CONVERGENCE OF PETVIASHVILI’S METHOD NEAR PERIODIC WAVES
IN THE FRACTIONAL KORTEWEG–DE VRIES EQUATION

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ABSTRACT. Petviashvili’s method has been successfully used for approximating of solitary waves
in nonlinear evolution equations. It was discovered empirically that the method may fail for
approximating of periodic waves. We consider the case study of the fractional Korteweg–de Vries
equation and explain divergence of Petviashvili’s method from unstable eigenvalues of the generalized
eigenvalue problem. We also show that a simple modification of the iterative method after the
mean value shift results in the unconditional convergence of Petviashvili’s method. The results are
illustrated numerically for the classical Korteweg–de Vries and Benjamin–Ono equations.

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1. INTRODUCTION

A robust iterative method for approximating solitary waves was proposed by V.I. Petviashvili in
1976 [36]. Since then, it has become a popular numerical toolbox [39] with many recent generali-
zations in [28, 29] and in [1, 2, 3].

In the context of Euler equations for water waves, Petviashvili’s iterative method turns out to be
very useful for computing the solitary gravity waves [13,18]. However, it has been found empirically
that the iterative algorithm does not converge for periodic waves, hence suitable generalizations were
proposed in the case of infinite [19] and finite [14] depths. The work [19] explores the generalization
of Petviashvili’s method for non-power nonlinearities proposed originally in [28]. The work of [14]
relies on an iteration-dependent shift of the field variable to enforce positivity of the periodic wave, after which the classical Petviashvili method can be employed.

In a setting of fractional Korteweg-de Vries (KdV) and extended Boussinesq equations, another modification of the Petviashvili method was proposed in [4, 17], where an iteration-independent shift of the field variable was computed from the underlying equation. Numerical results in [4] illustrated convergence of the Petviashvili method for the periodic waves after the shift.

The main purpose of this work is to explain analytically the failure of the classical Petviashvili method for approximating of periodic waves and to prove convergence of the same method after a suitable shift of the field variable. We consider the toy problem given by the fractional KdV equation with a quadratic nonlinearity, which is a simplified model arising from the Euler equations in the shallow limit [8]. The fractional KdV equation is taken in the normalized form

\[ u_t + 2uu_x + (D_\alpha u)_x = 0, \]

where \( D_\alpha \) is a fractional derivative operator defined by its Fourier symbol

\[ \hat{D}_\alpha u(\xi) = -|\xi|^\alpha \hat{u}(\xi), \quad \xi \in \mathbb{R}. \]

The case \( \alpha = 2 \) corresponds to the classical KdV equation, whereas the case \( \alpha = 1 \) corresponds to the integrable BO (Benjamin–Ono) equation. Henceforth, we assume that \( \alpha > 0 \).

Global existence in the fractional KdV equation (1.1) for the initial data in the energy space \( H^{\alpha/2} \) was proven in [30] for \( \alpha > 1/2 \) and for \( \alpha = 1/2 \) and small data. More recently, local existence for the initial data in \( H^s \) was shown for \( \alpha > 0 \) and \( s > 3/2 - 5\alpha/4 \) in [32].

Existence and stability of periodic waves in the fractional KdV equation (1.1) were analyzed by using perturbative [26] and variational [9, 10, 24] methods. For the classical KdV and BO equations, stability of periodic waves was also proven in [6]. These results, especially perturbation expansions in the limit of small wave amplitudes, are also useful in our analysis of convergence of iterative methods near the periodic waves.

Periodic traveling waves are solutions of the fractional KdV equation (1.1) in the form \( u(x,t) = \psi(x-ct) \), where \( \psi \) is a periodic function in its argument and \( c \) is the speed parameter for the wave travelling to the right. Without loss of generality, due to scaling and translation invariance of the fractional KdV equation (1.1), we scale the period of \( \psi \) to \( 2\pi \) and translate \( \psi \) to become an even function of its argument. Due to the Galilean invariance, integration of the nonlinear equation for \( \psi \) is performed with zero integration constant. All together, the wave profile \( \psi \) is a \( 2\pi \)-periodic even solution to the following boundary-value problem:

\[ (c - D_\alpha)\psi = \psi^2, \quad \psi \in H^\alpha_{\text{per}}(-\pi, \pi). \]

We say that the periodic wave has a single-lobe profile if there exist only one maximum and minimum of \( \psi \) on the period. For uniqueness of solutions, we place the maximum of \( \psi \) at \( x = 0 \) and the minimum of \( \psi \) at \( x = \pm \pi \).

In addition to the waves travelling to the right, the fractional KdV equation (1.1) has also periodic traveling waves in the form \( u(x,t) = \phi(x+ct) \), where \( \phi \) is a \( 2\pi \)-periodic even solution to the following boundary-value problem:

\[ (c + D_\alpha)\phi + \phi^2 = 0, \quad \phi \in H^\alpha_{\text{per}}(-\pi, \pi). \]

A very simple formula connects the right-propagating waves with the left-propagating waves:

\[ \phi(x) = -c + \psi(x). \]
The wave profile $w$ is a solution to the boundary-value problem (1.3) with some $c > 0$ if and only if $w$ is a solution to the boundary-value problem (1.2) with the same $c > 0$. Section 2 collects together some results on existence of solutions to the boundary-value problems (1.2) and (1.3).

Remark 1.1. Although most of the previous works (see, e.g., [6, 9, 10, 24, 26]) are devoted to the right-propagating waves with profile $w$, there are no apriori reasons to prefer these waves over the left-propagating waves with profile $w$. Perturbative expansions for waves of small amplitudes are more easily developed for the left-propagating waves with profile $w$ since they arise in the local bifurcation theory from linearization of the zero equilibrium (see Theorem 2.1 below). On the other hand, the proof of positivity of the wave profile $w$ is developed easier from the boundary-value problem (1.2) (see Theorem 2.2 below).

Let us now explain how Petviashvili’s iterative methods can be employed in order to approximate solutions to the boundary-value problems (1.2) and (1.3) numerically. In fact, the most interesting interplay between convergent and divergent iterations arises in the context of the boundary-value problem (1.3).

Suppose that $w \in H^\alpha_{\text{per}}(-\pi, \pi)$ is a solution to the boundary-value problem (1.3) for some $c > 0$. For uniqueness of solutions, we always denote by $w$ the single-lobed periodic solution in the sense of the definition above. The classical Petviashvili method for approximating of $w$ is defined as follows.

Consider $L_{c,\alpha} := -c - D_\alpha$ as a linear operator in $L^2_{\text{per}}(-\pi, \pi)$ with the domain $H^\alpha_{\text{per}}(-\pi, \pi)$ and define the Petviashvili quotient:

$$M(w) := \frac{\langle L_{c,\alpha}w, w \rangle}{\langle w^2, w \rangle}, \quad w \in H^\alpha_{\text{per}}(-\pi, \pi),$$

where $\langle \cdot, \cdot \rangle$ denotes the standard inner product in $L^2_{\text{per}}(-\pi, \pi)$. For $c \notin \{1, 2^\alpha, 3^\alpha, \ldots\}$, for which the linear operator $L_{c,\alpha} : H^\alpha_{\text{per}}(-\pi, \pi) \rightarrow L^2_{\text{per}}(-\pi, \pi)$ is invertible, and for any suitable initial guess $w_0 \in H^\alpha_{\text{per}}(-\pi, \pi)$, define a sequence $\{w_n\}_{n \in \mathbb{N}}$ in $H^\alpha_{\text{per}}(-\pi, \pi)$ by the iterative rule:

$$w_{n+1} = T_{c,\alpha}(w_n) := [M(w_n)]^2 L_{c,\alpha}^{-1}(w_n^2), \quad n \in \mathbb{N},$$

Here we have selected the quadratic exponent of $M(w_n)$ so that $T_{c,\alpha}(w)$ is a homogeneous power function in $w$ of degree zero. This ensures the fastest convergence rate of the iterative method (1.6) near a solution of the nonlinear equation (1.3).

As is well understood since the first proof of convergence in [35] (see also follow-up works in [2, 3, 11, 16, 28]), convergence of the iterative method is analyzed from contraction of the linearized operator at the fixed point $w \in H^\alpha_{\text{per}}(-\pi, \pi)$ of $T_{c,\alpha}$. By Lemma 1.2 in [35], the set of fixed points of $T_{c,\alpha}$ coincides with the set of solutions to the boundary-value problem (1.3). Contraction of the corresponding linearized operator is defined by the spectrum of the generalized eigenvalue problem

$$H_{c,\alpha}v = \lambda L_{c,\alpha}v, \quad v \in H^\alpha_{\text{per}}(-\pi, \pi),$$

where

$$H_{c,\alpha} := -c - D_\alpha - 2\phi$$

is the associated linearized operator in $L^2_{\text{per}}(-\pi, \pi)$ with the domain $H^\alpha_{\text{per}}(-\pi, \pi)$. Note that $H_{c,\alpha}$ is the Jacobian operator for the boundary-value problem (1.3), which also plays the crucial role in the stability analysis of the travelling periodic waves [6, 24, 26].

Section 3 presents the main result on convergence of the iterative method (1.6). Here and in what follows, the following critical values of $\alpha$ are important:

$$\alpha_0 := \frac{\log 3}{\log 2} - 1, \quad \alpha_1 := \frac{\log 5}{\log 2} - 1.$$
where $1/2 < \alpha_0 < 1 < \alpha_1 < 2$. The proof of the main result is achieved by the count of unstable eigenvalues in the generalized eigenvalue problem (1.7) and by perturbative arguments.

**Theorem 1.1.** For every $c > 1$ and $\alpha \in (\alpha_0, 2]$, there exists a unique single-lobe solution $\phi \in H^\alpha_{\text{per}}(-\pi, \pi)$ to the boundary-value problem (1.3). If $c \geq 1$, this unique solution is an unstable fixed point of the iterative method (1.6) for $\alpha \in (\alpha_0, \alpha_1)$ and an asymptotically stable fixed point (up to a translation) for $\alpha \in (\alpha_1, 2]$. If $c > 2^\alpha$, this unique solution is an unstable fixed-point of the iterative method (1.6) for $\alpha \in (\alpha_0, 2]$.

**Remark 1.2.** Notation $c \geq 1$ implies that there is $c_0 > 1$ near 1 such that the statement holds for every $c \in (1, c_0)$. The unique solution to the boundary-value problem (1.3) exists also for $\alpha < \alpha_0$ but is located for $c \lessgtr 1$.

**Remark 1.3.** The constraint $\alpha \leq 2$ is necessary to apply results of [24] on existence of single-lobe solution $\phi$ and the non-degeneracy of the kernel of $\mathcal{H}_{c,\alpha}$ at $\phi$. The periodic wave $\phi$ may develop oscillations for $\alpha > 2$ and sufficiently large $c$, in which case methods of [24] are not applicable.

**Remark 1.4.** Theorem 1.1 implies that the iterative method (1.6) diverges from $\phi$ for the classical BO equation with $\alpha = 1$. Although the iterative method (1.6) converges to $\phi$ for the classical KdV equation with $\alpha = 2$ for $c \geq 1$, we show numerically that it diverges from $\phi$ for $c \geq 2.3$. Instabilities of the iterative method (1.6) are explained by the unstable eigenvalues of the generalized eigenvalue problem (1.7).

