n = \pm 1, \pm 2, \ldots,
\]

encloses a single eigenvalue \( \pm ni \), and the circle

\[
\Gamma_0 = \{ z : |z| = \frac{1}{2} \}
\]
encloses the double eigenvalue 0. On \( \Gamma_n \) and \( \Gamma_0 \) we have
\[
|z - m\i| \geq \frac{1}{2}, \quad m \in \mathbb{Z}, \tag{3-9}
\]
so by (3-8),
\[
\|(\partial_x + H - z)^{-1}\| \leq 2, \quad z \in \Gamma_n, \ n \in \mathbb{Z}. \tag{3-10}
\]
Moreover the projection
\[
P_n = -\frac{1}{2\pi i} \int_{\Gamma_n} (\partial_x + H - z)^{-1} \, dz, \quad n = \pm 1, \pm 2, \ldots,
\]
is the projection on the span of \( e^{i(n+\text{sgn})x} \) and the projection
\[
P_0 = -\frac{1}{2\pi i} \int_{\Gamma_0} (\partial_x + H - z)^{-1} \, dz
\]
is the projection on the span of \( e^{ix} \) and \( e^{-ix} \).

Now when \( \epsilon \) is small enough and \( z \in \Gamma_n \), we have
\[
\partial_x + c_{\epsilon}^{-1}H + c_{\epsilon}^{-1}R_{\epsilon} - z = (\partial_x + H - z)(1 + (\partial_x + H - z)^{-1}R'_{\epsilon}),
\]
where
\[
R'_{\epsilon} = (\partial_x + c_{\epsilon}^{-1}H + c_{\epsilon}^{-1}R_{\epsilon}) - (\partial_x + H) = (c_{\epsilon}^{-1} - 1)H + c_{\epsilon}^{-1}R_{\epsilon} \tag{3-11}
\]
is analytic in \( \epsilon \) near 0, with \( R'_{\epsilon} = 0 \), thanks to the analyticity of \( c_{\epsilon} \). Taking the inverse gives
\[
(\partial_x + c_{\epsilon}^{-1}H + c_{\epsilon}^{-1}R_{\epsilon} - z)^{-1} = (1 + (\partial_x + H - z)^{-1}R'_{\epsilon})^{-1}(\partial_x + H - z)^{-1}
\]
and the Neumann series
\[
(1 + (\partial_x + H - z)^{-1}R'_{\epsilon})^{-1} = \sum_{n=0}^{\infty} ((\partial_x + H - z)^{-1}R'_{\epsilon})^n \tag{3-12}
\]
converges because
\[
\|(\partial_x + H - z)^{-1}R'_{\epsilon}\| \leq 2\|R'_{\epsilon}\| \lesssim k \epsilon < 1
\]
when \( \epsilon \) is small enough (depending on \( k \)). Moreover,
\[
\|(1 + (\partial_x + H - z)^{-1}R'_{\epsilon})^{-1} - I\| \lesssim k \epsilon
\]
and so
\[
\|(\partial_x + c_{\epsilon}^{-1}H + c_{\epsilon}^{-1}R_{\epsilon} - z)^{-1} - (\partial_x + H - z)^{-1}\| \lesssim \epsilon
\]
uniformly for \( z \in \Gamma_n \). Hence the projections
\[
Q_n(\epsilon) = -\frac{1}{2\pi i} \int_{\Gamma_n} (\partial_x + c_{\epsilon}^{-1}H + c_{\epsilon}^{-1}R_{\epsilon} - z)^{-1} \, dz, \quad n \in \mathbb{Z}, \tag{3-13}
\]
exist and satisfy
\[
\|Q_n(\epsilon) - P_n\| \lesssim k \epsilon, \quad n \in \mathbb{Z}, \tag{3-14}
\]
uniformly in \( n \). Then by [Kato 1976, Chapter I, Section 4.6], when \( \epsilon \) is small enough, \( Q_n(\epsilon) \) is conjugate to \( P_n \). Thus \( \dim \text{ran } Q_n(\epsilon) = 1 \) for \( n \neq 0 \) and \( \dim \text{ran } Q_0(\epsilon) = 2 \). So \( \partial_x + c_{\epsilon}^{-1}H + c_{\epsilon}^{-1}R_{\epsilon} \) has a single
eigenvalue enclosed by $\Gamma_n$ for $n \neq 0$. In Section 3A we showed that the action on the range of $Q_0(\epsilon)$ is given by a nonzero nilpotent 2-by-2 matrix. If $z$ is outside all these circles, then (3-10) still holds and the Neumann series (3-12) still converges to show that $\partial_x + c_\epsilon^{-1} H + c_\epsilon^{-1} R_\epsilon - z$ is invertible, so it has no other eigenvalues.

3D. Analyticity of eigenvalues and eigenvectors. By (3-8) and (3-9), $(\partial_x + H - z)^{-1}$ is analytic in $(z, \epsilon)$ for $z$ in a neighborhood $U$ of $\bigcup_{n \in \mathbb{Z}} \Gamma_n$, and $\epsilon$ near 0. By (3-11), $R_\epsilon'$ is analytic in $\epsilon$ near 0, so the series (3-12) shows that $(\partial_x + c_\epsilon^{-1} H + c_\epsilon^{-1} R_\epsilon - z)^{-1}$ is analytic in $(z, \epsilon)$ for $z \in U$ and $\epsilon$ near 0, and the integral (3-13) shows that all the projections $Q_n(\epsilon)$ ($n \in \mathbb{Z}$) are analytic in a neighborhood of 0 independent of $n$.

Let $\psi_n(\epsilon)$ be the corresponding eigenvectors to $Q_n(\epsilon)$ for $n \neq 0$. Thanks to (3-14), a good choice is $\psi_n(\epsilon) = Q_n(\epsilon)e^{i(n + \text{sgn} n)x}$, which is nonzero and analytic in a neighborhood of 0 independent of $n$. Then by (3-6),

$$Q_n(\epsilon)(\partial_x + c_\epsilon^{-1}(H + R_\epsilon))e^{i(n + \text{sgn} n)x} = (\partial_x + c_\epsilon^{-1}(H + R_\epsilon))\psi_n(\epsilon) = c_\epsilon^{-1}\lambda_n(\epsilon)\psi_n(\epsilon).$$

On the other hand, the left-hand side equals

$$(n + \text{sgn} n)iQ_n(\epsilon)e^{i(n + \text{sgn} n)x} + c_\epsilon^{-1}Q_n(\epsilon)(H + R_\epsilon)e^{\pm i(n + \text{sgn} n)x},$$

which is another vector analytic in $\epsilon$ near 0. Then by the next lemma, all the eigenvalues $c_\epsilon^{-1}\lambda_n(\epsilon)$, and hence $\lambda_n(\epsilon)$, are analytic in a neighborhood of 0 independent of $n$.

Lemma 3.3. Let $u(\epsilon)$ and $v(\epsilon)$ be two vectors analytic in $\epsilon \in U$ satisfying

$$u(\epsilon) \neq 0 \quad \text{and} \quad v(\epsilon) = \lambda(\epsilon)u(\epsilon), \quad \epsilon \in U.$$ 

Then $\lambda(\epsilon)$ is analytic in $\epsilon \in U$.

Proof: Without loss of generality assume that $0 \in U$. Since the result is local in $\epsilon$, it suffices to show that $\lambda(\epsilon)$ is analytic in a smaller neighborhood of 0.

Since $u(0) \neq 0$, we can find a linear functional $f$ such that $f(u(0)) \neq 0$. Then $f(u(\epsilon)) \neq 0$ in a neighborhood of 0, and so

$$\lambda(\epsilon) = \frac{f(v(\epsilon))}{f(u(\epsilon))}$$

is analytic in a neighborhood of 0.

Regarding the double eigenvalue 0, in Section 3A we showed that $u_\epsilon'$ and $\partial_\epsilon u_\epsilon$ are two generalized eigenvectors of the operator $L_\epsilon$. Using the relation given in Section 3B, they correspond to two generalized eigenvectors $\psi_0^-(\epsilon)$ and $\psi_0^+(\epsilon)$ of the operator $\partial_x + c_\epsilon^{-1} H + c_\epsilon^{-1} R_\epsilon$, via the relation $(\psi_0^-(\epsilon) \circ \phi_\epsilon)' = u_\epsilon'$ and $(\psi_0^+(\epsilon) \circ \phi_\epsilon)' = \partial_\epsilon u_\epsilon$. Then clearly $\psi_0^\pm(\epsilon)$ are both analytic in $\epsilon$.

From the analyticity of the eigenvalues $c_\epsilon^{-1}\lambda_n(\epsilon)$, it is easy to derive bounds on their Taylor coefficients.

Proposition 3.4. For $k \geq 1$ and $n \neq 0$, the coefficient of $\epsilon^k$ in $c_\epsilon^{-1}\lambda_n(\epsilon)$ is bounded in absolute value by $C^k$ for a constant $C > 0$ independent of $n$. 
Proof. At the end of Section 3C we showed that when \( \epsilon \) is in a neighborhood of 0 independent of \( n \), the eigenvalues \( c_\epsilon^{-1}\lambda_n(\epsilon) \) are enclosed in the circle \( \Gamma_n \). Then

\[
|c_\epsilon^{-1}\lambda_n(\epsilon) - ni| < \frac{1}{\epsilon}, \quad n = \pm 1, \pm 2, \ldots
\]

The result follows from Cauchy’s integral formula for Taylor coefficients. \( \square \)

Corollary 3.5. For \( k \geq 0 \) and \( n \neq 0 \), the coefficient of \( \epsilon^k \) in \( \lambda_n(\epsilon) \) is bounded in absolute value by \( |n|C^k \) for a constant \( C > 0 \) independent of \( n \).

Proof. Since \( c_\epsilon \) is analytic in \( \epsilon \) near 0 with \( c_0 = 1 \), and \( \lambda_n(0) = ni \), the result follows from Leibniz’s rule. \( \square \)

3E. Conjugation to a Fourier multiplier. We have conjugated the eigenspaces of \( T = \partial_x + c_\epsilon^{-1}H + c_\epsilon^{-1}R_\epsilon \) (and also of \( c_\epsilon \partial_x + H + R_\epsilon \)) to Fourier modes via the operator

\[
1 + W_\epsilon = \sum_{n \in \mathbb{Z}} P_n Q_n(\epsilon),
\]

where \( P_0 \) is the projection onto the span of \( e^{\pm ix} \), \( Q_0(\epsilon) \) is the projection onto the span of \( \psi_0^\pm(\epsilon) \), \( P_n \) is the projection onto the span of \( e^{i(n + \text{sgn} n)x} \), and \( Q_n(\epsilon) \) is the projection onto the span of \( \psi_n(\epsilon) \), \( n = \pm 1, \pm 2, \ldots \).

We will view \( T \) as a perturbation of \( \partial_x + c_\epsilon^{-1}H \) and follow the proof of [Kato 1976, Chapter V, Theorem 4.15a]. In the process we will extract more information from the fact that \( R_\epsilon \) is of class \( S \). Since

\[
P_n^2 = P_n, \quad \sum_{n \in \mathbb{Z}} P_n = 1, \quad \text{(3-15)}
\]

we have

\[
W_\epsilon = \sum_{n \in \mathbb{Z}} P_n (Q_n(\epsilon) - P_n) \quad \text{(3-16)}
\]

and \( W_0 = 0 \).

Proposition 3.6. \( W_\epsilon/\epsilon \) is of class \( S \) uniformly in \( \epsilon \).