As is suggested by Theorem 1.1, the iterative method (1.6) is unsuccessful in approximating the solution $\phi$ to the boundary-value problem (1.3). On the other hand, we can develop a similar method for the solution $\psi$ of the equivalent boundary-value problem (1.2), which is related to $\phi$ by the transformation (1.4). By setting $\tilde{\mathcal{L}}_{c,\alpha} := c - D_{\alpha}$, we denote

\[(1.10) \quad \tilde{M}(w) := \langle \tilde{\mathcal{L}}_{c,\alpha} w, w \rangle / \langle w^2, w \rangle, \quad w \in H^\alpha_{\text{per}}(-\pi, \pi),\]

and define a sequence $\{w_n\}_{n \in \mathbb{N}}$ in $H^\alpha_{\text{per}}(-\pi, \pi)$ for any suitable initial guess $w_0 \in H^\alpha_{\text{per}}(-\pi, \pi)$ by the iterative rule:

\[(1.11) \quad w_{n+1} = \tilde{T}_{c,\alpha} (w_n) := \left[ \tilde{M}(w_n) \right]^{2} \tilde{\mathcal{L}}_{c,\alpha}^{-1}(w_n^2), \quad n \in \mathbb{N}.\]

Contraction of the linearized operator of the iterative rule (1.11) is defined by the spectrum of the generalized eigenvalue problem

\[(1.12) \quad \tilde{\mathcal{H}}_{c,\alpha} v = \lambda \tilde{\mathcal{L}}_{c,\alpha} v, \quad v \in H^\alpha_{\text{per}}(-\pi, \pi),\]

where the new Jacobian operator for the boundary-value problem (1.2) is identical to the Jacobian operator (1.8) of the boundary-value problem (1.3):

\[(1.13) \quad \tilde{\mathcal{H}}_{c,\alpha} := c - D_{\alpha} - 2\psi = -c - D_{\alpha} - 2(-c + \psi) = \mathcal{H}_c,\]

where the transformation (1.4) has been used.

Section 4 presents the main result on convergence of the iterative method (1.11). In addition to the count of unstable eigenvalues in the generalized eigenvalue problem (1.12), we use here positivity of the wave profile $\psi$ for solutions to the boundary-value problem (1.2).

**Theorem 1.2.** For every $c > 1$ and $\alpha \in (\alpha_0, 2]$, there exists a unique single-lobe solution $\psi \in H^\alpha_{\text{per}}(-\pi, \pi)$ to the boundary-value problem (1.2) such that $\psi(x) > 0$ for every $x \in [-\pi, \pi]$. This unique solution is an asymptotically stable (up to a translation) fixed point of the iterative method (1.11) for every $c > 1$ and $\alpha \in (\alpha_0, 2]$. 

Remark 1.5. The unconditional convergence of the iterative method (1.11) compared to the iterative method (1.6) has a well-known physical interpretation. The phase velocity of the linear waves of the fractional KdV equation (1.1) on the zero background is strictly negative, hence the travelling wave \( u(x,t) = \phi(x + ct) \) propagating to the left is in resonance with the linear waves. On the other hand, the travelling wave on the constant background \( b := -c < 0 \) propagates to the right and avoids resonances with the linear waves on the background \( b < 0 \), which still have negative phase velocity.

Remark 1.6. The new iterative method (1.11) can be considered as a modification of the classical Petviashvili method (1.6) after the shift of the field variable proposed in [4]. The modified algorithm consists of three steps. In the first step, the constant value \( b \) is found from the constant solution of the stationary problem (1.3). Solving \( cb + b^2 = 0 \) for nonzero \( b \) yields \( b = -c \). In the second step, the change of variables \( \phi = b + \psi \) transforms the original problem (1.3) to the new problem (1.2), which is confirmed from the transformation formula (1.4) since \( b = -c \). Finally, the third step is the iterative method for the transformed problem (1.2), which is defined by the new iterative operator \( \tilde{T}_{c,\alpha} \) in (1.11).

Remark 1.7. In the case of solitary waves, the boundary-value problem (1.3) for \( \phi \) and \( c > 0 \) admits no solutions and the iterative method (1.6) cannot be defined since \( L_{c,\alpha} \) is not invertible in \( L^2(\mathbb{R}) \) for \( c > 0 \). On the other hand, the boundary-value problem (1.2) for \( \psi \) and \( c > 0 \) admits solitary wave solutions and the iterative method (1.11) is well-defined to approximate this solution, as shown numerically in [17].

2. Periodic waves of the fractional KdV equation

We collect together some results on existence of periodic wave solutions to the boundary-value problems (1.2) and (1.3). Some of the previous results have been improved and we specify explicitly where the improvement has been made. Section 2.1 presents results on the small-amplitude limit of the periodic waves with profile \( \phi \). Sections 2.2 and 2.3 collects together explicit expressions for the periodic waves in the classical KdV and BO equations, respectively. Section 2.4 gives results on the positivity of the wave profile \( \psi \).

2.1. Small-amplitude limit of the periodic waves. The following result reports on existence of the periodic wave \( \phi \) of the boundary-value problem (1.3) in the small-amplitude limit. The small-amplitude periodic waves bifurcate from the constant zero solution to the boundary-value problem (1.3). The construction of the small-amplitude periodic waves is nearly identical to Lemma 2.1 in [26] subject to the following two changes. First, the constant of integration is set to zero thanks to the Galilean invariance, while in [26] the constant was carried as an additional (redundant) parameter of the problem. Second, the speed \( c \) is used as the main parameter of the periodic solution while the period is set to \( 2\pi \), whereas in [26] \( c \) was set to 1 and the period was taken as the main parameter of the periodic solution.

Although the formal computations of the periodic waves in the small-amplitude limit hold for every \( \alpha > 0 \), the justification of the perturbative expansions requires \( \alpha > 1/2 \), for which \( H^\alpha_{\text{per}}(-\pi,\pi) \) is a Banach algebra with respect to multiplication with a continuous embedding into \( L^\infty_{\text{per}}(-\pi,\pi) \). A typical justification of the perturbative expansions is based on the method of Lyapunov–Schmidt reductions which requires smoothness of the nonlinear mappings. This smoothness is guaranteed in \( H^\alpha_{\text{per}}(-\pi,\pi) \) with \( \alpha > 1/2 \). Since refinement to \( \alpha \in (0,1/2) \) is not important for the subject of our work, we leave the restriction \( \alpha > 1/2 \) in the same way as it was used in Theorem A.1 in [26].
Theorem 2.1. For every \( c \geq 1 \) and \( \alpha > \alpha_0 \), there exists a unique single-lobe solution \( \phi \) of the boundary-value problem \([1.3]\) with the global maximum at \( x = 0 \). The wave profile \( \phi \) and the wave speed \( c \) are real-analytic functions of the wave amplitude \( a \) satisfying the following Stokes expansions:

\[
\phi_{a,\alpha}(x) = a \cos(x) + a^2 \phi_2(x) + a^3 \phi_3(x) + a^4 \phi_4(x) + \mathcal{O}(a^5),
\]

and

\[
c_{a,\alpha} = 1 + c_2 a^2 + c_4 a^4 + \mathcal{O}(a^6),
\]

where the \( \alpha \)-dependent corrections terms \( \{\phi_2,\phi_3,\phi_4\} \) and \( \{c_2,c_4\} \) are defined in \([2.3]–[2.7]\) below.

Proof. We give algorithmic computations of the higher-order coefficients to the periodic wave by using the classical Stokes expansions:

\[
\phi(x) = \sum_{k=1}^{\infty} a^k \phi_k(x), \quad c = 1 + \sum_{k=1}^{\infty} c_{2k} a^{2k}.
\]

The correction terms satisfy recursively,

\[
\begin{align*}
\mathcal{O}(a) : \quad (1 + D_a) \phi_1 &= 0, \\
\mathcal{O}(a^2) : \quad (1 + D_a) \phi_2 + \phi_1^2 &= 0, \\
\mathcal{O}(a^3) : \quad (1 + D_a) \phi_3 + c_2 \phi_1 + 2 \phi_1 \phi_2 &= 0, \\
\mathcal{O}(a^4) : \quad (1 + D_a) \phi_4 + c_2 \phi_2 + 2 \phi_1 \phi_3 + \phi_2^2 &= 0, \\
\mathcal{O}(a^5) : \quad (1 + D_a) \phi_5 + c_2 \phi_3 + c_4 \phi_1 + 2 \phi_1 \phi_4 + 2 \phi_2 \phi_3 &= 0,
\end{align*}
\]

For the single-lobe wave profile \( \phi \) with the global maximum at \( x = 0 \), we select uniquely \( \phi_1(x) = \cos(x) \) since \( \text{Ker}_{\text{even}}(1 + D_a) = \text{span}\{\cos(\cdot)\} \) in the space of even functions in \( L_{\text{per}}^2(-\pi,\pi) \). In order to select uniquely all other corrections to the Stokes expansion \([2.1]\), we require the corrections terms \( \{\phi_k\}_{k \geq 2} \) to be orthogonal to \( \phi_1 \) in \( L_{\text{per}}^2(-\pi,\pi) \).

Solving the inhomogeneous equation at \( \mathcal{O}(a^2) \) yields the exact solution in \( H_{\text{per}}^\alpha(-\pi,\pi) \):

\[
\phi_2(x) = -\frac{1}{2} + \frac{1}{2(2^\alpha - 1)} \cos(2x).
\]

The inhomogeneous equation at \( \mathcal{O}(a^3) \) admits a solution \( \phi_3 \in H_{\text{per}}^\alpha(-\pi,\pi) \) if and only if the right-hand side is orthogonal to \( \phi_1 \), which selects uniquely the correction \( c_2 \) by

\[
c_2 = 1 - \frac{1}{2(2^\alpha - 1)}.
\]

After the resonant term is removed, the inhomogeneous equation at \( \mathcal{O}(a^3) \) yields the exact solution in \( H_{\text{per}}^\alpha(-\pi,\pi) \):

\[
\phi_3(x) = \frac{1}{2(2^\alpha - 1)(3^\alpha - 1)} \cos(3x).
\]

By continuing the algorithm, we find the exact solution of the inhomogeneous equation at \( \mathcal{O}(a^4) \) in \( H_{\text{per}}^\alpha(-\pi,\pi) \):

\[
\phi_4(x) = \frac{1}{4} - \frac{1}{4(2^\alpha - 1)} - \frac{1}{8(2^\alpha - 1)^2} + \frac{1}{4(2^\alpha - 1)^2} \left[ \frac{2}{3^\alpha - 1} - \frac{1}{2^\alpha - 1} \right] \cos(2x)
\]

\[
+ \frac{1}{8(2^\alpha - 1)(4^\alpha - 1)} \left[ \frac{4}{3^\alpha - 1} + \frac{1}{2^\alpha - 1} \right] \cos(4x).
\]
Finally, the inhomogeneous equation at $O(a^5)$ admits a solution $\phi_5 \in H_\alpha^\per(-\pi, \pi)$ if and only if the right-hand side is orthogonal to $\phi_1$, which selects uniquely the correction $c_4$ by

\begin{equation}
(2.7) \quad c_4 = -\frac{1}{2} + \frac{1}{2(2^\alpha - 1)} + \frac{1}{4(2^\alpha - 1)^2} + \frac{1}{4(2^\alpha - 1)^3} - \frac{3}{4(2^\alpha - 1)^2(3^\alpha - 1)}.
\end{equation}

Note that $c_2 > 0$ if $\alpha > \alpha_0 := \log 3/\log 2 - 1$, which implies that the small-amplitude periodic wave with profile $\phi$ exists in the boundary-value problem (1.3) for $c \gtrsim 1$ and $\alpha > \alpha_0$. The periodic wave has a global maximum at $x = 0$ for small $a$ since $x = 0$ is the only maximum of $\phi_1(x) = \cos(x)$ and $\phi'(0) = 0$ with $\phi''(0) = -a + O(a^2) < 0$.