Proof. We bound each term on the right-hand side separately. By [Kato 1976, Chapter V, (4.38)],

\[
Q_n(\epsilon) - P_n = -c_\epsilon^{-1}Q_n(\epsilon)R_\epsilon Z_n(\epsilon) - c_\epsilon^{-1}Z_n'(\epsilon)R_\epsilon P_n,
\]

where

\[
Z_n(\epsilon) = \frac{1}{2\pi i} \int_{\Gamma_n} (z - (n + (1 - c_\epsilon^{-1}) \text{sgn} n)i)^{-1}(\partial_x + c_\epsilon^{-1}H - z)^{-1} dz,
\]

\[
Z_n'(\epsilon) = \frac{1}{2\pi i} \int_{\Gamma_n} (z - c_\epsilon^{-1}\lambda_n(\epsilon))^{-1}(T - z)^{-1} dz.
\]

We now bound the operator norms of the right-hand side, with uniformity in \( \epsilon \) and decay in \( n \), in order to show that the sum in \( n \) converges.

First note that it is clear from the frequency side that when \( \epsilon \) is in a neighborhood of 0 independent of \( n \) and \( z \in \bigcup_{n \in \mathbb{Z}} \Gamma_n \) for all \( m \geq 0 \), the operator \( (\partial_x + c_\epsilon^{-1}H - z)^{-1} \) is bounded from \( H^m \) to \( H^m \), uniformly in \( \epsilon \) and \( z \). Since \( R_\epsilon/\epsilon \) is of class \( S \) uniformly in \( \epsilon \) (see (3-5) and notice that \( R_0 = 0 \)), it follows from the Neumann series that \( \|(T - z)^{-1}\|_{H^m \to H^m} \) is finite and only depends on \( m \). Since \( |z - (n + (1 - c_\epsilon^{-1}) \text{sgn} n)i| \) and \( |z - c_\epsilon^{-1}\lambda_n(\epsilon)| \) are uniformly bounded from below, both \( Z_n(\epsilon) \) and \( Z_n'(\epsilon) \) are bounded from \( \hat{H}^m \)
to $\dot{H}^m$, uniformly in $\epsilon$ and $n$. Since $Q_n(\epsilon)$ is given by a similar integral (3-13), it also has this property, which is also trivially true for $P_n$. Now, for all $n, m, k \in \mathbb{Z}$, $m, k \geq 0$ and $\tilde{h} \in L^2$,

$$
\|Z_n(\epsilon)R_\epsilon P_n\tilde{h}\|_{\dot{H}^k} \lesssim_{n,k} \|R_\epsilon P_n\tilde{h}\|_{\dot{H}^k} \lesssim_{m,k} \|\epsilon\| \|P_n\tilde{h}\|_{\dot{H}^{-m-2}}
$$

because $P_n$ is the projection onto very specific Fourier modes. For the first term we have

$$
\|R_\epsilon Z_n(\epsilon)\tilde{h}\|_{\dot{H}^k} \lesssim_{n,k} \|Z_n(\epsilon)\tilde{h}\|_{\dot{H}^{-m}} \lesssim_{m,k} \|\epsilon\| \|\tilde{h}\|_{\dot{H}^{-m}}.
$$

To introduce the action of $Q_n(\epsilon)$, note that the image of $Q_n(\epsilon)$ lies in the eigenspace of the operator $c_\epsilon \partial_x + H + R_\epsilon$, with eigenvalue $\lambda_n(\epsilon)$, so for $n \neq 0$ and $u \in \text{Im} Q_n(\epsilon)$ we have

$$
u = \lambda_n(\epsilon)^{-1}(c_\epsilon u' + Hu + R_\epsilon u),$$

so $\|u\|_{\dot{H}^k} \lesssim |\lambda_n(\epsilon)|^{-1}\|u\|_{\dot{H}^{k+1}} \lesssim |n|^{-1}\|u\|_{\dot{H}^{k+1}}$. Hence

$$
\|Q_n(\epsilon)R_\epsilon Z_n(\epsilon)\|_{\dot{H}^k} \lesssim_n n^{-2}\|R_\epsilon Z_n(\epsilon)\|_{\dot{H}^{k+2}} \lesssim_{m,k} \|\epsilon\|(1 + |n|)^{-2}\|\tilde{h}\|_{\dot{H}^{-m}}.
$$

This also holds for $n = 0$ because $R_\epsilon/\epsilon$ is of class $S$ uniformly, so $W_\epsilon/\epsilon$ is of class $S$ uniformly in $\epsilon$ thanks to the convergence of $\sum_{n \in \mathbb{Z}} (1 + |n|)^{-2}$.

Now for $k = 0, 1, \ldots$, there is a neighborhood of 0 such that when $\epsilon$ is in this neighborhood, $\|W_\epsilon\|_{\dot{H}^k} < 1$, so $1 + W_\epsilon : \dot{H}^k \to \dot{H}^k$ is invertible. By (3-15) and (3-16) it follows easily that

$$
(1 + W_\epsilon)Q_n(\epsilon) = P_n(1 + W_\epsilon),
$$

so the eigenspace of $T$ is conjugated to the (span of) Fourier modes, and hence $T$ is conjugated to a Fourier multiplier.

We have proven the following lemma:

**Lemma 3.7.** For $\epsilon$ small enough, there exists an operator $W_\epsilon$ such that $W_\epsilon/\epsilon$ is of class $S$, uniformly in $\epsilon$. Moreover:

1. $1 + W_\epsilon : \dot{H}^k \to \dot{H}^k$ is invertible.
2. $(1 + W_\epsilon)Q_n(\epsilon) = P_n(1 + W_\epsilon), \ n \in \mathbb{Z}$.
3. If $\psi$ is in the closed linear span of the eigenvectors $\psi_n(\epsilon) \ (n \neq 0)$ of $c_\epsilon \partial_x + H + R_\epsilon$, then

$$
(1 + W_\epsilon)(c_\epsilon \partial_x + H + R_\epsilon)\psi = \Lambda_\epsilon(1 + W_\epsilon)\psi,
$$

where $\Lambda_\epsilon$ is a multiplier such that

$$
\Lambda_\epsilon e^{i(n + \text{sgn} n)x} = \lambda_n(\epsilon)e^{i(n + \text{sgn} n)x}, \quad n = \pm 1, \pm 2, \ldots.
$$

3F. **Taylor expansion of eigenvalues.** Now we Taylor expand the eigenvalues $\lambda_n(\epsilon)$ for $n \neq 0$. To do so it is more convenient to study the eigenvalue problem (3-2) for $h$:

$$
L_\epsilon g := ((u_\epsilon - v_\epsilon)g)' + Hg = \lambda(\epsilon)g.
$$
Recall the operator $L = L_0 = \partial_x + H$ whose action on the Fourier modes is

$$\mathcal{F}(Lg)(m) = i(m - \text{sgn } m)\hat{g}(m),$$

with eigenvalues $0$ (double), $\pm i$, $\pm 2i$, $\ldots$ ($g$ mean zero).

Since $(u_\epsilon, v_\epsilon)$ is analytic in $\epsilon$ on a neighborhood of $0$, and

$$\|h'\|_{L^2} \leq \|h' + Hh\|_{L^2} + \|Hh\|_{L^2} = \|Lh\|_{L^2} + \|h\|_{L^2},$$

by [Kato 1976, Chapter VII, Theorem 2.6], $L_\epsilon$ is a holomorphic family of operators of type (A), so by Chapter VII, Section 2.3, all the results in Chapter II, Sections 1 and 2 apply, and we can compute the Taylor coefficients of $\lambda(\epsilon)$ as if $L_\epsilon$ acted on a finite-dimensional vector space.

We start with computing the resolvent of $L$,

$$R(z) = (L - z)^{-1}$$

whose action on the Fourier modes is

$$\mathcal{F}(R(z)g)(m) = (i(m - \text{sgn } m) - z)^{-1}\hat{g}(m).$$

Around the eigenvalue $ni$ ($n = \pm 1, \pm 2, \ldots$) we have the expansion

$$R(z) = (ni - z)^{-1}P_n + \sum_{k=0}^{\infty} (z - ni)^k \hat{g}^{k+1}_n,$$

where $P_n$ is the projection on the span of $e^{i(n + \text{sgn } n)x}$ and

$$\mathcal{F}(S_ng)(m) = \frac{\hat{g}(m)}{i(m - \text{sgn } m - n)}, \quad m \neq n + \text{sgn } n. \quad (3-20)$$

By [Kato 1976, (II.2.33)],

$$\lambda_n(\epsilon) = ni + \sum_{k=1}^{\infty} e^{k\lambda_n^{(k)}}(\epsilon), \quad n = \pm 1, \pm 2, \ldots,$$

where

$$\lambda_n^{(k)} = \sum_{p=1}^{k} \frac{(-1)^p}{p} \sum_{v_1 + \cdots + v_p = n, v_j \geq 1} \text{Tr } L^{(v_p)} S_n^{(h_p)} \cdots L^{(v_1)} S_n^{(h_1)},$$

where $S_n^{(0)} = -P_n$ and, for $h \geq 1$, $S_n^{(h)} = S_n^{h}$, with $S_n$ defined in $(3-20)$, and $L^{(v)}$ is the coefficient of $\epsilon^v$ in the Taylor expansion of $L_\epsilon$. Note that the constraints in the summation imply that there is some $j \in \{1, \ldots, p\}$ such that $h_j = 0$ and so $S_n^{(h_j)} = -P_n$, so every summand is a finite-rank operator whose trace is thus well-defined.

**Lemma 3.8.** If $A$ is a finite-rank operator, then $\text{Tr } AB = \text{Tr } BA$.

**Proof.** By linearity we can assume $A$ has the form $A(\cdot) = f(\cdot)v$ for some (not necessarily continuous) linear functional $f$. Then $\text{Tr } A = f(v)$. Since $AB(\cdot) = f(B(\cdot))v$ and $BA(\cdot) = f(\cdot)Bv$, it follows that $\text{Tr } AB = f(Bv) = \text{Tr } BA$. \[\square\]
Using the lemma above, we can simplify the sum in \( \lambda_n^{(k)} \) a little. Indeed, there are \( p \) circular rotations of the tuple \((h_1, \ldots, h_p)\). Since \((\sum_j h_j, p) = 1\), the \( p \) circular rotations are all distinct, so we can choose the lexicographically smallest one as a representative. For such a representative, \( h_1 = \min_j h_j = 0 \), so \( S^{(h_1)} = -P_n \), and thus we only need to act \( L^{(v_p)} S_n^{(h_p)} \cdots L^{(v_1)}\) on \( e^{i(n+\text{sgn} n)x} \) and take the \((n + \text{sgn} n)\)-th mode to compute the trace. Thus

\[
\lambda_n^{(k)} = \sum_{p=1}^{k} (-1)^{p-1} \sum_{v_1 + \cdots + v_p = k, \; v_j \geq 1 \atop h_1 + \cdots + h_p = p-1} \mathcal{F}[L^{(v_p)} S_n^{(h_p)} \cdots L^{(v_1)} e^{i(n+\text{sgn} n)x}](n + \text{sgn} n), \tag{3-21}
\]

Let us compute some terms \( \lambda_n^{(k)} \) by using the formula (3-21). We have

\[
\lambda_n^{(1)} = \text{Tr} L^{(1)} P_n = 0
\]
because \( L_1 \) shifts the mode by 1, and

\[
\lambda_n^{(2)} = \text{Tr}(L^{(2)} P_n - L^{(1)} S_n L^{(1)} P_n).
\]

Put \( s = \text{sgn} n \). We extract the \((n + s)\)-th mode of each term:

\[
\text{Tr} L^{(2)} P_n = \mathcal{F}[L^{(2)} 2e^{i(n+s)x}](n + s) = \frac{i(n+s)}{4},
\]

\[
L^{(1)} S_n L^{(1)} e^{i(n+s)x} = \frac{i L^{(1)} S_n}{2}((n + s + 1)e^{i(n+s+1)x} + (n + s - 1)e^{i(n+s-1)x})
\]

\[
= \frac{L^{(1)} }{2}((n + s + 1)e^{i(n+s+1)x} - (n + s - 1)e^{i(n+s-1)x}),
\]

\[
\text{Tr} L^{(1)} S_n L^{(1)} P_n = \frac{i(n+s+1)(n+s) - i(n+s-1)(n+s)}{4} = \frac{i(n+s)}{2},
\]

so

\[
\lambda_n^{(2)} = \frac{i(n+s)}{4} - \frac{2i(n+s)}{4} = -\frac{i(n+s)}{4}.
\]

We can further compute that

\[
\lambda_n(\epsilon) = in - \frac{e^2 i(n+s)}{4} - \frac{11\epsilon^4 i(n+s)}{32} - \frac{527i\epsilon^6(n+s)}{768} + O(\epsilon^7)
\]

for \( n = \pm 1, \pm 2, \pm 3, \ldots \).