Justification of the existence, uniqueness, and analyticity of the Stokes expansions (2.1) and (2.2) is performed with the method of Lyapunov–Schmidt reductions for $\alpha > 1/2$, see Lemma 2.1 and Theorem A.1 in [26]. Since $\alpha_0 > 1/2$, the justification procedure applies for every $\alpha > \alpha_0$. $\square$

**Remark 2.1.** If $\alpha < \alpha_0$, then $c_2 < 0$ so that the small-amplitude periodic wave exists for $c \ll 1$. The critical value $\alpha_0$ can also be seen in the expansion of the wave period $T$ (for fixed $c = 1$) with respect to the wave amplitude $a$ in Lemma 2.1 of [26].

**Remark 2.2.** Variational results on existence of finite-amplitude periodic waves in the boundary-value problem (1.2) are obtained in Proposition 2.1 of [24] in the energy space $H_{\alpha/2}^\per(-\pi, \pi)$ for $\alpha \in (1/3, 2]$. It is shown that there exists a local minimizer of energy for fixed momentum and mass for every $c > 0$, however, it is overlooked in [24] that the local minimizer may coincide with the nonzero constant solution $\psi_c(x) = c$ for all $x \in [-\pi, \pi]$ to the same boundary-value problem (1.2), see also Theorem 2.2.

For further reference, we prove the following technical result. For notational convenience, we omit parameters $a$ and $\alpha$ when we refer to the periodic wave profile $\phi$ which solves the boundary-value problem (1.3) for some $c \gtrsim 1$.

**Lemma 2.1.** For every $c \gtrsim 1$, the periodic wave $\phi$ defined in Theorem 2.1 satisfies

\begin{equation}
(2.8) \quad \begin{cases}
\int_{-\pi}^{\pi} \phi^3 \, dx < 0, & \alpha > \alpha_0, \\
\int_{-\pi}^{\pi} \phi(\phi')^2 \, dx > 0, & \alpha < \alpha_0,
\end{cases}
\end{equation}

and

\begin{equation}
(2.9) \quad \begin{cases}
\int_{-\pi}^{\pi} \phi(\phi')^2 \, dx < 0, & \alpha > \alpha_1, \\
\int_{-\pi}^{\pi} \phi(\phi')^2 \, dx > 0, & \alpha < \alpha_1,
\end{cases}
\end{equation}

where $\alpha_0$ and $\alpha_1$ are given by (1.9).

**Proof.** By using Stokes expansions (2.1), we compute

\[ \int_{-\pi}^{\pi} \phi^3 \, dx = \frac{3\pi a^4}{4(2^\alpha - 1)}(3 - 2^{\alpha+1}) + O(a^6) \]

and

\[ \int_{-\pi}^{\pi} \phi(\phi')^2 \, dx = \frac{\pi a^4}{4(2^\alpha - 1)}(5 - 2^{\alpha+1}) + O(a^6), \]

from which (2.8) and (2.9) follows thanks to the definition (1.9). $\square$

Since the Fourier basis $\{e^{inx}\}_{n \in \mathbb{Z}}$ in $L_{\per}^2(-\pi, \pi)$ diagonalizes $L_{c,\alpha}$, we obtain the spectrum of $L_{c,\alpha}$ in $L_{\per}^2(-\pi, \pi)$ for every $c \in \mathbb{R}$ and $\alpha > 0$:

\begin{equation}
(2.10) \quad \sigma(L_{c,\alpha}) = \{-c + |n|^\alpha, \quad n \in \mathbb{Z}\}.
\end{equation}
The following lemma clarifies the number and multiplicity of negative and zero eigenvalues of the Jacobian operator $\mathcal{H}_{c,\alpha}$ in $L^2_{\text{per}}(-\pi, \pi)$, where the expression for $\mathcal{H}_{c,\alpha}$ is given by (1.8).

**Lemma 2.2.** For every $c \geq 1$ and $\alpha > \alpha_0$, $\sigma(\mathcal{H}_{c,\alpha})$ in $L^2_{\text{per}}(-\pi, \pi)$ consists of one simple negative eigenvalue, a simple zero eigenvalue, and a countable sequence of positive eigenvalues bounded away from zero.

**Proof.** Note that $\sigma(\mathcal{H}_{c,\alpha})$ in $L^2_{\text{per}}(-\pi, \pi)$ is purely discrete for every $c > 1$, thanks to the compactness of $[-\pi, \pi]$ and boundedness of $\phi \in L^\infty_{\text{per}}(-\pi, \pi)$. For $c = 1$, $\mathcal{H}_{c=1,\alpha}$ coincides with $\mathcal{L}_{c=1,\alpha}$, hence it follows from (2.10) that $\sigma(\mathcal{H}_{c=1,\alpha})$ has a simple negative eigenvalue, a double zero eigenvalue, and a countable sequence of positive eigenvalues bounded away from zero.

Since $\mathcal{H}_{c,\alpha} - \mathcal{L}_{c,\alpha} = -2\phi$ is a bounded perturbation and $(\phi, c)$ depend analytically on $a$, the analytic perturbation theory (Theorem VII.1.7 in [27]) guarantees continuity of eigenvalues for $c \geq 1$ close to their limiting values as $c \to 1$. Therefore, the proof is achieved if we can show that the double zero eigenvalue of $\mathcal{H}_{c,\alpha}$ in $L^2_{\text{per}}(-\pi, \pi)$ splits as $c \geq 1$ into a simple zero eigenvalue and a simple positive eigenvalue.

Since $\text{Ker}(\mathcal{H}_{c=1,\alpha}) = \text{span}\{\cos(\cdot), \sin(\cdot)\}$ and $\mathcal{H}_{c=1,\alpha}\phi' = 0$ for every $c > 1$ with odd $\phi$, the zero eigenvalue associated with the subspace $\text{Ker}_{\text{odd}}(\mathcal{H}_{c=1,\alpha}) = \text{span}\{\sin(\cdot)\}$ persists for $c > 1$. It remains to check the shift of the zero eigenvalue associated with the subspace $\text{Ker}_{\text{even}}(\mathcal{H}_{c=1,\alpha}) = \text{span}\{\cos(\cdot)\}$. Hence, we expand $\mathcal{H}_{c,\alpha}$ in powers of $a$ by using (2.1):

\begin{equation}
(2.11) \quad \mathcal{H}_{c,\alpha} = -1 - D_\alpha - 2a \cos(x) - \frac{a^2}{2\alpha - 1} \left[ \cos(2x) - \frac{1}{2} \right] + \mathcal{O}(a^3)
\end{equation}

and look for solutions $(\lambda, v) \in \mathbb{R} \times H^0_{\text{per}}(-\pi, \pi)$ of the eigenvalue problem $\mathcal{H}_{c,\alpha}v = \lambda v$ near $(\lambda, v) = (0, \cos(\cdot))$ by using the expansions

$$v(x) = \cos(x) + av_1(x) + a^2v_2(x) + \mathcal{O}(a^3),$$
$$\lambda = a\lambda_1 + a^2\lambda_2 + \mathcal{O}(a^3).$$

The correction terms in $H^0_{\text{per}}(-\pi, \pi)$ satisfy recursively,

$$\begin{cases}
\mathcal{O}(a) : & (1 + D_\alpha)v_1 + 1 + \cos(2x) + \lambda_1 \cos(x) = 0, \\
\mathcal{O}(a^2) : & (1 + D_\alpha)v_2 + 2 \cos(x)v_1 + \frac{a^2}{2\alpha - 1} \left[ \cos(2x) - \frac{1}{2} \right] \cos(x) + \lambda_2 \cos(x) = 0.
\end{cases}$$

In order to determine them uniquely, we impose orthogonality conditions of $\{v_k\}_{k \geq 1}$ to $\cos(\cdot)$ in $L^2_{\text{per}}(-\pi, \pi)$. The linear inhomogeneous equation at $\mathcal{O}(a)$ admits a solution $v_1 \in H^0_{\text{per}}(-\pi, \pi)$ if and only if $\lambda_1 = 0$, after which the solution is found explicitly:

$$v_1(x) = \frac{1}{2\alpha - 1} \cos(2x) - 1.$$

The linear inhomogeneous equation at $\mathcal{O}(a^2)$ admits a solution $v_2 \in H^0_{\text{per}}(-\pi, \pi)$ if and only if $\lambda_2 = 2c_2^2$, where $c_2$ is defined by (2.4). Since $c_2 > 0$ if $\alpha > \alpha_0$, the small positive eigenvalue $\lambda = 2c_2a^2 + \mathcal{O}(a^3)$ bifurcates from the zero eigenvalue as $c \geq 1$. Functional-analytic setup for justification of perturbative expansions can be found in [26] (see also [23]) for $\alpha > 1/2$, which is met since $\alpha_0 > 1/2$. \hfill \Box

**Remark 2.3.** By using variational methods, it was shown in Proposition 3.1 and Lemma 3.3 of [24] that $\text{ker}(\mathcal{H}_{c,\alpha}) = \text{span}\{\phi'\}$ is one-dimensional, the zero eigenvalue is the lowest eigenvalue in the subspace of odd functions in $L^2_{\text{per}}(-\pi, \pi)$, and $\sigma(\mathcal{H}_{c,\alpha})$ has either one or two negative eigenvalues for every $c > 1$ and $\alpha \in (1/3, 2]$. By Lemma 2.2, $\sigma(\mathcal{H}_{c,\alpha})$ has only one simple negative eigenvalue for $\alpha > \alpha_0$ if $c \geq 1$. 

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The following lemma gives the isospectrality result for the linearized operator $\mathcal{H}_{c,\alpha}$ for all $c > 1$.

**Lemma 2.3.** For every $c > 1$ and $\alpha \in (\alpha_0, 2]$, $\sigma(\mathcal{H}_{c,\alpha})$ in $L^2_{\text{per}}(-\pi, \pi)$ consists of one simple negative eigenvalue, a simple zero eigenvalue, and a countable sequence of positive eigenvalues bounded away from zero.

**Proof.** By Proposition 2.1 of [24], the single-lobe solution $\psi$ of the boundary-value problem (1.2) exists for every $c > 1$ and $\alpha \in (1/3, 2]$ and the solution is a $C^1$ function of $c$ for $c > 1$. This result is extended to the single-lobe solution $\phi$ of the boundary-value problem (1.3) thanks to the transformation (1.4), where it is uniquely identified with the small-amplitude periodic wave in Theorem 2.1.

By Proposition 3.1 of [24], the kernel of $\mathcal{H}_{c,\alpha}$ at the single-lobe solution $\phi \in H^a_{\text{per}}(-\pi, \pi)$ is simple with $\ker(\mathcal{H}_{c,\alpha}) = \text{span}\{\phi^j\}$ for every $c > 1$ and $\alpha \in (1/3, 2]$. The number of negative eigenvalues of $\mathcal{H}_{c,\alpha}$ may change in the parameter continuations in $c$ if and only if the eigenvalues pass through zero. By Lemma 2.2, $\sigma(\mathcal{H}_{c,\alpha})$ at the single-lobe solution $\phi$ in $L^2_{\text{per}}(-\pi, \pi)$ consists of one simple negative eigenvalue, a simple zero eigenvalue, and a countable sequence of positive eigenvalues bounded away from zero for $c \gtrsim 1$ if $\alpha > \alpha_0$. By the continuity argument and Proposition 3.1 of [24], the same remains true for $\sigma(\mathcal{H}_{c,\alpha})$ for every $c > 1$ and $\alpha \in (\alpha_0, 2]$.