**Proposition 3.9.** For \( n = \pm 1, \pm 2, \ldots \),

\[
\lambda_n^{(k)} = \begin{cases} 
0, & 2 \nmid k, \\
2i c^{(k)}(n + \text{sgn} n), & k \leq 2|n| + 2,
\end{cases}
\]

where \( c^{(k)} \) is the \( k \)-th Taylor coefficient of \( c_\epsilon \) as defined in (3-7).

When \( k \geq 2|n| + 4 \), \( \lambda_n^{(k)} \) is still purely imaginary but the formula \( \lambda_n^{(k)} = ic^{(k)}(n + \text{sgn} n) \) does not hold in general.
Proof. Firstly we notice that, for \( n = \pm 1 \), the coefficient of \( \epsilon^6 \) in \( \lambda_{\pm 1}(\epsilon) \) is

\[
\lambda_1(\epsilon) = i - \frac{\epsilon^2 i}{2} - \frac{11\epsilon^4 i}{16} - \frac{529\epsilon^6 i}{384} + O(\epsilon^7),
\]

which does not hold for \( \lambda_{\pm 1}^{(6)} = \pm 2ic^{(6)} \).

Next, we prove the fist part of the lemma. In each summand of (3-21), all the coefficients are real, except that each operator \( L \) brings a factor of \( i \) to the Fourier coefficients (via the operator \( \partial_x \)), and each operator \( S_n \) removes a factor of \( i \) (see (3-20)). Hence each summand is purely imaginary, and so is \( \lambda_n^{(k)} \).

In each summand of (3-21), the operator \( S_n^{(h_p)} \) is a Fourier multiplier that does not shift the modes, while the operator \( L^{(m)}g = ((u^{(m)} - v^{(m)})g) \) shifts the modes by at most \( m \) because \( u^{(m)} \) only contains modes up to \( e^{\pm i mx} \). Also the amount of shift is equal to \( m \) (mod 2). Thus when acting the sequence \( L^{(v_1)}S_n^{(h_p)} \cdots L^{(v_i)} \) on \( e^{i(n+s)x} \), the mode is consecutively shifted by at most \( v_1, v_2, \ldots, v_p \), and the total amount of shift is equal to \( \sum_j v_j = k \) (mod 2). Since in the end we are taking the \( (n+s) \)-th mode, the total amount of shift must be 0 in order to count, so when \( k \) is odd \( \lambda_n^{(k)} = 0 \). When \( k \) is even, the mode \( e^{i(n+s)x} \) can only be shifted as far as \( e^{i(n+s\pm k/2)x} \), otherwise it can never be shifted back. Hence when \( k \leq 2|n| + 2 = 2|n + s| \), the frequency always has the same sign as \( n \) or becomes 0. In the former case we can take \( \text{sgn} m = \text{sgn} n \) in (3-20), while in the latter case the derivative in \( L \) kills it, so it does not hurt if we still take \( \text{sgn} m = \text{sgn} n \) in (3-20). Either way we can take \( \text{sgn} m = \text{sgn} n \) in (3-20). Thus the action of \( S_n \) is the same as that of \( S'_n \), where

\[
\mathcal{F}(S'_n g)(m) = \frac{\hat{g}(m)}{i(m - n - \text{sgn} n)}, \quad m \neq n + \text{sgn} n.
\]

For \( n > 0 \), the operator \( S'_n \) is the analog of \( S_n \) for \( L^+ \), with

\[
\mathcal{F}(L^+ g)(m) = i(m - 1)\hat{g}(m),
\]

i.e., \( L^+ g = g' - ig \). Hence \( \lambda_n^{(k)} \) remains the same if we replace \( L \) with \( L^+ \). Now we have

\[
L^+_\epsilon g := L^+ g + \sum_{n=1}^{\infty} \epsilon^n L^{(n)} g = -v_\epsilon g' - ig + (u_\epsilon g)' = ((u_\epsilon - v_\epsilon)g)' - ig,
\]

whose eigenvalue problem is

\[
((u_\epsilon - v_\epsilon)g)' - ig = \lambda^+_\epsilon g.
\]

Using the same change of variable as in Section 3B, the problem above can be transformed to

\[
\tilde{h}' - ic_\epsilon^{-1} \tilde{h} = c_\epsilon^{-1} \lambda^+_\epsilon \tilde{h},
\]

whose eigenvalues are

\[
\lambda_n^{+}(\epsilon) = n' c_\epsilon i - i.
\]

Since when \( \epsilon \to 0 \), \( \lambda_n(\epsilon) \to ni \) and \( c_\epsilon \to 1 \), we must have \( n' = n + 1 \), and so

\[
\lambda_n(\epsilon) = (n + 1)c_\epsilon i - i + O_n(\epsilon^{2n+4}).
\]

For \( n < 0 \), note that since \( L \) preserves real-valued functions, its eigenvalues come in conjugate pairs, so \( \lambda_n(\epsilon) = \overline{\lambda_{|n|}(\epsilon)} = -\lambda_{|n|}(\epsilon) \) has the same property. \( \square \)
Corollary 3.10. When $|\epsilon|$ is small enough,

$$|\lambda_n(\epsilon) - (n + \text{sgn } n) c_\epsilon i + i \text{ sgn } n| < |n|(Ce)^{2|n|+4} < C'\epsilon^6, \quad n \in \mathbb{Z}\setminus\{0\},$$

$$|\lambda_n'(\epsilon) - (n + \text{sgn } n) \partial_\epsilon c_\epsilon i| < |n|(Ce)^{2|n|+3} < C'\epsilon^5, \quad n \in \mathbb{Z}\setminus\{0\},$$

for some constant $C, C' > 0$ independent of $n$.

Proof. By Proposition 3.9, the Taylor expansions of $\lambda_n(\epsilon)$ and $(n + \text{sgn } n)c_\epsilon i - i \text{ sgn } n$ differ only from the term $\epsilon^{2|n|+4}$. By Corollary 3.5, the error terms of the former sum up to $O\left(|n| \sum_{k=2|n|+4}^\infty (Ce)^k\right) = O\left(|n|(Ce)^{2|n|+4}\right)$ if, say, $C|\epsilon| < \frac{1}{2}$. The error term of the latter clearly also satisfy this bound.

To extend the chain of inequalities it suffices to note that $|n|(Ce)^{2|n|−2}$ is uniformly bounded for $n \neq 0$ if $|C\epsilon| < \frac{1}{2}$.

\[\square\]

3G. Time resonance analysis. For $m, n$ and $l \in \mathbb{Z}$ we consider

$$\lambda_m(\epsilon) + \lambda_n(\epsilon) + \lambda_l(\epsilon) = (m + n + l)c_\epsilon i + (\text{sgn } m + \text{sgn } n + \text{sgn } l)(c_\epsilon - 1)i + O(\epsilon^6).$$

Proposition 3.11. If $m, n, l \in \mathbb{Z}$ and $mnl \neq 0$, then when $\epsilon$ is small enough, $|\lambda_m(\epsilon) + \lambda_n(\epsilon) + \lambda_l(\epsilon)| > \frac{1}{2}\epsilon^2$.

Proof. By (3-7) and (2-7),

$$\frac{c_\epsilon}{2\pi} = \left(\int_0^{2\pi} \frac{dy}{u_\epsilon(y) - v_\epsilon}\right)^{-1} = \left(\int_0^{2\pi} \frac{dy}{1 + \epsilon \cos y - \frac{1}{2}\epsilon^2 \cos 2y + \frac{1}{4}\epsilon^2}\right)^{-1} + O(\epsilon^3)$$

$$= \left(\int_0^{2\pi} (1 - \epsilon \cos y + \epsilon^2 \cos^2 y + \frac{1}{2}\epsilon^2 \cos 2y - \frac{1}{4}\epsilon^2) dy\right)^{-1} + O(\epsilon^3).$$

$$c_\epsilon = (1 + \frac{1}{4}\epsilon^2)^{-1} + O(\epsilon^3) = 1 - \frac{1}{4}\epsilon^2 + O(\epsilon^3).$$

We distinguish three cases.

Case 1: $m + n + l \neq 0$. Then $|m + n + l| \geq 1$. Since $c_\epsilon - 1 \lesssim \epsilon^2$,

$$\lambda_m(\epsilon) + \lambda_n(\epsilon) + \lambda_l(\epsilon) = (m + n + l)c_\epsilon i + O(\epsilon^2).$$

Since $c_\epsilon \to 1$ as $\epsilon \to 0$, we have $|\lambda_m(\epsilon) + \lambda_n(\epsilon) + \lambda_l(\epsilon)| > \frac{1}{2}|m + n + l|$ for small $\epsilon$.

Case 2: $m + n + l = 0$ and $mnl \neq 0$. Then

$$\lambda_m(\epsilon) + \lambda_n(\epsilon) + \lambda_l(\epsilon) = -\frac{1}{4}(\text{sgn } m + \text{sgn } n + \text{sgn } l)e^2i + O(\epsilon^3).$$

Since $|\text{sgn } m| = |\text{sgn } n| = |\text{sgn } l| = 1$, we have $|\text{sgn } m + \text{sgn } n + \text{sgn } l| \geq 1$, so $|\lambda_m(\epsilon) + \lambda_n(\epsilon) + \lambda_l(\epsilon)| > \frac{1}{2}\epsilon^2$ when $\epsilon$ is small enough.

\[\square\]

When $m + n + l = 0$ and $mnl = 0$, since $\lambda_n(\epsilon)$ is odd in $n$, it follows that $\lambda_m(\epsilon) + \lambda_n(\epsilon) + \lambda_l(\epsilon) = 0$. We do have time resonance in this case. We will eliminate this case by choosing a new frame of reference.

4. A new frame of reference

Recall that the traveling wave solution

$$f_\epsilon(x, t) = u_\epsilon(x + v_\epsilon t)$$
We now find the solution to the equation
\[ \partial_t f_\epsilon = Hf_\epsilon + f_\epsilon \partial_x f_\epsilon, \]
i.e.,
\[ v_\epsilon u_\epsilon' = Hu_\epsilon + u_\epsilon u_\epsilon'. \]

Now we aim to find a new reference frame. Let \( P_0^\pm(\epsilon) \) be the projection on the 1-dimensional space spanned by the eigenvector \( \varphi_0^+(\epsilon) = \partial_x u_\epsilon \) and \( \varphi_0^-(\epsilon) = -\epsilon^{-1}u_\epsilon' \), respectively. Then we aim to rewrite
\[ f(x, t) = u_{\epsilon(t)}(x + a(t)) + g(x + a(t), t), \]
where \( \epsilon, a \in \mathbb{R} \) and \( P_0^\pm(\epsilon(t))g = 0 \). We first show that it is always possible, provided that \( f \) is close to a traveling wave.

**Proposition 4.1.** Let \( k \geq 2 \). Then there is \( r = r(k) > 0 \) such that if \( |\epsilon| < r \) and \( \|f - u_{\epsilon_0}\|_{H^k} < r|\epsilon_0| \), then there is \( \epsilon \in \mathbb{R}, a \in \mathbb{R}/2\pi\mathbb{Z} \) and \( g \in H^k \) such that
\[ f(x) = u_\epsilon(x + a) + g(x + a), \tag{4-1} \]
\[ P_0^\pm(\epsilon)g = 0, \tag{4-2} \]
\[ |\epsilon - \epsilon_0| + \|g\|_{H^k} \lesssim \|f - u_{\epsilon_0}\|_{H^k}. \tag{4-3} \]

Moreover, \( \epsilon, a \) and \( g \) depend smoothly on \( f \).