**Remark 2.4.** For the KdV case with $\alpha = 2$, a different homotopy argument for the proof of isospectrality of $\sigma(\mathcal{H}_{c,\alpha})$ can be developed, see, e.g., [25], based on the classical results on the non-degeneracy of the energy-to-period function in [37] and [21]. For the BO case with $\alpha = 1$, explicit computations based on complex analysis techniques were developed much earlier in [5].

### 2.2. Periodic waves in the KdV equation.

For the KdV equation (see, e.g., Proposition 4.1 in [22]), the solution $\phi$ to the boundary-value problem (1.3) with $\alpha = 2$ is given by

\begin{equation} \label{eq:2.12} \phi(x) = \frac{2K(k)^2}{\pi^2} \left[ 1 - 2k^2 - \sqrt{1 - k^2 + k^4} + 3k^2\text{cn}^2 \left( \frac{K(k)}{\pi} x ; k \right) \right] \end{equation}

where $\text{cn}$ is the Jacobi elliptic function, $K(k)$ is a complete elliptic integral of the first kind, and $k \in (0, 1)$ is the elliptic modulus that parameterizes the wave speed $c$ given by

\begin{equation} \label{eq:2.13} c = \frac{4K(k)^2}{\pi^2} \sqrt{1 - k^2 + k^4}. \end{equation}

The small-amplitude expansions (2.11)–(2.12) is recovered from (2.12)–(2.13) with the wave amplitude $a := 3k^2/4 + O(k^4)$ as $k \to 0$.

We prove that the map $(0, 1) \ni k \mapsto c \in (1, \infty)$ is strictly increasing, hence the explicit solution (2.12)–(2.13) exists for every $c > 1$ (see also [6]). We also extend the inequalities (2.8) and (2.9) with $\alpha = 2$ for every $c > 1$.

**Lemma 2.4.** The map $(0, 1) \ni k \mapsto c \in (1, \infty)$ for the solution (2.12)–(2.13) is strictly increasing. In addition, for every $c > 1$, we have

\begin{equation} \label{eq:2.14} \int_{-\pi}^{\pi} \phi^3 dx < 0, \quad \int_{-\pi}^{\pi} \phi(\phi')^2 dx < 0. \end{equation}

**Proof.** We have $\phi = 0$ and $c = 1$ at $k = 0$. Thanks to the smoothness of $\phi$ and $c$ in $k$, it holds from (2.13) by explicit differentiation:

\[ \frac{\pi^2 \sqrt{1 - k^2 + k^4}}{4K(k)} \frac{dc}{dk} = 2(1 - k^2 + k^4) \frac{dK(k)}{dk} - k(1 - 2k^2)K(k). \]
By using the differential relation,
\[ \frac{dK(k)}{dk} = \frac{E(k) - (1 - k^2)K(k)}{k(1 - k^2)}, \]
the previous expression can be reduced to the form
\[ \frac{\pi^2k(1 - k^2)\sqrt{1 - k^2} + k^2}{4K(k)} \frac{dc}{dk} = 2(1 - k^2 + k^4)E(k) - (2 - 3k^2 + k^4)K(k) =: I(k), \]
where \( E(k) \) is a complete elliptic integral of the second kind and \( I(k) \) is introduced for convenience. Note that \( I(0) = 0 \). We claim that the map \((0,1) \ni k \mapsto I \) is strictly increasing. Indeed, by using the differential relation
\[ \frac{dE(k)}{dk} = \frac{E(k) - K(k)}{k}, \]
we obtain after straightforward computations
\[ \frac{dI(k)}{dk} = 5k [(1 - k^2)K(k) - (1 - 2k^2)E(k)] > 0, \]
where the last inequality follows from the fact that \( K(k) > E(k) \) for every \( k \in (0,1) \). Since \( I(0) = 0 \), we have \( I(k) > 0 \) for every \( k \in (0,1) \), which implies that \( \frac{dk}{dc} > 0 \) for every \( k \in (0,1) \).

Let us now prove the inequalities (2.14) for every \( c > 1 \). Since \( \phi \) and \( c \) are smooth in \( k \), we differentiate the nonlinear equation in the boundary-value problem (1.3) with \( \alpha = 2 \) in \( k \) and obtain
\[ [c + D_{\alpha=2} + 2\phi] \frac{\partial \phi}{\partial k} + \frac{dc}{dk} \phi = 0. \]
Multiplying this equation by \( \phi \) and integrating on \([-\pi, \pi]\) imply that
\[ \int_{-\pi}^{\pi} \phi \partial_k \phi \, dx = -\frac{dc}{dk} \int_{-\pi}^{\pi} \phi^2 \, dx, \]
where we have used the facts that \( D_{\alpha=2} \) is self-adjoint in \( L_{\text{per}}^2(-\pi, \pi) \) and \( \phi, \partial_k \phi \in H_{\text{per}}^{\alpha=2}(-\pi, \pi) \). Since \( \frac{dc}{dk} > 0 \) for every \( k \in (0,1) \), the map \( k \mapsto \int_{-\pi}^{\pi} \phi \partial_k \phi^2 \, dx \) is strictly decreasing with \( \int_{-\pi}^{\pi} \phi \partial_k \phi^2 \, dx = 0 \) at \( k = 0 \). Therefore, \( \int_{-\pi}^{\pi} \phi \partial_k \phi^2 \, dx < 0 \) for \( k \in (0,1) \) by the continuity argument in \( k \).

Finally, the inequality \( \int_{-\pi}^{\pi} \phi(\phi')^2 \, dx < 0 \) for every \( c > 1 \) follows from the boundary-value problem (1.3) with \( \alpha = 2 \):
\[ \int_{-\pi}^{\pi} \phi(\phi')^2 \, dx = -\frac{1}{c} \left[ \int_{-\pi}^{\pi} (\phi')^2 \phi'' \, dx + \int_{-\pi}^{\pi} \phi^2 (\phi')^2 \, dx \right], \]
where the first term in the right-hand side is zero thanks to the smoothness of \( \phi \). \( \square \)

2.3. Periodic waves in the BO equation. For the BO equation (see, e.g., [31]), the solution \( \phi \) to the boundary-value problem (1.3) with \( \alpha = 1 \) is given by
\[ \phi(x) = \cosh \gamma \cos x - \frac{1}{\sinh \gamma} \frac{1}{\cosh \gamma - \cos x}, \quad c = \coth \gamma. \]
The small-amplitude expansions (2.11)–(2.22) is recovered from (2.15) with the wave amplitude \( a := 2e^{-\gamma} + \mathcal{O}(e^{-3\gamma}) \) as \( \gamma \to \infty \). It follows from the simple expression \( c = \coth \gamma \) that the map \((0, \infty) \ni \gamma \mapsto c \in (1, \infty) \) is strictly decreasing, hence the explicit solution (2.15) exists for every \( c > 1 \).

Let us now show that the inequalities (2.8) and (2.9) with \( \alpha = 1 \) holds for every \( c > 1 \), that is,
\[ \int_{-\pi}^{\pi} \phi^3 \, dx < 0, \quad \int_{-\pi}^{\pi} \phi(\phi^2) \, dx > 0. \]
Indeed, by using the explicit formula (2.15) and symbolic computations with Wolfram’s MATHEMATICA, we obtain
\[ \int_{-\pi}^{\pi} \phi^3 dx = -\pi(c - 1)^2(2c + 1) \]
and
\[ \int_{-\pi}^{\pi} \phi(\phi')^2 dx = \frac{1}{4}\pi(c^2 - 1)^2, \]
from which the inequalities (2.16) hold for every \( c > 1 \).

2.4. Positivity of the periodic waves. The following result states that the single-lobe wave profile \( \psi \) in the boundary-value problem (1.2) for every \( c > 1 \) and \( \alpha \in (\alpha_0, 2] \) is positive and satisfies \( \psi(x) \geq \psi(\pm \pi) > 0 \) for every \( x \in [-\pi, \pi] \). The result has not appeared in the literature, e.g. a remark in the proof of Proposition 2.1 in [24] states that a periodic solution need not be positive everywhere. On the other hand, positivity of the Fourier coefficients in the Fourier series for the periodic wave \( \psi \) is proven in Theorem 3.5 of [9] for every \( \alpha > 1/2 \) and for sufficiently large periods (which is equivalent to \( c > 1 \) at the 2\( \pi \)-period).

Our proof has similarity to the work of [38] on the second-order differential equations. However, the existence of constant solutions is eliminated in [38] by the space-dependent coefficients in the boundary-value problem. For the problem (1.2), we have to use the Leray–Schauder index to single out single-lobe periodic solutions from the constant solutions.

**Theorem 2.2.** For every \( c > 1 \) and \( \alpha \in (\alpha_0, 2] \), there exists a unique single-lobe solution \( \psi \) of the boundary-value problem (1.2) such that \( \psi(x) > 0 \) for every \( x \in [-\pi, \pi] \).

**Proof.** For \( c \geq 1 \), the assertion of the lemma follows from Theorem 2.1 thanks to the transformation (1.3) and smallness of \( a \) in the Stokes expansion (2.1). In order to prove the same for every \( c > 1 \), we introduce the Green function \( G_{c,\alpha} \in L^2_{\text{per}}(-\pi, \pi) \) for the positive operator \((c - D_\alpha)\) from solution \( \varphi(x) = \int_{-\pi}^{\pi} G_{c,\alpha}(x-s)h(s)ds \) of the linear inhomogeneous equation

\[ (c - D_\alpha)\varphi = h, \quad h \in L^2_{\text{per}}(-\pi, \pi). \]

By Fourier series, the solution for \( G \) is available in the Fourier series form:

\[ G_{c,\alpha}(x) = \frac{1}{2\pi} \sum_{n \in \mathbb{Z}} \frac{e^{inx}}{c + |n|^{\alpha}}, \]

from which it follows that \( G_{c,\alpha} \in L^2_{\text{per}}(-\pi, \pi) \) if \( c > 1/2 \) but \( G_{c,\alpha}(0) = \infty \) if \( \alpha \leq 1 \). It is proven in [33] for \( \alpha \in (0,1) \) (and the proof is extended for \( \alpha \in [1,2] \), see [7]) that there is a positive \((c,\alpha)\)-dependent constant \( m_{c,\alpha} \) such that

\[ G_{c,\alpha}(x) \geq m_{c,\alpha}, \quad x \in [-\pi, \pi], \]

In addition, for \( \alpha > 1/2 \), \( M_{c,\alpha} := \|G_{c,\alpha}\|_{L^2_{\text{per}}} \) for a positive \((c,\alpha)\)-dependent constant \( M_{c,\alpha} \).

Let us consider a positive cone in the space of \( L^2_{\text{per}}(-\pi, \pi) \)-functions defined by

\[ P_{c,\alpha} := \left\{ \psi \in L^2_{\text{per}}(-\pi, \pi) : \psi(x) \geq \frac{m_{c,\alpha}}{M_{c,\alpha}}\|\psi\|_{L^2_{\text{per}}}, \quad x \in [-\pi, \pi] \right\}. \]

Define the following nonlinear operator \( A_{c,\alpha}(\psi) : L^2_{\text{per}}(-\pi, \pi) \to L^2_{\text{per}}(-\pi, \pi) \) for any \( c > 0 \):

\[ A_{c,\alpha}(\psi) := (c - D_\alpha)^{-1}\psi^2 \quad \Rightarrow \quad A_{c,\alpha}(\psi)(x) = \int_{-\pi}^{\pi} G_{c,\alpha}(x-s)\psi(s)^2ds. \]
The operator $A_{c,\alpha}$ is bounded and continuous in $L^2_{\text{per}}(-\pi, \pi)$ thanks to the generalized Young inequality:

\begin{equation}
\|A_{c,\alpha}(\psi)\|_{L^2_{\text{per}}} \leq \|G_{c,\alpha}\|_{L^2_{\text{per}}} \|\psi\|_{L^1_{\text{per}}} \leq M_{c,\alpha} \|\psi\|_{L^2_{\text{per}}}.
\end{equation}

Moreover, $A_{c,\alpha}$ is compact because it is the limit of compact operators $A_{c,\alpha}^{(N)}$ given by the first $2N + 1$ Fourier coefficients. Indeed, we have

\begin{equation}
\|A_{c,\alpha}(\psi) - A_{c,\alpha}^{(N)}(\psi)\|_{L^2_{\text{per}}}^2 = \frac{1}{2\pi} \sum_{|n| > N} \frac{|(\psi^2)_n|^2}{(c + |n|\alpha)^2} \leq \frac{1}{2\pi} \|(\psi^2)_n\|_{L^\infty}^2 \sum_{|n| > N} \frac{1}{(c + |n|\alpha)^2}
\end{equation}

\begin{equation}
\leq \frac{1}{2\pi} \|\psi^2\|_{L^2_{\text{per}}}^2 \sum_{|n| > N} \frac{1}{(c + |n|\alpha)^2} = \frac{1}{2\pi} \|\psi\|_{L^2_{\text{per}}}^2 \sum_{|n| > N} \frac{1}{c + |n|\alpha}^2,
\end{equation}

where the numerical series converges for every $\alpha > 1/2$. Therefore, for every $\psi \in L^2_{\text{per}}(-\pi, \pi)$,

\[\lim_{N \to \infty} \|A_{c,\alpha}(\psi) - A_{c,\alpha}^{(N)}(\psi)\|_{L^2_{\text{per}}} = 0,\]

so that $A_{c,\alpha}$ maps bounded sets in $L^2_{\text{per}}(-\pi, \pi)$ to pre-compact sets in $L^2_{\text{per}}(-\pi, \pi)$.

By using positivity of the Green function in (2.19), we confirm that the operator $A_{c,\alpha}(\psi)$ is closed in $P_{c,\alpha} \subset L^2_{\text{per}}(-\pi, \pi)$:

\begin{equation}
A_{c,\alpha}(\psi)(x) \geq m_{c,\alpha} \|\psi\|_{L^2_{\text{per}}}^2 \geq \frac{m_{c,\alpha}}{M_{c,\alpha}} \|A_{c,\alpha}(\psi)\|_{L^2_{\text{per}}}^2.
\end{equation}

A fixed point $\psi$ of $A_{c,\alpha}(\psi)$ in $P_{c,\alpha} \subset L^2_{\text{per}}(-\pi, \pi)$ corresponds to the positive function $\psi$ such that $\psi(x) > 0$ for every $x \in [-\pi, \pi]$.

Let $B_r := \{\psi \in L^2_{\text{per}}(-\pi, \pi) : \|\psi\|_{L^2_{\text{per}}} < r\}$ be a ball of radius $r$ in $L^2_{\text{per}}(-\pi, \pi)$. The existence of a fixed point of $A_{c,\alpha}(\psi)$ in $P_{c,\alpha} \cap (B_{r_+} \setminus B_{r_-})$ for some $0 < r_- < r_+ < \infty$ follows from Krasnoselskii’s fixed-point theorem (see, e.g., Corollary 20.1 in [15]) if there exist $r_-$ and $r_+$ such that

\begin{equation}
\|A_{c,\alpha}(\psi)\|_{L^2_{\text{per}}} \leq \|\psi\|_{L^2_{\text{per}}}, \quad \psi \in P_{c,\alpha} \cap \partial B_{r_-}
\end{equation}

and

\begin{equation}
\|A_{c,\alpha}(\psi)\|_{L^2_{\text{per}}} > \|\psi\|_{L^2_{\text{per}}}, \quad \psi \in P_{c,\alpha} \cap \partial B_{r_+}.
\end{equation}

Bound (2.24) follows from (2.22) with $M_{c,\alpha} r_- < 1$. Bound (2.25) follows from (2.23) with $\sqrt{2\pi m_{c,\alpha}} r_+ > 1$, hence the two radii satisfy the constraints

\begin{equation}
0 < r_- < \frac{1}{M_{c,\alpha}} \leq \frac{1}{\sqrt{2\pi m_{c,\alpha}}} < r_+ < \infty,
\end{equation}

where $\sqrt{2\pi m_{c,\alpha}} \leq M_{c,\alpha}$ follows from (2.19). Hence, there exists a fixed point of $A_{c,\alpha}(\psi)$ in $P_{c,\alpha} \cap (B_{r_+} \setminus B_{r_-})$.

We use bootstrapping arguments similar to those used in the proof of Proposition 2.1 in [24] and show that the fixed point of $A_{c,\alpha}$ in $L^2_{\text{per}}(-\pi, \pi)$ also exists in $H^1_{\text{per}}(-\pi, \pi)$, hence $\psi$ is a positive solution of the boundary-value problem (1.24). Indeed, if $\psi \in L^4_{\text{per}}(-\pi, \pi)$, then $\psi \in H^1_{\text{per}}(-\pi, \pi)$ thanks to the estimate:

$$\|D_\alpha \psi\|_{L^2_{\text{per}}} = \|D_\alpha (c - D_\alpha)^{-1} \psi\|_{L^2_{\text{per}}} \leq \|\psi^2\|_{L^2_{\text{per}}} = \|\psi\|_{L^2_{\text{per}}}^2.$$
In order to show that \( \psi \in L^4_{\text{per}}(-\pi, \pi) \), we use the generalized Young and Hölder inequalities:

\[
\|\psi\|_{L^p_{\text{per}}} \leq \|G\|_{L^p_{\text{per}}} \|\psi\|^2_{L^q_{\text{per}}}, \\
\|G\|_{L^p_{\text{per}}} \|\psi\|^2_{L^q_{\text{per}}}, \\
1 + \frac{1}{r} = \frac{1}{p} + \frac{1}{q}, \quad p, q, r \geq 1,
\]

\[
(2.28) \\
\|G\|_{L^p_{\text{per}}} \|\psi\|_{L^q_{\text{per}}} \|\psi\|_{L^{sq(s-1)}_{\text{per}}}, \quad s \geq 1.
\]

By using the Hausdorff–Young inequality

\[
\|G\|_{L^p_{\text{per}}} \leq C_p \|c + |n|^{\alpha}\|_{L^p/(p-1)}, \quad p \geq 2,
\]

we can see that \( \|G\|_{L^p_{\text{per}}} < \infty \) if \( \alpha p/(p-1) > 1 \). If \( \alpha \geq 1 \), then \( G \in L^p_{\text{per}}(-\pi, \pi) \) for every \( p \in [2, \infty) \). Applying (2.27) with \( r = p \) and \( q = 1 \), we have \( \psi \in L^p_{\text{per}}(-\pi, \pi) \) for every \( p \in [2, \infty) \).

If \( \alpha \in (\alpha_0, 1) \), we set \( p_0 = 1/(1 - \alpha_0) > 2 \) and obtain with the same argument that \( G, \psi \in L^{p_0}_{\text{per}}(-\pi, \pi) \). Then, using bound (2.28) with \( s = 2 \) and \( s/(s-1) = p_0 \), that is, with \( s = 1 + 2/p_0 \) and \( q = 2p_0/(2 + p_0) \), we obtain \( \psi \in L^r_{\text{per}}(-\pi, \pi) \) with \( r = 2p_0/(4 - p_0) > p_0 \) (because \( p_0 > 2 \)). Iterating bound (2.28) with \( s = 2 \) and \( s/(s-1) = r \), we obtain a bigger value for \( r = p_0/(3 - p_0) > 2p_0/(4 - p_0) \), hence by further iterations, we get \( \psi \in L^p_{\text{per}}(-\pi, \pi) \) for every \( p \in [2, \infty) \) including \( p = 4 \).

The fixed point \( \psi \in P_{\epsilon, \alpha} \cap (B_{r_+} \setminus B_{r_-}) \) for \( r_- < r_+ \) satisfying (2.26) exists for every \( c > 0 \). However, the constant periodic solution

\[
(2.29) \\
\psi_c(x) = c, \quad x \in [-\pi, \pi]
\]

is a fixed point of \( A_{\epsilon, \alpha} \) in \( P_{\epsilon, \alpha} \cap (B_{r_+} \setminus B_{r_-}) \) for every \( c > 0 \) and \( \alpha > 0 \). Indeed, \( A_{\epsilon, \alpha}(\psi_c) = \psi_c \) for every \( \alpha \geq 0 \) and \( \psi_c \in P_{\epsilon, \alpha} \cap (B_{r_+} \setminus B_{r_-}) \) for every \( c > 0 \) thanks to the condition \( \sqrt{2\pi m_{\epsilon, \alpha}} \leq M_{\epsilon, \alpha} \).

In order to be able to claim that there exists a non-trivial fixed point \( \psi \in P_{\epsilon, \alpha} \cap (B_{r_+} \setminus B_{r_-}) \) for \( c > 1 \) in addition to the constant fixed point \( \psi_c \), we look at the Leray–Schauder index of the fixed point in the subspace of even functions in \( L^2_{\text{per}}(-\pi, \pi) \), defined as \((-1)^N\), where \( N \) is the number of unstable eigenvalues of \( A'_{\epsilon, \alpha}(\psi) \) outside the unit disk with the account of their multiplicities.

For the fixed point \( \psi_c \), we have \( A'_{\epsilon, \alpha}(\psi_c) = 2c(c - D_\alpha)^{-1} \psi_c \), hence there exists \( N = K + 1 \) unstable eigenvalues of \( A'_{\epsilon, \alpha}(\psi_c) \) outside the unit disk for every \( c \in (K^\alpha, (K + 1)^\alpha) \), where \( K \in \mathbb{N} \). Therefore, the index of \( \psi_c \) changes sign every time \( c \) crosses values in the set \( \{K^\alpha\}_{K \in \mathbb{N}} \), as is shown on Figure 1. On the other hand, for \( K = 1, c = 1 \) is a bifurcation value by Theorem 2.1 and two non-trivial fixed points \( \psi \in P_{\epsilon, \alpha} \cap (B_{r_+} \setminus B_{r_-}) \) bifurcate for \( c \geq 1 \) if \( \alpha > \alpha_0 \), one is single-lobe with maximum at \( x = 0 \) and the other one is single-lobe with minimum at \( x = 0 \), both are strictly positive. For the non-trivial fixed points \( \psi \), we have

\[
A'_{\epsilon, \alpha}(\psi) = 2(c - D_\alpha)^{-1}\psi = \text{Id} - (c - D_\alpha)^{-1}\tilde{H}_{\epsilon, \alpha},
\]

where it follows from positivity of \( \psi \) that \( A'_{\epsilon, \alpha}(\psi) \geq 0 \). By Lemma 2.3 for \( c > 1 \) and \( \alpha \in (\alpha_0, 2] \), \( \tilde{H}_{\epsilon, \alpha} = H_{\epsilon, \alpha} \) has only one simple negative eigenvalue, hence there exists \( N = 1 \) unstable eigenvalues of \( A'_{\epsilon, \alpha}(\psi) \). Therefore, the pair of non-trivial fixed points \( \psi \in P_{\epsilon, \alpha} \cap (B_{r_+} \setminus B_{r_-}) \) is distinct from the constant fixed point \( \psi_c \) for every \( c > 1 \), as is shown on Figure 1.