**Proof.** Define the map \( F: (-r, r)^2 \to \mathbb{R}^2, (\epsilon, a) \mapsto (y^+, y^-) \), with
\[ P_0^\pm(\epsilon)(f(x-a) - u_\epsilon(x)) = y^\pm \varphi_0^\pm(\epsilon). \tag{4-4} \]

We now find the solution to the equation \( F(\epsilon, a) = 0 \). Since \( P_0^\pm(\epsilon) \) is uniformly bounded in \( L^2 \) and \( \|\varphi_0^\pm(\epsilon)\| \) is uniformly bounded from below,
\[ |F(\epsilon, a)| \lesssim \|f(x-a) - u_\epsilon\|_{L^2}. \tag{4-5} \]

Summing the two equations in (4-4) and taking the total derivative yields
\[ -(P_0^+(\epsilon) + P_0^-(\epsilon))(f'(x-a))da - \varphi_0^+(\epsilon)d\epsilon + (\partial_\epsilon P_0^+(\epsilon) + \partial_x P_0^-(\epsilon))(f(x-a) - u_\epsilon(x))d\epsilon = \varphi_0^+(\epsilon)dy^+ + \varphi_0^-(\epsilon)dy^- + y^+ \partial_\epsilon \varphi_0^+(\epsilon)d\epsilon + y^- \partial_x \varphi_0^-(\epsilon)d\epsilon. \tag{4-6} \]
Since \( \|f\|_{H^2} \leq \|u_{\epsilon_0}\|_{H^2} + r|\epsilon_0| \lesssim |\epsilon_0| \), we have
\[ \|f(x-a) - u_\epsilon\|_{H^1} \leq \|f(x-a) - f(x)\|_{H^1} + \|f - u_{\epsilon_0}\|_{H^1} + \|u_\epsilon - u_{\epsilon_0}\|_{H^1} \lesssim |a|\epsilon_0| + r|\epsilon_0| + |\epsilon - \epsilon_0|. \tag{4-8} \]
Since both \( P_0^\pm(\epsilon) \) and \( \partial_\epsilon P_0^\pm(\epsilon) \) are uniformly bounded on \( L^2 \), and \( u_\epsilon' = -\epsilon \varphi_0^-(\epsilon) \),
\[ \|(4-6) - \epsilon \varphi_0^-(\epsilon)da + \varphi_0^+(\epsilon)d\epsilon\|_{L^2} \lesssim (|a|\epsilon_0| + r|\epsilon_0| + |\epsilon - \epsilon_0|)(|da| + |d\epsilon|). \]
By (4-5) and (4-8),
\[ \|y^\pm \partial_\epsilon \varphi_0^\pm(\epsilon)\|_{L^2} \lesssim |F(\epsilon, a)| \lesssim |a|\epsilon_0| + r|\epsilon_0| + |\epsilon - \epsilon_0|. \]
so

\[ \|(4-7) - \varphi^+_0(\epsilon)d y^+ - \varphi^-_0(\epsilon)d y^-\|_{L^2} \lesssim (|a\epsilon_0| + r|\epsilon_0| + |\epsilon - \epsilon_0|)d\epsilon. \]

Hence the equality between (4-6) and (4-7) gives an estimate of the differential

\[ \|dF(\epsilon, a) - \left( \begin{array}{l}
1 \\
0 \\
-\epsilon_0 
\end{array} \right) \| \lesssim |a\epsilon_0| + r|\epsilon_0| + |\epsilon - \epsilon_0|. \]

We assume that the solution \((\epsilon, a)\) satisfies \(|\epsilon - \epsilon_0| + |a\epsilon_0| < r_0|\epsilon_0|\), where \(r_0\) is small enough. This in particular implies \(\frac{1}{2}|\epsilon_0| < |\epsilon| < 2|\epsilon_0|\). Then

\[ \|dF(\epsilon, a) - \left( \begin{array}{l}
1 \\
0 \\
-\epsilon_0 
\end{array} \right) \| \lesssim (r_0 + r)|\epsilon_0| \]

is also small enough. Let

\[ G = \mathbb{I} + \left( dF(\epsilon, a) - \left( \begin{array}{l}
1 \\
0 \\
-\epsilon_0 
\end{array} \right) \right) \left( \begin{array}{l}
1 \\
0 \\
1/\epsilon_0 
\end{array} \right). \]

Then

\[ dF = G \left( \begin{array}{l}
1 \\
0 \\
-\epsilon_0 
\end{array} \right) \]

and

\[ \|G - \mathbb{I}\| \lesssim r_0 + r. \]

If \(r_0\) and \(r\) are small enough, then \(\|G\|\) and \(\|G^{-1}\| < 2\).

Let \((\epsilon_1, a_1) = (\epsilon_0, 0) - dF(\epsilon_0, 0)^{-1}F(\epsilon_0, 0)\). Then (recalling (4-5))

\[ |\epsilon_1 - \epsilon_0| + |a_1\epsilon_0| \lesssim |G^{-1}F(\epsilon_0, 0)| \lesssim |F(\epsilon_0, 0)| \lesssim \|f - u_\epsilon_0\|_{L^2} \lesssim r|\epsilon_0|. \]

Since \(|\partial_\epsilon^2 F|\) and \(|\partial_{a\epsilon} F| \lesssim 1\), and \(|\partial_\epsilon^2 F| \lesssim \|f\|_{H^2} \lesssim |\epsilon_0|\), by Taylor’s theorem,

\[ |F(\epsilon_1, a_1)| \lesssim |\epsilon_1 - \epsilon_0|^2 + |\epsilon_1 - \epsilon_0| |a_1| + |\epsilon_0| |a_1|^2 \lesssim r|F(\epsilon_0, 0)|. \]

Hence the iteration \((\epsilon_{n+1}, a_{n+1}) = (\epsilon_n, a_n) + dF(\epsilon_n, a_n)^{-1}F(\epsilon_n, a_n)\) converges when \(r\) is small enough. Moreover \(|\epsilon_n - \epsilon_0| + |a_n\epsilon_0| \lesssim |F(\epsilon_0, 0)|\). Then \((\epsilon, a) := \lim_{n\to\infty}(\epsilon_n, a_n)\) satisfies \(F(\epsilon, a) = 0\) and \(|\epsilon - \epsilon_0| + |a\epsilon_0| \lesssim |F(\epsilon_0, 0)| \lesssim r|\epsilon_0| < r_0|\epsilon_0|\) if \(r\) is small compared to \(r_0\).

Let \(g = f(x - a) - u_\epsilon\). Then (4-1) and (4-2) clearly hold. Moreover,

\[ \|g\|_{H^k} = \|g(x + a)\|_{H^k} = \|f(x) - u_\epsilon(x + a)\|_{H^k} \]

\[ \leq \|f - u_\epsilon_0\|_{H^k} + \|u_\epsilon(x + a) - u_\epsilon_0(x)\|_{H^k} \]

\[ \lesssim \|f - u_\epsilon_0\|_{H^k} + |\epsilon - \epsilon_0| + |a\epsilon_0| \]

\[ \lesssim \|f - u_\epsilon_0\|_{H^k} + |F(\epsilon_0, 0)| \lesssim \|f - u_\epsilon_0\|_{H^k} \]

showing (4-3). The smooth dependence of \(\epsilon, a\) and \(g\) on \(f\) is also clear. \(\square\)

By translation symmetry, if \(f\) is \(r|\epsilon_0|\)-close to \(u_\epsilon_0(x + a)\) for some \(a \in \mathbb{R}/2\pi\mathbb{Z}\), we can reach a similar conclusion. Then we can write

\[ f(x, t) = u_\epsilon(t)(x + a(t)) + g(x + a(t), t). \]
We will obtain an energy estimate for $g$. Combined with local well-posedness of (1-1) and Proposition 4.1, we can show that the solution extends as long as the energy estimate closes, see the end of Section 5B.

To get the energy estimate, we first need to derive an evolution equation for $g$. Since $f$ is differentiable in $t$, so are $\epsilon(t), a(t)$ and $g$, and we get

$$f_t(x, t) = a'(t)(u'_e + g_x)(x + a(t)) + \epsilon'(t)\partial_x u_e(x + a(t)) + g_t(x + a(t), t)$$

and

$$(H f + ff_x)(x, t) = (Hu_e + u_e u'_e)(x + a(t)) + Hg(x + a(t), t) \\
+ \partial_x(u_e(x + a(t))g(x + a(t), t)) + (g g_x)(x + a(t), t).$$

The equation for $g$ is then

$$g_t = v_e u'_e - a'(t)(u'_e + g_x) - \epsilon'(t)\partial_x u_e + Hg + (u_e g)_x + g g_x$$

$$= L\epsilon g + (v_e - a'(t))(u'_e + g_x) - \epsilon'(t)\partial_x u_e + g g_x.$$

Since $P^\pm_0(\epsilon)g(t) = 0$, we have $P^\pm_0(\epsilon)g_t = -\epsilon'(t)\partial_x P^\pm_0(\epsilon)g$, so the action of the projections $P^\pm_0(\epsilon)$ on the above equation is

$$(v_e - a'(t))P^\pm_0(\epsilon)g_x + \epsilon'(t)(\partial_x P^\pm_0(\epsilon)g - \partial_x u_e) + P^\pm_0(\epsilon)(g g_x) = 0,$$

$$(v_e - a'(t))(u'_e + P^-_0(\epsilon)g_x) + \epsilon'(t)\partial_x P^-_0(\epsilon)g + P^-_0(\epsilon)(g g_x) = 0.$$ 

Since $P^\pm_0(\epsilon)$ are bounded on $L^2$, we have $\|P^\pm_0(\epsilon)g_x\|L^2 \lesssim \|g\|_{H^1}$. Since $P^\pm_0(\epsilon)$ are analytic in $\epsilon$, we have $\|\partial_\epsilon P^\pm_0(\epsilon)g\|L^2 \lesssim \|g\|_{L^2}$. Since $P^\pm_0(\epsilon)$ is a projection, we have $P^\pm_0(\epsilon)^2 = P^\pm_0(\epsilon)$. Taking the derivative in $\epsilon$ and using the constraint $P^\pm_0(\epsilon)g = 0$, we have $P^\pm_0(\epsilon)\partial_\epsilon P^\pm_0(\epsilon)g = 0$, i.e., $\partial_\epsilon P^\pm_0(\epsilon)g$ is in the 1-dimensional space spanned by $\varphi^\pm_0(\epsilon)$. Hence

$$|P^\pm_0(\epsilon)g_x/\varphi^\pm_0(\epsilon)| \lesssim \|g\|_{H^1}, \quad |\partial_\epsilon P^\pm_0(\epsilon)g/\varphi^\pm_0(\epsilon)| \lesssim \|g\|_{L^2}.$$ 

Thus, dividing the two equations by $\varphi^\pm_0(\epsilon)$ we get

$$\left|\begin{pmatrix} 0 & 1 \\ \epsilon & 0 \end{pmatrix} + O(\|g\|_{H^1})\right| \left|\begin{pmatrix} v_e - a'(t) \\ \epsilon'(t) \end{pmatrix} \right| = \left|\begin{pmatrix} P^+_0(\epsilon)(g g_x)/\varphi^+_0(\epsilon) \\ P^-_0(\epsilon)(g g_x)/\varphi^-_0(\epsilon) \end{pmatrix} \right| \lesssim \|g(t)\|_{H^1}^2.$$ 

Assuming $\|g(t)\|_{H^1}/|\epsilon|$ is small enough we have

$$\begin{pmatrix} v_e - a'(t) \\ \epsilon'(t) \end{pmatrix} = \begin{pmatrix} O(\|g(t)\|_{H^1}^2/|\epsilon|) \\ O(\|g(t)\|_{H^1}^2) \end{pmatrix}.$$ 

(4-9)

**4A. Diagonalization.** To find the evolution of other modes, we diagonalize the equation for $g$. Let $g = h_x$ and $h = \tilde{h} \circ \phi_e$, where $\phi_e$ satisfies (3-3). Recall from (3-1) that $L\epsilon g = -v_e g_x + Hg + (u_e g)_x$, so

$$h_t = -v_e h_x + Hh + u_e h_x - \epsilon'(t)\partial_x U_{\epsilon} + (v_e - a'(t))(u_e + h_x) + \frac{1}{2}h^2_x \pmod{1},$$

where $U_{\epsilon}$ is a primitive of $u_e$. Differentiating $h = \tilde{h} \circ \phi_e$ with respect to $\epsilon$ we get

$$h_t = \tilde{h}_t \circ \phi_e + \epsilon'(t)(\partial_\epsilon \phi_e)(\tilde{h}_x \circ \phi_e).$$
On the other hand,
\[
(-v_e h_x + H h + u_e h_x)_x = L_e g = (((c_e \partial x + H + R_e)\tilde{h}) \circ \phi_e)_x,
\]
so
\[
\tilde{h}_t = (c_e \partial_x + H + R_e)\tilde{h} - \epsilon'(t)(\partial_e \phi_e \circ \phi_e^{-1})\tilde{h}_x - \epsilon'(t)\partial_e U_e \circ \phi_e^{-1} + (v_e - a'(t))(u_e + h_x) \circ \phi_e^{-1} + h_x^2 \circ \phi_e^{-1} \quad \text{(mod 1)}.
\]
By the chain rule, \( h_x = \phi'_e(h_x \circ \phi_e) \), so \( h_x \circ \phi_e^{-1} = (\phi'_e \circ \phi_e^{-1})h_x \), and
\[
\tilde{h}_t = (c_e \partial_x + H + R_e)\tilde{h} + \Phi_e \tilde{h} - \epsilon'(t)\partial_e U_e \circ \phi_e^{-1} + (v_e - a'(t))u_e \circ \phi_e^{-1} + \frac{1}{2}(\phi'_e \circ \phi_e^{-1})^2 h_x^2 \quad \text{(mod 1)},
\]
\( \Phi_e = -\epsilon'(t)(\partial_e \phi_e \circ \phi_e^{-1}) + (v_e - a'(t))(\phi'_e \circ \phi_e^{-1}) \).

Using the operator \( W_\epsilon \) from Lemma 3.7 we have
\[
(1 + W_\epsilon)(c_e \partial_x + H + R_\epsilon) = \Lambda_\epsilon(1 + W_\epsilon),
\]
where \( \Lambda_\epsilon \) is a Fourier multiplier whose action on the Fourier mode \( e^{i(n+2\epsilon)n} \) is multiplication by \( \lambda_n(\epsilon) \).
Since \( W_\epsilon/\epsilon \) is of class \( S \), uniformly in \( \epsilon \), for any smooth function \( F \), the operator
\[
\tilde{h} \mapsto \mathcal{R}_\epsilon(F)\tilde{h} := (1 + W_\epsilon)(F\tilde{h}_x) - F((1 + W_\epsilon)\tilde{h})_x
\]
is of class \( S \), with the implicit constants depending on the \( C^k \) norms of \( F \).

Let \( \tilde{h} = (1 + W_\epsilon)\tilde{h} \). Then
\[
(1 + W_\epsilon)\tilde{h}_t = \Lambda_\epsilon \tilde{h} + \Phi_\epsilon \tilde{h}_x - \epsilon'(t)(1 + W_\epsilon)(\partial_e U_e \circ \phi_e^{-1}) + (v_e - a'(t))(1 + W_\epsilon)(u_e \circ \phi_e^{-1}) + N_\epsilon[\tilde{h}, \tilde{h}] + \mathcal{R}_\epsilon(\Phi_\epsilon)\tilde{h} \quad \text{(mod 1)},
\]
where
\[
N_\epsilon[\tilde{h}, \tilde{h}] = \frac{1}{2}(\phi'_e \circ \phi_e^{-1})^2((1 + W_\epsilon)^{-1}h)_x^2. \tag{4-10}
\]
Both \( \mathcal{R}_\epsilon(\partial_e \phi_e \circ \phi_e^{-1}) \) and \( \mathcal{R}_\epsilon(\phi'_e \circ \phi_e^{-1} - 1)/\epsilon \) are of class \( S \), uniformly in \( \epsilon \) when \( \epsilon \) is small. Moreover, since \( W_\epsilon \) is analytic in \( \epsilon \) with \( W_0 = 0 \), so is \( \mathcal{R}_\epsilon(1) \) with \( \mathcal{R}_0(1) = 0 \). Hence \( \mathcal{R}_\epsilon(1)/\epsilon \) is of class \( S \) uniformly in \( \epsilon \), and so is \( \mathcal{R}_\epsilon(\phi'_e \circ \phi_e^{-1})/\epsilon \).

Since \( \partial_e u_e \) and \( u'_e \) are in the generalized eigenspace of \( L_\epsilon \) associated with the eigenvalue 0, we have \( \partial_e U_e \circ \phi_e^{-1} \) and \( u_e \circ \phi_e^{-1} \) are in the corresponding space of \( c_e \partial_x + H + R_\epsilon \), so \( (1 + W_\epsilon)(\partial_e U_e \circ \phi_e^{-1}) \) and \( (1 + W_\epsilon)(u_e \circ \phi_e^{-1}) \) are in the space spanned by \( \sin x \) and \( \cos x \), according to Lemma 3.7.

Now we have
\[
\tilde{h}_t = (1 + W_\epsilon)\tilde{h}_t + \epsilon'(t)\partial_e W_\epsilon \tilde{h}
= \Lambda_\epsilon \tilde{h} + \Phi_\epsilon \tilde{h}_x + N_\epsilon[\tilde{h}, \tilde{h}] + \text{Rest (mod 1, sin } x, \cos x), \tag{4-11}
\]
where \( N_\epsilon[\tilde{h}, \tilde{h}] \) is given by (4-10) and
\[
\text{Rest} = \epsilon'(t)(\partial_e W_\epsilon)\tilde{h} + \mathcal{R}_\epsilon(\Phi_\epsilon)\tilde{h}
\]
is also of class \( S \) uniformly in \( \epsilon \) when \( \epsilon \) is small.
Recall that \( \epsilon'(t) \) and \( a'(t) \) are chosen such that \( P_0(\epsilon)g(t) = 0 \) for all \( t \), where \( P_0(\epsilon) \) is the projection onto the span of \( \partial_\epsilon u_\epsilon \) and \( u_\epsilon' \). This implies \( Q_0(\epsilon)\hat{h}(t) = 0 \) for all \( t \), where \( Q_0(\epsilon) \) is the projection onto the span of \( \partial_\epsilon U_\epsilon \circ \phi_{\epsilon}^{-1} \) and \( u_\epsilon \circ \phi_{\epsilon}^{-1} \). Since \( 1 + W_\epsilon \) maps the span of \( \partial_\epsilon U_\epsilon \circ \phi_{\epsilon}^{-1} \) and \( u_\epsilon \circ \phi_{\epsilon}^{-1} \) to the span of \( \sin x \) and \( \cos x \), we have \( \hat{h}(1) = \hat{h}(-1) = 0 \) for all \( t \).

5. Energy estimates

Since \( \hat{h}(1) = \hat{h}(-1) = 0 \) for all \( t \), for \( k = 0, 1, \ldots \) we define the energy

\[
E_k = \frac{1}{2} \| h \|^2_{\dot{H}^k} = \frac{1}{2} \| \dot{h} \|^2_{\dot{H}^k/(1, \sin x, \cos x)}
\]

and aim to control its growth.

Using the evolution equation (4-11) for \( \hat{h} \) and the anti-self-adjointness of \( \Lambda_\epsilon \) we get

\[
\frac{d}{dt} E_k(t) = E_\Phi(t) + E_N(t) + E_{\text{Rest}}(t),
\]

\[
E_\Phi(t) = \langle \Phi_\epsilon h_x, h \rangle_{\dot{H}^k},
\]

\[
E_N(t) = \langle N_\epsilon[h(t), h(t)], h(t) \rangle_{\dot{H}^k},
\]

\[
E_{\text{Rest}}(t) = \langle \epsilon'(t) \partial_\epsilon W_\epsilon \hat{h}(t) + R_\epsilon(\Phi_\epsilon)\hat{h}(t), h(t) \rangle_{\dot{H}^k}.
\]

Recall that \( g = h_x, \ h = \tilde{h} \circ \phi_\epsilon \) and \( h = (1 + W_\epsilon)\tilde{h} \). When \( \epsilon \) is small enough, the last two are bounded operators with bounded inverse between \( \hat{H}^k, k = 0, 1, \ldots \), so

\[
\| g \|_{\dot{H}^k} \approx_k \| h \|_{\dot{H}^k+1} \approx_k \| \tilde{h} \|_{\dot{H}^k+1} \approx_k \| \dot{h} \|_{\dot{H}^k+1}.
\]  
(5-1)

Since \( R_\epsilon(\partial_\epsilon \phi_\epsilon \circ \phi_{\epsilon}^{-1}), R_\epsilon(\phi_\epsilon' \circ \phi_{\epsilon}^{-1})/\epsilon \) and \( \partial_\epsilon W_\epsilon \) are of class \( S \) uniformly in \( \epsilon \),

\[
\| (\epsilon'(t) \partial_\epsilon W_\epsilon - \epsilon'(t) R_\epsilon(\partial_\epsilon \phi_\epsilon \circ \phi_{\epsilon}^{-1}))\hat{h}(t) \|_{\dot{H}^k} \lesssim_k \| g(t) \|_{\dot{H}^1} \| \hat{h}(t) \|_{\dot{H}^1} \approx_k E_2(t)^{3/2},
\]

\[
\| (v_\epsilon - a'(t)) R_\epsilon(\phi_\epsilon' \circ \phi_{\epsilon}^{-1})\hat{h}(t) \|_{\dot{H}^k} \lesssim_k (\| g(t) \|_{\dot{H}^1/\epsilon} \| \hat{h}(t) \|_{\dot{H}^1} \| \hat{h}(t) \|_{\dot{H}^1}) \approx_k E_2(t)^{3/2}
\]

so

\[
|E_{\text{Rest}}(t)| \lesssim_k E_2(t)^{3/2} E_k(t)^{1/2}.
\]  
(5-2)

To bound \( E_\Phi \) we use (4-9) and (5-1) to get

\[
\| \Phi_\epsilon' C_k \lesssim_k \| g(t) \|_{\dot{H}^1}^2 + (\| g(t) \|_{\dot{H}^1/\epsilon}) \| \epsilon \| \lesssim_k E_2(t).
\]

Since \( E_\Phi \) loses only one derivative in \( h \), we have

\[
|E_\Phi(t) - \langle \Phi_\epsilon \partial_\epsilon^{k+1} h(t), \partial_\epsilon^{k} h(t) \rangle_{L^2/(1)}| \lesssim_k E_2(t) E_k(t).
\]  
(5-3)

For the sake of bounding this term, since the inner product is taken in the space \( L^2/(1) \), we can without loss of generality assume that \( \hat{h}(0) = 0 \) (which is not true in general) and integrate by parts to get

\[
2 \langle \Phi_\epsilon \partial_\epsilon^{k+1} h(t), \partial_\epsilon^{k} h(t) \rangle_{L^2/(1)} = \int_0^{2\pi} \Phi_\epsilon \partial_\epsilon (\partial_\epsilon^{k} h(t))^2 dx = - \int_0^{2\pi} \Phi_\epsilon' (\partial_\epsilon^{k} h(t))^2 dx
\]

so again by (4-9) and (5-1),

\[
|E_\Phi(t)| \lesssim_k E_2(t) E_k(t).
\]  
(5-4)
Combining (5-2), (5-3) and (5-4) shows that
\[ \left| \frac{d}{dt} E_k(t) - E_N(t) \right| \lesssim_k E_2(t) E_k(t). \] (5-5)

5A. Normal form transformation. To bound \( E_N \) we recall the expression of \( N_\epsilon \) from (4-10). Since \( N_\epsilon \) does not depend on the constant mode of \( \mathfrak{h} \), we can also assume without loss of generality that \( \mathfrak{h}(0) = 0 \). We further have the decompositions
\[
E_N(t) = E_{N1}(t) + E_{N2}(t),
\]
where \( c_{kj} \in \mathbb{R} \) are constants and we integrated by parts to get rid of the terms with \( k + 1 \) derivatives falling on a single factor of \( \mathfrak{h} \).