The pair of non-trivial fixed points for the single-lobe solution remains inside \( P_{\epsilon, \alpha} \cap (B_{r_+} \setminus B_{r_-}) \) in continuation of the solution family in \( c \) for a fixed \( \alpha \in (\alpha_0, 2] \), thanks to the conditions (2.24), (2.25), and (2.26). Their indices also remain invariant with respect to \( c \) thanks to Lemma 2.3. Therefore, these fixed points cannot coalesce with any other fixed points of \( A_{\epsilon, \alpha} \) in \( P_{\epsilon, \alpha} \cap (B_{r_+} \setminus B_{r_-}) \). By continuity, these fixed points coincide with the single-lobe solutions, existence of which is proven in Proposition 2.1 in [2].
Remark 2.5. At every bifurcation point \( c = K^\alpha \) with \( K \geq 2 \), a pair of additional fixed points of \( A_{c,\alpha} \) bifurcates in \( P_{c,\alpha} \cap (\bar{B}_r \setminus B_r) \), as is shown on Figure 1 for \( K = 2 \) and \( \alpha = 2 \). These fixed points are not single-lobe solutions for \( K \geq 2 \) but instead these are concatenations of the single-lobe solutions with \( K \) periods on \([-\pi, \pi]\).

Remark 2.6. Theorem 4.1 in [6] states that \( \tilde{\mathcal{H}}_{c,\alpha} = \mathcal{H}_{c,\alpha} \) in (1.13) has only one simple negative eigenvalue and a simple zero eigenvalue if \( \psi \) and its Fourier transform are strictly positive. These properties have been verified in [6] for the integrable cases \( \alpha = 2 \) and \( \alpha = 1 \), for which the exact solutions (2.30) and (2.31) are available. With Theorem 3.5 in [9] and Theorem 2.2 above, Theorem 4.1 in [6] can be applied to the periodic waves for every \( c > 1 \) and \( \alpha \in (\alpha_0, 2] \). This argument gives an alternative proof of Lemma 2.3.

Let us illustrate positivity of \( \psi \) for the classical cases \( \alpha = 2 \) and \( \alpha = 1 \). For the KdV equation with the solution (2.12) and (2.13), we use \( \psi(x) = c + \phi(x) \) and obtain

\[
(2.30) \quad \psi(x) = \frac{2K(k)^2}{\pi^2} \left[ 1 - 2k^2 + \sqrt{1 - k^2 + k^4 + 3k^2 \cn^2 \left( \frac{K(k)}{\pi} x; k \right)} \right],
\]

from which \( \psi(x) \geq \psi(\pm \pi) > 0 \) holds for every \( x \in [-\pi, \pi] \) and every \( k \in (0, 1) \). Indeed, if \( \alpha = 2 \), the boundary-value problem (1.2) can be formulated as a planar Hamiltonian system on the phase plane \((\psi, \psi')\) and a set of closed orbits for periodic solutions is located on the phase plane between the saddle point \((0, 0)\) and the center point \((c, 0)\), hence, \( \psi(x) > 0 \) for every \( x \in [-\pi, \pi] \).

For the BO equation with the solution (2.15), we use \( \psi(x) = c + \phi(x) \) and obtain

\[
(2.31) \quad \psi(x) = \frac{\sinh \gamma}{\cosh \gamma - \cos x},
\]

from which \( \psi(x) \geq \psi(\pm \pi) = \tanh \gamma > 0 \) holds for every \( x \in [-\pi, \pi] \) and every \( \gamma \in (0, \infty) \).
3. Proof of Theorem 1.1

In what follows, we always use \( \phi \) to denote the single-lobe periodic wave, which is even with a maximum at \( x = 0 \) and minimum at \( x = \pm \pi \). We always assume that

\[
\int_{-\pi}^{\pi} \phi^2 dx \neq 0 \quad \text{and} \quad \int_{-\pi}^{\pi} \phi(\phi')^2 dx \neq 0.
\]

Recall that although \( \phi \in H^\alpha_{\text{per}}(-\pi, \pi) \), it is extended to \( \phi \in \tilde{H}^\alpha_{\text{per}}(-\pi, \pi) \) by bootstrapping arguments similar to those used in the proof of Theorem 2.2.

Linearizing \( T_{c,\alpha} \) at \( \phi \) with \( w_n = \phi + \omega_n \), where \( \omega_n \in H^\alpha_{\text{per}}(-\pi, \pi) \), yields the linearized iterative rule:

\[
\omega_{n+1} = - \frac{2\langle L_{c,\alpha} \phi, \omega_n \rangle}{\langle L_{c,\alpha} \phi, \phi \rangle} \phi + L_{c,\alpha}^{-1}(2\phi \omega_n), \quad n \in \mathbb{N}.
\]

Since \( L_{c,\alpha}^{-1}(\phi^2) = \phi \) and \( L_{c,\alpha}^{-1}(2\phi \phi') = \phi' \), the linearized iterative rule (3.2) is invariant in the constrained space

\[
L^2_c := \{ \phi \in L^2_{\text{per}}(-\pi, \pi) : \langle \phi^2, \omega \rangle = \langle \phi \phi', \omega \rangle = 0 \}.
\]

To satisfy the two constraints, one can expand \( \omega_n = a_n \phi + b_n \phi' + \beta_n \) with \( \beta_n \in H^\alpha_{\text{per}}(-\pi, \pi) \cap L^2_c \) and derive from (3.2):

\[
a_{n+1} = 0, \quad b_{n+1} = b_n, \quad \beta_{n+1} = L_T \beta_n,
\]

where

\[
L_T := L_{c,\alpha}^{-1}(2\phi') = \text{Id} - L_{c,\alpha}^{-1} H_{c,\alpha} : \tilde{H}^\alpha_{\text{per}}(-\pi, \pi) \cap L^2_c \rightarrow \tilde{H}^\alpha_{\text{per}}(-\pi, \pi) \cap L^2_c
\]

is the linearized iterative operator with \( H_{c,\alpha} \) given by (1.8). The following two results provide sufficient conditions for divergence or convergence of the iterative method (1.6).

**Theorem 3.1.** Assume \( \int_{-\pi}^{\pi} \phi^3 dx \neq 0 \). There exists \( w_0 \in H^\alpha_{\text{per}}(-\pi, \pi) \) near \( \phi \in \tilde{H}^\alpha_{\text{per}}(-\pi, \pi) \) such that the iterative method (1.6) diverges from \( \phi \) if \( \sigma(L_T) \) in \( L^2_c \) includes at least one eigenvalue outside the unit disk.

**Proof.** If \( \sigma(L_T) \) in \( L^2_c \) admits at least one eigenvalue outside the unit disk, the corresponding eigenfunction of \( L_T \) defines a direction in \( \tilde{H}^\alpha_{\text{per}}(-\pi, \pi) \) along which the sequence \( \{w_n\}_{n \in \mathbb{N}} \) diverges from the fixed point \( \phi \), as follows from the unstable manifold theorem.

**Theorem 3.2.** Assume \( \int_{-\pi}^{\pi} \phi^3 dx \neq 0 \) and \( \int_{-\pi}^{\pi} \phi(\phi')^2 dx \neq 0 \). There exists a small \( \epsilon_0 > 0 \) such that for every \( w_0 \in H^\alpha_{\text{per}}(-\pi, \pi) \) satisfying

\[
\epsilon := \|w_0 - \phi\|_{H^\alpha_{\text{per}}} \leq \epsilon_0,
\]

there exist \( b_\ast \) satisfying \( |b_\ast| \leq C \epsilon \) for some \( \epsilon \)-independent \( C > 0 \) such that the iterative method (1.6) converges to \( \phi(\cdot - b_\ast) \) if \( \sigma(L_T) \) in \( L^2_c \) is located inside the unit disk.

**Proof.** Let us first assume that \( w_0 \in H^\alpha_{\text{per}}(-\pi, \pi) \) is even, in which case the assertion is true with \( b_\ast = 0 \). Since \( L_{c,\alpha} \) maps even functions to even functions, the sequence of functions \( \{w_n\}_{n \in \mathbb{N}} \) in \( H^\alpha_{\text{per}}(-\pi, \pi) \) generated by (1.6) is even. Therefore, the linearization \( w_n = \phi + \omega_n \) and the decomposition \( \omega_n = a_n \phi + b_n \phi' + \beta_n \) yields \( b_n = 0 \) for every \( n \geq 0 \). The linear iterative formula (3.4) yields \( a_n = 0 \) for every \( n \geq 1 \) even if \( a_0 \neq 0 \). The linearized operator \( L_T \) given by (3.5) is a strict contraction if \( \sigma(L_T) \) in \( L^2_c \) is located inside the unit disk. Convergence of the sequence to \( \phi \) follows by Banach’s fixed-point theorem (Theorem 1.A in [10]).
Let us now relax the condition that the initial guess \( w_0 \in H^\alpha_{\text{per}}(-\pi, \pi) \) is even. In order to control the projection \( b_n \) in the decomposition \( \omega_n = a_n \phi + b_n \phi' + \beta_n \), we need to use tools of the modulation theory for periodic waves, see, e.g., Section 5 in [20]. Instead of defining \( b_n \) by \( \omega_n = a_n \phi + b_n \phi' + \beta_n \), we define \( b_n \in \mathbb{R} \) by using the decomposition
\[
(3.7) \quad w_n(x) = \phi(x - b_n) + \omega_n(x - b_n)
\]
and the orthogonality condition
\[
(3.8) \quad \langle \phi \phi', \omega_n \rangle = 0.
\]
By a standard application of the implicit function theorem, see, e.g., Lemma 6.1 in [20], for every \( w_n \in H^\alpha_{\text{per}}(-\pi, \pi) \) satisfying
\[
(3.9) \quad \epsilon_n := \inf_{b \in [-\pi, \pi]} \| w_n - \phi(\cdot - b) \|_{H^\alpha_{\text{per}}} \leq \epsilon_0,
\]
the decomposition (3.7)–(3.8) is unique under the assumption \( \int_{-\pi}^\pi \phi(\phi')^2 dx \neq 0 \) with uniquely defined \( b_n \) near the argument of the infimum in (3.9) and uniquely defined \( \omega_n \) satisfying
\[
(3.10) \quad \| \omega_n \|_{H^\alpha_{\text{per}}} \leq C_0 \epsilon_n
\]
for some \( \epsilon_n \)-independent constant \( C_0 > 0 \).

Substituting the decomposition (3.7) into the iterative method (1.6) and using the translational invariance in \( x \), we obtain the equivalent iterative scheme:
\[
(3.11) \quad \omega_{n+1} = \phi(\cdot + \Delta b_n) - \phi + T'(\phi(\cdot + \Delta b_n))\omega_n(\cdot + \Delta b_n) + N(\omega_n(\cdot + \Delta b_n)),
\]
where \( \Delta b_n := b_{n+1} - b_n \), \( T'(\phi)\omega_n \) denotes the linearized iterative operator given by the right-hand side in (3.2), and \( N(\omega_n) \) is the nonlinear terms satisfying
\[
(3.12) \quad \| N(\omega_n) \|_{H^\alpha_{\text{per}}} \leq C \| \omega_n \|_{H^\alpha_{\text{per}}}^2,
\]
for every \( \omega_n \in B_\rho(0) := \{ \omega \in H^\alpha_{\text{per}}(-\pi, \pi) : \| \omega \|_{H^\alpha_{\text{per}}} \leq \rho \} \), where the constant \( C > 0 \) does not depend on \( \rho \) provided the radius \( \rho \) of the ball \( B_\rho(0) \) is small. Thanks to (3.6) and (3.10), we work with \( \rho = C \epsilon \) for some positive \( \epsilon \)-independent constant \( C \).

By using the constraint (3.8) both for \( \omega_n \) and \( \omega_{n+1} \), we derive the following equation for \( \Delta b_n \):
\[
(3.13) \quad 0 = \langle \phi \phi', \phi(\cdot + \Delta b_n) - \phi \rangle + \langle \phi \phi', T'(\phi(\cdot + \Delta b_n))\omega_n(\cdot + \Delta b_n) \rangle + \langle \phi \phi', N(\omega_n(\cdot + \Delta b_n)) \rangle.
\]
This equation can be treated as the root-finding problem \( F(\Delta b_n, \omega_n) = 0 \), where
\[
F : \mathbb{R} \times H^\alpha_{\text{per}}(-\pi, \pi) \mapsto \mathbb{R}
\]
is a smooth function in its variables satisfying \( F(0, 0) = 0 \) and \( \partial_{\Delta b_n} F(0, 0) \neq 0 \) thanks to smoothness of \( \phi \in H^\infty_{\text{per}}(-\pi, \pi) \) and \( N(\omega_n) \) as well as the assumption \( \int_{-\pi}^\pi \phi(\phi')^2 dx \neq 0 \). By the implicit function theorem, the root-finding problem (3.13) is uniquely solvable in \( \Delta b_n \) for every \( \omega_n \in B_\rho(0) \) with small \( \rho > 0 \). Moreover, thanks to \( \langle \phi \phi', T'(\phi)\omega_n \rangle = \langle \phi \phi', \omega_n \rangle = 0 \) and (3.12), the uniquely found \( \Delta b_n \) satisfies the bound
\[
(3.14) \quad |\Delta b_n| \leq C \| \omega_n \|_{H^\alpha_{\text{per}}}^2,
\]
for some constant \( C > 0 \) that does not depend on the small radius \( \rho \).

Substituting \( \Delta b_n \) satisfying (3.14) into (3.11) and decomposing \( \omega_n = a_n \phi + \beta_n \) with \( a_n \in \mathbb{R} \) and \( \beta_n \in H^\alpha_{\text{per}}(-\pi, \pi) \cap L^2_\pi \), we obtain the linearized problem
\[
(3.15) \quad a_{n+1} = 0, \quad \beta_{n+1} = \mathcal{L}_T \beta_n.
\]
Since $\mathcal{L}_T$ is a strict contraction in $L^2_T$, convergence $a_n \to 0$, $\Delta b_n \to 0$, and $\beta_n \to 0$ as $n \to \infty$ follows by Banach’s fixed-point theorem (Theorem 1.4 in [10]). Moreover, these sequences converge exponentially fast so that the sequence $\{b_n\}_{n \in \mathbb{N}}$ converges to a limit denoted by $b_*$. Since $|b_* - b_0| \leq C e^2$ thanks to (3.10) and (3.14), whereas $|b_0| \leq C$ thanks to (3.6), (3.9), and triangle inequality, we also have $|b_*| \leq C$ for some $\epsilon$-independent $C > 0$. The assertion is proven thanks to the decomposition (3.7) with $\omega_n = a_n \phi + \beta_n$. □

Remark 3.1. Compared to Section 6 in [20], where standard orthonormality condition $\langle \phi', w \rangle = 0$ was used together with the energy conservation, we have to use the modified orthogonality condition $\langle \phi \phi', w \rangle = 0$ in order to comply with the iterative scheme (3.11), which results in the non-self-adjoint linearized operator $T'(\phi)\omega_n$ given by the right-hand side of (3.2).

In order to compute $\sigma(\mathcal{L}_T)$ in $L^2_T$ used in Theorems 3.1 and 3.2, we study the spectrum of $\mathcal{L}^{-1}_{c,\alpha} \mathcal{H}_{c,\alpha}$ in $L^2_{\text{per}}(-\pi, \pi)$. Analytical results on convergence of the method for $c \geq 1$ and divergence for $c > 2^\alpha$ are obtained in Sections 3.1 and 3.2 respectively. These results give the proof of Theorem 1.1. Numerical results showing convergence or divergence of the method for $c$ in $(1, 2^\alpha)$ are obtained in Section 3.3 for $\alpha = 2$ and $\alpha = 1$.

3.1. Case $c \geq 1$. Here we prove that the iterative method converges near the single-lobe periodic wave $\phi$ in the small-amplitude limit for $c \geq 1$ if $\alpha > \alpha_1$ and diverges if $\alpha \in (\alpha_0, \alpha_1)$, where $\alpha_0$ and $\alpha_1$ are given by (1.9). Note that $\alpha_0 \approx 0.585$ and $\alpha_1 \approx 1.322$ so that $1/2 < \alpha_0 < 1 < \alpha_1 < 2$.

The following lemma characterizes the spectrum of $\mathcal{L}^{-1}_{c,\alpha} \mathcal{H}_{c,\alpha}$ in $L^2_{\text{per}}(-\pi, \pi)$ for $c \geq 1$ and $\alpha > \alpha_0$.

**Lemma 3.1.** For every $c \geq 1$ and $\alpha > \alpha_0$, $\sigma(\mathcal{L}^{-1}_{c,\alpha} \mathcal{H}_{c,\alpha})$ in $L^2_{\text{per}}(-\pi, \pi)$ consists of a countable sequence of eigenvalues in a neighborhood of 1 and simple eigenvalues $\{-1, 0, \lambda_1, \lambda_2\}$ with

$$
\lambda_1 \to \frac{2^{\alpha+1} - 5}{2^{\alpha+1} - 3} \quad \text{and} \quad \lambda_2 \to 2 \quad \text{as} \quad c \to 1.
$$

Moreover, $\lambda_2 < 2$ for $c \geq 1$, whereas $\lambda_1 < 0$ if $\alpha \in (\alpha_0, \alpha_1)$ and $\lambda_1 \in (0, 1)$ if $\alpha > \alpha_1$.

**Proof.** It follows from (2.10) that $\lambda_1 \to 1$, the operator $\mathcal{L}_{c,\alpha}$ in $L^2_{\text{per}}(-\pi, \pi)$ is invertible and

$$
\sigma(\mathcal{L}^{-1}_{c,\alpha}) = \{(-c + |n|^\alpha)^{-1}, \ n \in \mathbb{Z}\}.
$$

Since the sequence of eigenvalues is square summable if $\alpha > 1/2$, the linear bounded operator $\mathcal{L}^{-1}_{c,\alpha}$ is of the Hilbert-Schmidt class (see Example 2 in Section 5.16 of [10]), hence it is compact. The linear operator $\mathcal{L}_T$ in $L^2_{\text{per}}(-\pi, \pi)$ is a composition of a bounded operator $2\phi$ and a compact (Hilbert–Schmidt) operator $\mathcal{L}^{-1}_{c,\alpha}$, hence $\mathcal{L}_T$ is a compact operator and $\sigma(\mathcal{L}_T)$ in $L^2_{\text{per}}(-\pi, \pi)$ consists of a sequence of eigenvalues converging to 0. Thanks to the representation (3.5), $\sigma(\mathcal{L}^{-1}_{c,\alpha} \mathcal{H}_{c,\alpha})$ in $L^2_{\text{per}}(-\pi, \pi)$ consists of a sequence of eigenvalues converging to 1.

Eigenvalues $\{-1, 0\}$ of $\mathcal{L}^{-1}_{c,\alpha} \mathcal{H}_{c,\alpha}$ in $L^2_{\text{per}}(-\pi, \pi)$ follow from exact computations for every $c > 1$:

$$
(3.16) \quad \mathcal{L}^{-1}_{c,\alpha} \mathcal{H}_{c,\alpha} \phi = -\phi \quad \text{and} \quad \mathcal{L}^{-1}_{c,\alpha} \mathcal{H}_{c,\alpha} \phi' = 0.
$$

In order to identify other eigenvalues of $\mathcal{L}^{-1}_{c,\alpha} \mathcal{H}_{c,\alpha}$ in $L^2_{\text{per}}(-\pi, \pi)$, we consider the generalized eigenvalue problem (1.7) defined by linear operators $\mathcal{L}_{c,\alpha}$ and $\mathcal{H}_{c,\alpha}$ in $L^2_{\text{per}}(-\pi, \pi)$ with the domains in $H^1_{\text{per}}(-\pi, \pi)$.

Since $\mathcal{H}_{c=1,\alpha}$ coincides with $\mathcal{L}_{c=1,\alpha}$, the generalized eigenvalue problem (1.7) for $c = 1$ admits only one solution $\lambda = 1$ for every $v \in H^1_{\text{per}}(-\pi, \pi) \backslash \{e^{ix}, e^{-ix}\}$. Since $(\phi, c)$ depend analytically on $a$ in Theorem 2.1 by the analytic perturbation theory (Theorem VII.1.7 in [27]), the eigenvalues of $\mathcal{L}^{-1}_{c,\alpha} \mathcal{H}_{c,\alpha}$ in $L^2_{\text{per}}(-\pi, \pi)$ for every $c \geq 1$ are divided into two sets: a countable sequence of eigenvalues...
near 1 and converging to 1 related to the subspace $L^2_{\text{per}}(-\pi, \pi) \backslash \{e^{ix}, e^{-ix}\}$ and a finite number of eigenvalues related to the subspace $\{e^{ix}, e^{-ix}\}$. The second set includes eigenvalues $\{-1, 0\}$ due to the exact solutions (3.16) for every $c > 1$. The subspace $\{e^{ix}, e^{-ix}\}$ may be related to more than two simple eigenvalues in the generalized eigenvalue problem (1.7) because both $\mathcal{H}_{c=1,\alpha}$ and $\mathcal{L}_{c=1,\alpha}$ vanish on the subspace.

In order to study all possible eigenvalues of $\mathcal{L}_{c,\alpha}^{-1}\mathcal{H}_{c,\alpha}$ in $L^2_{\text{per}}(-\pi, \pi)$ related to the subspace $\{e^{ix}, e^{-ix}\}$, we perform perturbation expansions. Since $\mathcal{L}_{c,\alpha}$ and $\mathcal{H}_{c,\alpha}$ are closed in the subspaces of even and odd functions in $L^2_{\text{per}}(-\pi, \pi)$, the generalized eigenvalue problem (1.7) can be uncoupled in these subspaces. By using (2.2) and (2.11), we rewrite the generalized eigenvalue problem (1.7) in the perturbed form:

$$
(\lambda - 1) \left[ 1 + D_\alpha + c_2 a^2 + c_4 a^4 + \mathcal{O}(a^6) \right] v \\
-2 \left[ a \cos(x) + a^2 \phi_2(x) + a^3 \phi_3(x) + a^4 \phi_4(x) + \mathcal{O}(a^5) \right] v = 0.
$$

Assuming $\lambda \neq 1$, we are looking for perturbative expansions of the eigenvalues related to the even and odd subspace of $\{e^{ix}, e^{-ix}\}$ separately from each other. For the even subspace, we set

$$
v(x) = \cos(x) + av_1(x) + a^2 v_2(x) + \mathcal{O}(a^3)
$$

and obtain recursively

$$
\begin{cases}
\mathcal{O}(a) : (\lambda - 1) (1 + D_\alpha) v_1 = 1 + \cos(2x), \\
\mathcal{O}(a^2) : (\lambda - 1) (1 + D_\alpha) v_2 + (\lambda - 1) c_2 \cos(x) = 2 \cos(x)(v_1 + \phi_2).
\end{cases}
$$

At $\mathcal{O}(a)$, we obtain the exact solution in $H^\alpha_{\text{per}}(-\pi, \pi)$:

$$
v_1(x) = \frac{1}{\lambda - 1} \left[ \frac{\cos(2x)}{\lambda - 1} \right].
$$