We use the normal form transformation to bound them. Define the trilinear map
\[
D_\epsilon[f_1, f_2, f_3] = \sum_{mnl \neq 0} \frac{1}{\lambda_m(\epsilon) + \lambda_n(\epsilon) + \lambda_l(\epsilon)} \int_0^{2\pi} \hat{f}_1(m + \text{sgn} m)e^{i(m+\text{sgn} m)x} \times \hat{f}_2(n + \text{sgn} n)e^{i(n+\text{sgn} n)x} \hat{f}_3(l + \text{sgn} l)e^{i(l+\text{sgn} l)x} \, dx
\]
and put
\[
D_{1,k,j}(t) = D_\epsilon(t)[\partial^{k}_x h(t), \partial^{k+2-j}_x h(t), \partial^{j}_x h(t)].
\]
Then
\[
\frac{d}{dt} D_{1,k,j}(t) = \epsilon'(t) (\partial_\epsilon D_\epsilon)[\partial^{k}_x h(t), \partial^{k+2-j}_x h(t), \partial^{j}_x h(t)]
+ D_\epsilon[\partial^{k}_x \partial_\epsilon h(t), \partial^{k+2-j}_x h(t), \partial^{j}_x h(t)]
+ D_\epsilon[\partial^{k}_x h(t), \partial^{k+2-j}_x \partial_\epsilon h(t), \partial^{j}_x h(t)]
+ D_\epsilon[\partial^{k}_x h(t), \partial^{k+2-j}_x h(t), \partial^{j}_x \partial_\epsilon h(t)].
\]

Note that \( E_{N1}(t) \) is a linear combination of the last three lines on the right-hand side, with \( \partial_\epsilon \) replaced with \( \Lambda_\epsilon \), so \( (d/dt) \sum_{j=2}^{[k/2]+1} c_{kj} D_{1,k,j}(t) - E_{N1}(t) \) is a linear combination of
\[
\epsilon'(t) (\partial_\epsilon D_\epsilon)[\partial^{k}_x h(t), \partial^{k+2-j}_x h(t), \partial^{j}_x h(t)],
\]
\[
D_\epsilon[\partial^{k}_x (\partial_\epsilon - \Lambda_\epsilon) h(t), \partial^{k+2-j}_x h(t), \partial^{j}_x h(t)],
\]
\[
D_\epsilon[\partial^{k}_x h(t), \partial^{k+2-j}_x (\partial_\epsilon - \Lambda_\epsilon) h(t), \partial^{j}_x h(t)],
\]
\[
D_\epsilon[\partial^{k}_x h(t), \partial^{k+2-j}_x h(t), \partial^{j}_x (\partial_\epsilon - \Lambda_\epsilon) h(t)].
\]

We estimate these terms one by one.

By the definition of \( D_\epsilon \),
\[
(5-7) = \epsilon'(t) \sum_{mnl \neq 0} \frac{(\lambda'_m(\epsilon) + \lambda'_n(\epsilon) + \lambda'_l(\epsilon))}{2(\lambda_m(\epsilon) + \lambda_n(\epsilon) + \lambda_l(\epsilon))^2}
\times \int_0^{2\pi} \hat{h}(m + \text{sgn} m, t) \partial^{k}_x e^{i(m+\text{sgn} m)x} \hat{h}(n + \text{sgn} n, t) \partial^{k+2-j}_x e^{i(n+\text{sgn} n)x} \hat{h}(l + \text{sgn} l, t) \partial^{j}_x e^{i(l+\text{sgn} l)x} \, dx.
\]
We first bound the fraction. By Corollary 3.10, when \( \varepsilon \) is small enough,
\[
\lambda_m' \varepsilon + \lambda_n' \varepsilon + \lambda_l' \varepsilon = (m + n + l + \text{sgn} m + \text{sgn} n + \text{sgn} l) \partial_c c \varepsilon i + O(\varepsilon^5)
\]
\[
\lesssim (|m + n + l| + 1)|\varepsilon|.
\] (5-11)

On the other hand, the integral vanishes unless
\[
m + n + l + \text{sgn} m + \text{sgn} n + \text{sgn} l = 0,
\] (5-12)
in which case \( m + n + l \) is an odd number, and so is nonzero. Then by Case 1 of Proposition 3.11,
\[
|\lambda_m(\varepsilon) + \lambda_n(\varepsilon) + \lambda_l(\varepsilon)| > \frac{1}{2}|m + n + l|,
\] (5-13)
so
\[
\frac{|\lambda_m'(\varepsilon) + \lambda_n'(\varepsilon) + \lambda_l'(\varepsilon)|}{|\lambda_m(\varepsilon) + \lambda_n(\varepsilon) + \lambda_l(\varepsilon)|^2} \lesssim |\varepsilon|.
\] (5-14)

Then for \( k \geq 3 \),
\[
(|5-7| \lesssim |\varepsilon(t)\varepsilon'(t)| \sum_{m \neq 0, \text{sgn} m \neq 0} (m + \text{sgn} m)^k \hat{h}(m + \text{sgn} m, t)
\[
\times (n + \text{sgn} n)^{k+2-j} \hat{h}(n + \text{sgn} n, t)(l + \text{sgn} l)^j \hat{h}(l + \text{sgn} l, t)
\]
\[
\approx |\varepsilon(t)\varepsilon'(t)| \int_0^{2\pi} \partial_x^k H(x, t) \partial_x^{k+2-j} H(x, t) \partial_x^j H(x, t) \, dx
\]
\[
\lesssim \varepsilon(t)\varepsilon'(t) \|H(x, t)\|_{H_x^k}^2 \|H(x, t)\|_{W_x^{[k/2]+1, \infty}} \lesssim \varepsilon(t)\varepsilon'(t) \|H(x, t)\|_{H_x^k}^3
\] (5-15)
since \( k \geq [k/2] + 2 \), where
\[
H(x, t) = \sum_{m \neq 0} \hat{h}(m + \text{sgn} m, t)e^{i(m + \text{sgn} m)x}
\]
satisfies
\[
\|H(x, t)\|_{H_x^k} = \|\hat{h}(t)\|_{H_x^k} \lesssim E_k(t)^{1/2}
\]
so by (4-9) and (5-1),
\[
(|5-7| \lesssim \varepsilon|E_2(t)|E_k(t)^{3/2}.
\] (5-16)

To bound the other terms (5-8), (5-9) and (5-10), we use the evolution equation (4-11) of \( \hat{h} \), which loses one derivative in \( \hat{h} \), so
\[
\|\partial_t \Lambda_\varepsilon \hat{h}(t)\|_{H_x^{k-1}} \lesssim (\|g\|_{H_x^1}^2/|\varepsilon|) \|\hat{h}(t)\|_{H_x^k} + \|\hat{h}(t)\|_{H_x^k}.
\]
If \( \|g(t)\|_{H_x^1}/|\varepsilon| \) is small enough and \( k \geq 2 \), the first term is dominated by the second term thanks to (5-1). Since in the summation of \( D_\varepsilon \) it holds that \( m + n + l \neq 0 \), the denominator is uniformly bounded from below thanks to (5-13). Unless \( j = 2 \) in (5-8) and (5-9), we can integrate by parts if necessary to ensure that at most \( k - 1 \) derivatives in \( x \) hit each factor of \( j \). Then similarly to (5-15) it follows that for \( k \geq 5 \),
\[
|((5-8), j \geq 3) + ((5-9), j \geq 3) + (5-10)| \lesssim E_k(t)^2.
\] (5-17)
For $j = 2$, by symmetry of $D_ε$ it is clear that

$$(5-9), j = 2) = ((5-8), j = 2),$$  
(5-18)

which according to (4-11) equals

$$D_ε[∂^k_x(Φ_ε h_x(t) + N_ε[h(t), h(t)] + R(t)), ∂^k_x h(t), ∂^2_x h(t)].$$

Similarly to (5-15),

$$|D_ε[∂^k_x R(t), ∂^k_x h(t), ∂^2_x h(t)]| ≲ k E_3(t)^2 E_k(t)^{1/2}. 
(5-19)$$

Similarly to (5-3),

$$|D_ε[∂^k_x(Φ_ε h_x(t)) - Φ_ε ∂^{k+1}_x h(t), ∂^k_x h(t), ∂^2_x h(t)]| ≲ k E_3(t)^{3/2} E_k(t). 
(5-20)$$

By the definition of $D_ε$,

$$D_ε[Φ_ε ∂^{k+1}_x h(t), ∂^k_x h(t), ∂^2_x h(t)]$$

$$= \sum_{mnl \neq 0} \frac{1}{λ_m(ε) + λ_n(ε) + λ_l(ε)} \int_0^{2π} \hat{Φ}_ε(p) e^{ipx} \hat{h}(m + sgn m, t) ∂^{k+1}_x e^{(m + sgn m)x} \hat{h}(n + sgn n, t)$$

$$× ∂^k_x e^{i(n + sgn n)x} \hat{h}(l + sgn l, t) ∂^2_x e^{l(n + sgn l)x} dx, 
(5-21)$$

where $m' + sgn m' = p + m + sgn m \neq 0, ± 1$. We break the summation into several parts.

Part 1: $|p| ≥ \frac{1}{3} |m + sgn m|$. Then we can transfer the extra derivative from $h$ to $Φ_ε$, and compute as in (5-3) to get

$$|Part 1| ≲ k E_3(t)^{3/2} E_k(t). 
(5-22)$$

Part 2: $|p| < |m + sgn m|/3$ but $|p| ≥ |n + sgn n|/3$. If $|n + sgn n| ≥ |m|/3$ then $|p| ≥ |m|/9$, and we get the same bound as before. Otherwise, since the integral vanishes unless

$$p + m + n + l + sgn m + sgn n + sgn l = 0 
(5-23)$$

in which case we have $|l + sgn l| > |n + sgn n|/3$, we can transfer the extra derivative to the factor $∂^2_x h$ to get (note that $\|Φ_ε\|_{C^3} ≲ k \|g\|_{H^1}/|ε|$)

$$|Part 2| ≲ k (\|g(t)\|_{H^1}/|ε|) E_4(t)^{1/2} E_k(t) ≲ E_4(t) E_k(t) 
(5-24)$$

provided that $\|g(t)\|_{H^1}/|ε|$ is small enough.

Part 3: $|p| < \frac{1}{3} |m + sgn m|$ and $|p| < \frac{1}{3} |n + sgn n|$. Then $sgn(m' + sgn m') = sgn(m + sgn m)$, i.e., $sgn m' = sgn m$, so $m' = m + p$. By symmetry,

$$Part 3 = \sum_{mnl \neq 0} \frac{1}{λ_m(ε) + λ_p(ε) + λ_l(ε)} \int_0^{2π} \hat{h}(l + sgn l, t) ∂^2_x e^{i(sgn l)x} \hat{Φ}_ε(p) e^{ipx} \hat{h}(m + sgn m, t)$$

$$× ∂^{k+1}_x e^{(m + sgn m)x} \hat{h}(n + sgn n, t) ∂^k_x e^{i(m + sgn n)x} dx 
+ \sum_{mnl \neq 0} \frac{1}{λ_m(ε) + λ_p(ε) + λ_l(ε)} \int_0^{2π} \hat{h}(l + sgn l, t) ∂^2_x e^{i(sgn l)x} \hat{Φ}_ε(p) e^{ipx} \hat{h}(m + sgn m, t)$$

$$× ∂^{k+1}_x e^{i(m + sgn m)x} \hat{h}(n + sgn n, t) ∂^k_x e^{i(m + sgn n)x} dx.$$
Note that the two denominators are uniformly bounded from below. Also, \( \text{sgn}(m + p) = \text{sgn} m \) and \(|m + p| > \frac{1}{3}(2|m| - 1) \), and similarly for \( l \). Then by Corollary 3.10, the two denominators differ by \( O(|m|e^{4|m|/3} + |n|e^{4|n|/3}) \), so

\[
\text{Part 3} = \sum_{\substack{mnl \neq 0 \\mid p \mid < |m + sgn m|/3 \\mid p \mid < |n + sgn n|/3}} \frac{1}{\lambda_{m+p}(\epsilon) + \lambda_{n}(\epsilon) + \lambda_l(\epsilon)} \int_0^{2\pi} \hat{h}(l+sgn l, t) \partial_x^2 e^{i(l+sgn l)x} \hat{\Phi}_\epsilon(p) e^{ipx} \partial_x^3 \hat{h}(m+sgn m, t) dx \times \partial_x^k e^{i(m+sgn m)x} \hat{h}(n+sgn n, t) \partial_x^k e^{i(n+sgn n)x} dx
\]

\[
+ \sum_{(5-23)} O(|m|e^{4|m|/3} + |n|e^{4|n|/3}) \int_0^{2\pi} |(l+sgn l)^2 \hat{h}(l+sgn l, t) \Phi_\epsilon(p)(m+sgn m)^k \times \hat{h}(m+sgn m, t)(n+sgn n)^k \hat{h}(n+sgn n, t)| \]

where we integrated by parts in the first integral and used the bounds \(|m|e^{4|m|/3} + |n|e^{4|n|/3}| \lesssim \epsilon^4 \) in the second. Then as in (5-15) it follows that

\[
|\text{Part 3}| \lesssim_k (\|g(t)\|_{H^1/|\epsilon|}^2) E_4(t)^{1/2} E_k(t) + \epsilon^4(\|g(t)\|_{H^1/|\epsilon|}^2) E_3(t)^{1/2} E_k(t)
\]

(5-25)

provided that \( \epsilon \) and \( \|g(t)\|_{H^1/|\epsilon|} \) are small enough.

Combining (5-20), (5-22), (5-24) and (5-25) shows that

\[
|D_\epsilon[\partial_x^k(\Phi_\epsilon h(t)), \partial_x^k h(t), \partial_x^2 h(t)]| \lesssim_k E_4(t)(1 + E_4(t)^{1/2}) E_k(t)
\]

(5-26)

provided that \( \epsilon \) and \( \|g(t)\|_{H^1/|\epsilon|} \) are small enough.

We now turn to \( D_\epsilon[\partial_x^k N_\epsilon[h(t), h(t)], \partial_x^k h(t), \partial_x^2 h(t)] \). Similarly to (5-3),

\[
|D_\epsilon[\partial_x^k N_\epsilon[h(t), h(t)], \partial_x^k h(t), \partial_x^2 h(t)]| - D_\epsilon[(\phi_\epsilon^{-1})^2 \partial_x ((1 + W_\epsilon)^{-1} h(t)) (\partial_x^{k+1}(1 + W_\epsilon)^{-1} h(t)), \partial_x^k h(t), \partial_x^2 h(t)]| \lesssim_k |\epsilon| E_3(t)^{1/2} E_k(t)^{3/2}
\]

(5-27)

Since \( W_\epsilon/\epsilon \) is of class \( S \) uniformly in \( \epsilon \), so is \( (1 + W_\epsilon)^{-1} = (1 + W_\epsilon)^{-1} - 1/\epsilon \), so

\[
|D_\epsilon[(\phi_\epsilon^{-1})^2 (\partial_x (1 + W_\epsilon)^{-1} h(t)) (\partial_x^{k+1}(1 + W_\epsilon)^{-1} - 1) h(t)), \partial_x^k h(t), \partial_x^2 h(t)]| \lesssim_k |\epsilon| E_3(t)^{3/2} E_k(t)^{1/2}
\]

(5-28)
Finally, $D_\epsilon[(\phi'_\epsilon \circ \phi^{-1}_\epsilon)^2(\partial_x (1 + W_\epsilon)^{-1} h(t))(\partial_x^{k+1} h(t)), \partial_x^k h(t), \partial_x^2 h(t)]$ is of the same form as the left-hand side of (5-21), so we trace the same argument to get

$$|\text{Part 1}| \lesssim_k E_3(t)E_k(t),$$

$$|\text{Part 2}| \lesssim_k E_4(t)E_k(t),$$

$$|\text{Part 3}| \lesssim_k E_4(t)E_k(t) + \epsilon^4 E_3(t)E_k(t) \lesssim_k E_4(t)E_k(t)$$

provided that $\epsilon$ is small enough. Hence

$$|D_\epsilon[(\phi'_\epsilon \circ \phi^{-1}_\epsilon)^2(\partial_x (1 + W_\epsilon)^{-1} h(t))(\partial_x^{k+1} h(t)), \partial_x^k h(t), \partial_x^2 h(t)]| \lesssim_k E_4(t)E_k(t). \quad (5-29)$$

Combining (5-27), (5-28) and (5-29) shows that, for $k \geq 4$,

$$|D_\epsilon[\partial_x^k N_\epsilon[h(t)], \partial_x^k h(t), \partial_x^2 h(t)]| \lesssim_k E_4(t)^{1/2}E_k(t)^{3/2} \quad (5-30)$$

provided that $\epsilon$ is small enough.

Combining (5-19), (5-26) and (5-30) shows that, for $k \geq 4$,

$$|((5-8), j = 2)| \lesssim_k E_4(t)^{1/2}(1 + E_4(t)^{1/2})E_k(t)^{3/2} \quad (5-31)$$

provided that $\epsilon$ and $\|g(t)\|_{H^1/|\epsilon|}$ are small enough.

Finally, combining (5-16), (5-17), (5-18) and (5-31) shows that, for $k \geq 5$,

$$\left| \frac{d}{dt} \sum_{j=2}^{[k/2]+1} c_{jk} D_{1,k,j}(t) - E_{N1}(t) \right| \lesssim_k (1 + E_4(t)^{1/2})E_k(t)^2 \quad (5-32)$$

provided that $\epsilon$ and $\|g(t)\|_{H^1/|\epsilon|}$ are small enough.

**5B. Lifespan when $\delta \ll \epsilon$.** In this section we will obtain a preliminary bound for $E_{N2} = E_N - E_{N1}$ and show a lifespan of $1/(\epsilon \delta)$ when $\|g_0\|_{H^5(\Gamma)} = \delta \ll \epsilon$, i.e., $\delta \leq c\epsilon$ for some $c > 0$ independent of $\epsilon$.

Recall from (5-6) that

$$E_N(t) = \frac{1}{2} \int_0^{2\pi} \partial_x^k h(t) \partial_x^k ((\phi'_\epsilon \circ \phi^{-1}_\epsilon)^2((1 + W_\epsilon)^{-1} h(t)) \partial_x^k dx.$$  

Similarly to (5-3), for $k \geq 3$,

$$E_N(t) - \int_0^{2\pi} (\phi'_\epsilon \circ \phi^{-1}_\epsilon)^2 \partial_x^k h(t) \partial_x^k ((1 + W_\epsilon)^{-1} h_x(t))^2 dx \lesssim_k |\epsilon| E_k(t)^{3/2}.$$

Since $((1 + W_\epsilon)^{-1} - 1)/\epsilon$ is of class $S$ uniformly in $\epsilon$,

$$\int_0^{2\pi} (\phi'_\epsilon \circ \phi^{-1}_\epsilon)^2 \partial_x^k h(t) \partial_x^k (((1 + W_\epsilon)^{-1} h_x(t) - h_x(t))^2 dx \lesssim_k \epsilon^2 E_k(t)^{3/2},$$

$$2 \left| \int_0^{2\pi} (\phi'_\epsilon \circ \phi^{-1}_\epsilon)^2 \partial_x^k h(t) \partial_x^k (((1 + W_\epsilon)^{-1} h_x(t) - h_x(t))h_x(t)) dx - \int_0^{2\pi} (\phi'_\epsilon \circ \phi^{-1}_\epsilon)^2 ((1 + W_\epsilon)^{-1} h_x(t) - h_x(t)) \partial_x^k h(t) \partial_x^{k+1} h(t) dx \right| \lesssim_k |\epsilon| E_k(t)^{3/2}.$$
Finally, by integration by parts,
\[
2 \int_0^{2\pi} (\phi'_\varepsilon \circ \phi^{-1}_\varepsilon)^2 ((1 + W_\varepsilon)^{-1} h(x, t) - h_\varepsilon(t)) \partial_x^k \phi(t) \partial_x^{k+1} \phi(t) \, dx
= \int_0^{2\pi} \partial_x ((\phi'_\varepsilon \circ \phi^{-1}_\varepsilon)^2 ((1 + W_\varepsilon)^{-1} h(x, t) - h_\varepsilon(t))) (\partial_x^k \phi(t))^2 \, dx \lesssim_k |\varepsilon| E_k(t)^{3/2}.
\]
Combining the bounds above shows that, for \( k \geq 3 \),
\[
|E_{N_2}(t)| = |E_N(t) - E_{N_1}(t)| \lesssim_k |\varepsilon| E_k(t)^{3/2}
\] (5-33)
provided that \( \varepsilon \) is small enough.

Now combining (5-5), (5-32) and (5-33) shows that, for \( k \geq 5 \),
\[
\frac{d}{dt} \left[ \sum_{j=2}^{[k/2]+1} c_{jk} D_{1,k,j}(t) - E_k(t) \right] \lesssim_k (1 + E_4(t)^{1/2}) E_k(t)^2 + |\varepsilon| E_k(t)^{3/2}.
\] (5-34)
provided that \( \varepsilon \) and \( \|g(t)\|_{H^1}/|\varepsilon| \) are small enough. Hence
\[
E_k(t) - E_k(0) = \sum_{j=2}^{[k/2]+1} c_{jk} (D_{1,k,j}(t) - D_{1,k,j}(0)) + O_k(1 + E_4(t)^{1/2}) E_k^2 + |\varepsilon| E_k^{3/2} L^1([0,t]),
\]
Similarly to (5-15),
\[
|D_{1,k,j}(t)| = |D_{\varepsilon(t)}(\partial_x^k \phi(t), \partial_x^{k+2-j} \phi(t), \partial_x^j \phi(t))| \lesssim_k E_k(t)^{3/2}.
\]
Now we are able to show a lifespan longer than what follows from local well-posedness. Assume that the initial data is
\[
f(x, 0) = u_\varepsilon(x) + g(x),
\]
where \( |\varepsilon| \leq \varepsilon_0 \) is small enough, the energy \( E_k(0) \) computed from \( g \) is \( E_k(0) = \delta^2 \), and \( \delta/|\varepsilon| \) is also small enough. Let
\[
T^* = \sup \left\{ T : \text{there exists a solution } f(x, t) = u_{\varepsilon(t)}(x + a(t)) + g(x + a(t), t), \right. \]
\[
\left. t \in [0, T] \text{ such that } \frac{1}{2} |\varepsilon| \leq |\varepsilon(t)| \leq 2|\varepsilon|, \ E_k(t) \leq 4\delta^2 \right\}. \] (5-35) (5-36)
Then the above conditions hold for all \( t < T^* \). Moreover, the energy estimate implies
\[
E_k(t) = \delta^2 + O_k(\delta^3 + t(\delta^4 + |\varepsilon|\delta^3)) = \delta^2 + O_k(\delta^3(1 + t|\varepsilon|)).
\]
Then there is \( c_k > 0 \) such that if \( T^* \leq c_k/|\varepsilon| \), then \( E_k(t) \leq 2\delta^2 \). Also,
\[
\|f(x, t)\|_{L^2} - \|u_\varepsilon\|_{L^2} = \|f(x, 0)\|_{L^2} - \|u_\varepsilon\|_{L^2} \leq \|g\|_{L^2} \lesssim \delta
\]
by conservation of the \( L^2 \) norm. Meanwhile \( \|f(x, t)\|_{L^2} - \|u_{\varepsilon(t)}\|_{L^2} \lesssim \delta \), so \( \|u_{\varepsilon(t)}\|_{L^2} - \|u_\varepsilon\|_{L^2} \lesssim \delta \).
When \( |\varepsilon| \) is small enough, \( \|u_\varepsilon\|_{L^2} \) is differentiable in \( \varepsilon \) with nonzero derivative at \( \varepsilon = 0 \). Since \( \delta/|\varepsilon| \) is small enough, \( |\varepsilon(t) - \varepsilon| \lesssim \delta \).
By local well-posedness, the solution can be extended to a time \( t^* > T^* \), with
\[
\|f(x, t) - f(x, T^*)\|_{H^2} \lesssim (t^* - T^*)^{\frac{1}{4}} \|f(x, t)\|_{H^3} + \|f(x, t)\|_{H^3}^2 \leq (t^* - T^*)|\epsilon|
\]
for \( t \in [T^*, t^*] \). Then \( \|f(x, t) - u_{\epsilon(T^*)}(x + a(T^*))\|_{H^2} \lesssim (t^* - T^*)|\epsilon| + \delta \). Take \( t^* = T^* + \delta/|\epsilon| \). Then \( f(x, t) \) satisfies the conditions in Proposition 4.1, so (5-35) holds up to time \( t^* \). Since \( f(x, T^*) \) is small in \( H^4 \), \( f(x, t) \) is uniformly bounded in \( H^4 \) on \([T^*, t^*]\), so it stays within a compact set in \( H^2 \). Since \( \epsilon \) is differentiable in \( f \in H^2 \), \( |\epsilon(t) - \epsilon(T^*)| \lesssim (t^* - T^*)|\epsilon| \leq \delta \), so \( |\epsilon(t)| \leq |\epsilon(t)| \leq 2|\epsilon| \) holds up to time \( t^* \). The energy estimate then implies \( E_k \leq 3\delta^2 \) also up to time \( t^* \), so (5-36) holds up to time \( t^* \), contradicting the definition of \( T^* \). Hence the lifespan \( T^* \geq_\delta 1/|\epsilon| \).

5C. **Longer lifespan when \( \delta \ll \epsilon^2 \).** When the perturbation \( g \) is very small compared to \( \epsilon^2 \), that is, \( \|g_0\|_{H^5(\Omega)} = \delta \ll \epsilon^2 \), we can obtain a longer lifespan by applying the normal form transformation to
\[
E_{N2} = E_N - E_{N1} = E_{N21} + E_{N22} + E_{N23} + E_{N24},
\]
where
\[
E_{N21} = \sum_{j=1}^{[k/2]+1} c'_{kj} \int_0^{2\pi} \partial_x^k h(t) \partial_x^{k+2-j}(\phi' \circ \phi^{-1})(1 + W_\epsilon)^{-1} h(t) \partial_x^j((\phi' \circ \phi^{-1})(1 + W_\epsilon)^{-1} h(t)) dx,
\]
\[
E_{N22} = \sum_{j=1}^{[k/2]+1} \sum_{i=1}^j c_{kji} \int_0^{2\pi} \partial_x^k h(t) \partial_x^i(\phi' \circ \phi^{-1}) \partial_x^{k+2-i-j} h(t) \partial_x^j((\phi' \circ \phi^{-1})(1 + W_\epsilon)^{-1} h(t)) dx,
\]
\[
E_{N23} = \sum_{j=2}^{[k/2]+1} c_{kj} \int_0^{2\pi} \partial_x^k h(t)(\phi' \circ \phi^{-1} - 1) \partial_x^{k+2-j} h(t) \partial_x^j((\phi' \circ \phi^{-1})(1 + W_\epsilon)^{-1} h(t)) dx,
\]
\[
E_{N24} = \sum_{j=2}^{[k/2]+1} c_{kj} \int_0^{2\pi} \partial_x^k h(t) \partial_x^{k+2-j} h(t) \partial_x^j((\phi' \circ \phi^{-1})(1 + W_\epsilon)^{-1} h - h) dx,
\]
where \( c_{kj}, c'_{kj} \) and \( c_{kji} \in \mathbb{R} \) are constants and we integrated by parts to get rid of the terms with \( k + 1 \) derivatives falling on a single factor of \( h \), except for the term with \( j = 1 \) in \( E_{N21} \), in which the \( k + 1 \) derivatives do not matter in view of the fact that the operator \((\phi' \circ \phi^{-1})(1 + W_\epsilon)^{-1})\) is of class \( S \).

Now we define
\[
D_{\epsilon,21}[f_1, f_2, f_3] = \sum_{j=1}^{[k/2]+1} \frac{c'_{kj}}{\lambda_m(\epsilon) + \lambda_n(\epsilon) + \lambda_l(\epsilon)} \int_0^{2\pi} f_1(m + sgn m) e^{i(m + sgn m)x} \times \partial_x^{k+2-j}((\phi' \circ \phi^{-1})(1 + W_\epsilon)^{-1} f_2(n + sgn n) e^{i(n + sgn n)x}) \times \partial_x^j((\phi' \circ \phi^{-1})(1 + W_\epsilon)^{-1} f_3(l + sgn l) e^{i(l + sgn l)x}),
\]
and
\[
D_{21}(t) = D_{\epsilon,21}[h(t), h(t), h(t)],
\]
and similarly define $D_{22}$, $D_{23}$ and $D_{24}$. Then
\[
\frac{d}{dt} D_{21}(t) - E_{N21}(t) = \epsilon'(t)(\partial_\epsilon D_{\epsilon,21})[h(t), h(t), h(t)] + D_{\epsilon,21}[(\partial_t - \Lambda_\epsilon)h(t), h(t), h(t)] + D_{\epsilon,21}[h(t), h(t), (\partial_t - \Lambda_\epsilon)h(t)].
\]

We estimate these terms one by one.

For (5-37), (5-11) still holds, but there are nontrivial actions on $h$ in the slots, so no frequency restriction such as (5-12) exists. When $m + n + l \neq 0$, we are in Case 1 of Proposition 3.11, so (5-13), and hence (5-14), still hold. When $m + n + l = 0$, by Case 2 of Proposition 3.11, when $\epsilon$ is small enough,
\[
|\lambda_m(\epsilon) + \lambda_n(\epsilon) + \lambda_l(\epsilon)| > \frac{1}{2}\epsilon^2,
\]
which, combined with (5-11), shows that the multiplier in $\partial_\epsilon D_\epsilon$ is bounded by
\[
\frac{|\lambda'_m(\epsilon) + \lambda'_n(\epsilon) + \lambda'_l(\epsilon)|}{|\lambda_m(\epsilon) + \lambda_n(\epsilon) + \lambda_l(\epsilon)|^2} \lesssim |\epsilon|^{-3}
\]
instead of (5-14). Since both $(\phi'_\epsilon \circ \phi^{-1}_\epsilon)((1 + W_\epsilon)^{-1} - 1)/\epsilon$ and $\partial_\epsilon(\phi'_\epsilon \circ \phi^{-1}_\epsilon)((1 + W_\epsilon)^{-1} - 1)$ are of class $S$ uniformly in $\epsilon$, it follows that, for $k \geq 3$,
\[
|(5-37)| \lesssim_k |\epsilon'(t)|\epsilon^{-2}E_k(t)^{3/2} \lesssim \epsilon^{-2}E_2(t)E_k(t)^{3/2}
\]
provided that $\epsilon$ is small enough.

The terms (5-38), (5-39) and (5-40) are like (5-8), (5-9) and (5-10) respectively, except that instead of the uniform lower bound of $\lambda_m(\epsilon) + \lambda_n(\epsilon) + \lambda_l(\epsilon)$ we now have (5-41), which loses two factors of $\epsilon$, but we are helped by the $\epsilon$-smallness of $(\phi'_\epsilon \circ \phi^{-1}_\epsilon)((1 + W_\epsilon)^{-1} - 1)$, which wins back a factor of $\epsilon$. All told we lose a factor of $\epsilon$ compared to (5-32), so, for $k \geq 5$,
\[
|(5-38) + (5-39) + (5-40)| \lesssim_k |\epsilon|^{-1}(1 + E_4(t)^{1/2})E_k(t)^2
\]
provided that $\epsilon$ and $\|g(t)\|_{H^1}/|\epsilon|$ are small enough.

Combining (5-43) and (5-44) shows that, for $k \geq 5$,
\[
\left|\frac{d}{dt} D_{21}(t) - E_{N21}(t)\right| \lesssim_k |\epsilon|^{-1}(1 + E_4(t)^{1/2})E_k(t)^2
\]
provided that $\epsilon$ and $\|g(t)\|_{H^1}/|\epsilon|$ are small enough. We can also save a factor of $\epsilon$ in the other terms $E_{N22}$, $E_{N23}$ and $E_{N24}$ thanks to the $\epsilon$-smallness of $(\phi'_\epsilon \circ \phi^{-1}_\epsilon)'$ and $\phi'_\epsilon \circ \phi^{-1}_\epsilon - 1$. Hence the bound (5-45) also holds for $E_{N22}$, $E_{N23}$ and $E_{N24}$.

Combining (5-5), (5-32) and (5-45) shows that, for $k \geq 5$,
\[
E_k(t) - E_k(0) = \sum_{j=2}^{[k/2]+1} c_{k,j}(D_{1,k,j}(t) - D_{1,k,j}(0)) + \sum_{j=1}^{4} (D_{2j}(t) - D_{2j}(0)) + O_k(|\epsilon|^{-1}(1 + E_4^{1/2})E_k^2L^1((0,t)))
\]
provided that $\epsilon$ and $\|g(t)\|_{H^1}/|\epsilon|$ are small enough. Similarly to (5-33), for $k \geq 3$,

$$|D_{2,k,j}(t)| \lesssim_k \epsilon(t)^{-2}|\epsilon(t)|E_k(t)^{3/2} = E_k(t)^{3/2}/|\epsilon|.$$  

Hence if $E_k(0) = \delta^2 \lesssim 1$ and $E_k \leq 2\delta^2$ on $[0, t]$ then

$$E_k(t) = \delta^2 + |\epsilon|^{-1}\delta^3 + O_k(t)|\epsilon|^{-1}\delta^4).$$

Assume $\delta/\epsilon^2$ is small. Then the second term on the right-hand side is $\lesssim \delta^{5/2}$, so we close the estimate for a time $t \lesssim_k |\epsilon|/\delta^2$, which is also the lifespan in this case.

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ÁNGEL CASTRO: angel_castro@icmat.es
Instituto de Ciencias Matemáticas ICMAT-CSIC-UAM-UCM-UC3M, Madrid, Spain

DIEGO CÓRDOBA: dcg@icmat.es
Instituto de Ciencias Matemáticas ICMAT-CSIC-UAM-UCM-UC3M, Madrid, Spain

FAN ZHENG: fan.zheng@icmat.es
Instituto de Ciencias Matemáticas ICMAT-CSIC-UAM-UCM-UC3M, Madrid, Spain
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