The linear inhomogeneous equation at $\mathcal{O}(a^2)$ admits a solution $v_2 \in H^\alpha_{\text{per}}(-\pi, \pi)$ if and only if $\lambda$ satisfies

$$
\left[ \lambda - \frac{2}{\lambda - 1} \right] c_2 = 0.
$$

If $\alpha > \alpha_0$, then $c_2 \neq 0$ and $\lambda$ satisfies the quadratic equation $\lambda(\lambda - 1) = 2$ with two roots $\{-1, 2\}$. For each of the two roots, we obtain the exact solution in $H^\alpha_{\text{per}}(-\pi, \pi)$:

$$
v_2(x) = \frac{(3 - \lambda) \cos(3x)}{2(\lambda - 1)^2(2^\alpha - 1)(3^\alpha - 1)}.
$$

For the odd subspace, we set

$$
v(x) = \sin(x) + av_1(x) + a^2 v_2(x) + \mathcal{O}(a^3)
$$

and obtain recursively

$$
\begin{cases}
\mathcal{O}(a) : (\lambda - 1) (1 + D_\alpha) v_1 = \sin(2x), \\
\mathcal{O}(a^2) : (\lambda - 1) (1 + D_\alpha) v_2 + (\lambda - 1) c_2 \sin(x) = 2(\cos(x)v_1 + \sin(x)\phi_2).
\end{cases}
$$

At $\mathcal{O}(a)$, we obtain the exact solution in $H^\alpha_{\text{per}}(-\pi, \pi)$:

$$
v_1(x) = \frac{-\sin(2x)}{(\lambda - 1)(2^\alpha - 1)}.
$$

The linear inhomogeneous equation at $\mathcal{O}(a^2)$ admits a solution $v_2 \in H^\alpha_{\text{per}}(-\pi, \pi)$ if and only if $\lambda$ satisfies

$$
\lambda c_2 + \frac{\lambda}{(\lambda - 1)(2^\alpha - 1)} = 0.
$$
If $\alpha > \alpha_0$, then $c_2 \neq 0$ and $\lambda$ satisfies the quadratic equation $\lambda \left[ (2^{\alpha+1} - 3)\lambda - (2^{\alpha+1} - 5) \right] = 0$ with two roots \( \left\{ 0, \frac{2^{\alpha+1}-5}{2^{\alpha+1}-3} \right\} \). For each of the two roots, we obtain the exact solution in $H^0_{\mathrm{per}}(\pi,\pi)$:

(3.23) \[ v_2(x) = \frac{(3 - \lambda) \sin(3x)}{2(\lambda - 1)^2(2^\alpha - 1)(3^\alpha - 1)}. \]

Summarizing, we have obtained four eigenvalues related to the subspace \( \{e^{ix}, e^{-ix}\} \), which are located as $c \to 1$ at the points \( \{-1, 0, \frac{2^{\alpha+1}-5}{2^{\alpha+1}-3}, 2\} \).

The eigenvalues \( \{-1, 0\} \) are preserved for every $c > 1$ thanks to the exact solution (3.16). However, the eigenvalues \( \{\lambda_1, \lambda_2\} \) near \( \left\{ \frac{2^{\alpha+1}-5}{2^{\alpha+1}-3}, 2 \right\} \) depend generally on $c$. It follows by the perturbation theory that $\lambda_1 < 0$ for $c \gtrsim 1$ if $\alpha \in (\alpha_0, \alpha_1)$ and $\lambda_1 \in (0,1)$ for $c \gtrsim 1$ if $\alpha > \alpha_1$. We now claim that $\lambda_2 < 2$ for $c \gtrsim 1$ if $\alpha > \alpha_0$. To prove this claim, we use the extended spectral problem (3.17) up to the order $O(a^4)$. Hence, instead of the expansion (3.18) with (3.19) and (3.20), we use the expansions

(3.24) \[ \begin{cases} v(x) = \cos(x) + a v_1(x) + a^2 v_2(x) + a^3 v_3(x) + a^4 v_4(x) + O(a^5), \\
\lambda = 2 + \Lambda_2 a^2 + O(a^4), \end{cases} \]

where $v_1(x) = 1 - \frac{\cos(2x)}{2^\alpha - 1}$, $v_2(x) = \frac{\cos(3x)}{2(2^\alpha - 1)(3^\alpha - 1)}$.

We obtain from the extended spectral problem (3.17) the linear inhomogeneous equations:

\[
\begin{cases}
O(a^3): & (1 + D_\alpha)v_3 + \Lambda_2 (1 + D_\alpha)v_1 + c_2 v_1 = 2 [\cos(x)(v_2 + \phi_3) + \phi_2 v_1], \\
O(a^4): & (1 + D_\alpha)v_4 + \Lambda_2 (1 + D_\alpha)v_2 + c_2 v_2 + (c_4 + c_2 \Lambda_2) \cos(x) = 2 [\cos(x)(v_3 + \phi_4) + \phi_2 v_2 + \phi_3 v_1].
\end{cases}
\]

The linear inhomogeneous equation at $O(a^3)$ admits the explicit solution:

\[ v_3(x) = \frac{3^\alpha - 3 + 1}{2(2^\alpha - 1)^2(3^\alpha - 1)(4^\alpha - 1)} \cos(4x) + \left[ \frac{\Lambda_2}{2^\alpha - 1} - \frac{1}{2(2^\alpha - 1)^2(3^\alpha - 1)} \right] \cos(2x) - \left( \Lambda_2 + c_2 + 1 + \frac{1}{2(2^\alpha - 1)^2} \right). \]

The linear inhomogeneous equation at $O(a^4)$ admits a solution $v_4 \in H^0_{\mathrm{per}}(\pi,\pi)$ if and only if $\Lambda_2$ is given by

(3.25) \[ \Lambda_2 = -1 + \frac{3}{2^\alpha - 1} - \frac{7}{2^{\alpha+1} - 3}. \]

It is easy to see that $\Lambda_2$ has a vertical asymptote at $\alpha = \alpha_0$. By plotting $\Lambda_2$ versus $\alpha$ on Figure 2, we verify that $\Lambda_2 < 0$ for every $\alpha > \alpha_0$. Hence the eigenvalue $\lambda = 2 + \Lambda_2 a^2 + O(a^4)$ satisfies $\lambda < 2$ for every $c \gtrsim 1$ and $\alpha > \alpha_0$.

**Corollary 3.1.** For every $c \gtrsim 1$, the iterative method (1.6) converges to $\phi$ in $H^0_{\mathrm{per}}(\pi,\pi)$ if $\alpha > \alpha_1$ and diverges from $\phi$ if $\alpha \in (\alpha_0, \alpha_1)$.

**Proof.** Assumptions (3.21) used in Theorems (3.1) and (3.2) have been verified for $c \gtrsim 1$ in Lemma 2.4.

If $\alpha > \alpha_1$, then $\lambda_1 \in (0,1)$ for $c \gtrsim 1$ by Lemma 3.1. By using the representation (3.5) and the count of eigenvalues of the generalized eigenvalue problem (1.7) in Lemma 3.1, we can see that $\sigma(L_T)$ in $L^2_{\mathrm{per}}(\pi,\pi)$ consists of a countable sequence of eigenvalues in a neighborhood of $0$ and converging to $0$ for every $c \gtrsim 1$, two simple eigenvalues inside the interval $(-1,1)$, and two additional simple eigenvalues: $1$ related to the eigenfunction $\phi'$ and $2$ related to the eigenfunction $\phi$. The two constraints in (3.3) remove the latter two eigenvalues so that the operator $L_T$ is a strict
contraction in $L^2_c$ for every $c \geq 1$ if $\alpha > \alpha_1$. Convergence of the iterative method (1.6) for $\alpha > \alpha_1$ follows by Theorem 3.2.

If $\alpha \in (\alpha_0, \alpha_1)$, then $\lambda_1 < 0$ for $c \geq 1$ by Lemma 3.1. Then, $\sigma(L_T)$ in $L^2_{\text{per}}(-\pi, \pi)$ consists of a countable sequence of eigenvalues in a neighborhood of 0 and converging to 0 for every $c \geq 1$, one simple eigenvalue inside the interval $(-1,1)$, simple eigenvalue 1 related to the eigenfunction $\phi'$, simple eigenvalue 2 related to the eigenfunction $\phi$, and an additional simple eigenvalue bigger than 1 with an odd eigenfunction denoted by $v_*$. Because of the orthogonality conditions

$$\langle L_{c,\alpha} v_j, v_k \rangle = 0, \quad j \neq k,$$

between eigenfunctions $v_j$ and $v_k$ of the generalized eigenvalue problem (1.7) for distinct eigenvalues, we verify that $\langle \phi^2, v_* \rangle = \langle \phi \phi', v_* \rangle = 0$, which implies that $v_* \in L^2_c$. Therefore, $\sigma(L_T)$ in $L^2_c$ contains exactly one eigenvalue outside the unit disk for every $c \geq 1$ if $\alpha \in (\alpha_0, \alpha_1)$. Divergence of the iterative method (1.6) for $\alpha \in (\alpha_0, \alpha_1)$ follows by Theorem 3.1.

Remark 3.2. Since the unstable eigenfunction $v_*$ is odd, divergence of the iterative method (1.6) for $\alpha \in (\alpha_0, \alpha_1)$ is only observed if the initial guess $w_0 \in H^\alpha_{\text{per}}(-\pi, \pi)$ is not even but of a general form.

Although Theorem 1.1 follows already from Corollary 3.1, we would like to add few more details on the eigenfunctions of the generalized eigenvalue problem (1.7).

The numbers of negative eigenvalues of operators $L_{c,\alpha}$ and $H_{c,\alpha}$ are affected by the constraint $\langle \phi^2, \alpha \rangle = 0$ in (3.3). As is well-known (see, e.g., Theorem 4.1 in [34]), if $n$ is the number of negative eigenvalues of a self-adjoint invertible operator $L$ in a Hilbert space and if $\langle L^{-1} \phi^2, \phi^2 \rangle < 0$, then the restriction of the self-adjoint operator to the constraint $\langle \phi^2, \alpha \rangle = 0$ has one less negative eigenvalues $n - 1$. We compute:

$$\langle L_{c,\alpha}^{-1} \phi^2, \phi^2 \rangle = \langle \phi, \phi^2 \rangle, \quad \langle H_{c,\alpha}^{-1} \phi^2, \phi^2 \rangle = -\langle \phi, \phi^2 \rangle.$$

By Lemma 2.1, we have $\langle \phi, \phi^2 \rangle = \int_{-\pi}^{\pi} \phi(x)^3 dx < 0$ for every $c \geq 1$ if $\alpha > \alpha_0$. Therefore, $L_{c,\alpha}$ restricted to $L^2_c$ has one less negative eigenvalue compared to $L_{c,\alpha}$ in $L^2_{\text{per}}(-\pi, \pi)$, whereas $H_{c,\alpha}$ restricted to $L^2_c$ has still one simple negative eigenvalue. In the space of even functions, $L_{c,\alpha}$ and $H_{c,\alpha}$ restricted to $L^2_c$ have only one simple negative eigenvalue. By Theorem 1 in [12], the
generalized eigenvalue problem (1.7) admits one of the following in the subspace of even functions in $L^2_{\text{per}}(-\pi, \pi)$:

- two simple negative eigenvalues $\lambda$ with the two eigenfunctions $v$ for which the sign of $\langle L_{c,\alpha} v, v \rangle$ is opposite to the sign of $\langle H_{c,\alpha} v, v \rangle$;
- a simple positive eigenvalue $\lambda$ with the eigenfunction $v$ for which the sign of $\langle L_{c,\alpha} v, v \rangle$ and $\langle H_{c,\alpha} v, v \rangle$ are negative;
- a double defective real eigenvalue $\lambda$ with only one eigenfunction $v$ for which $\langle L_{c,\alpha} v, v \rangle = \langle H_{c,\alpha} v, v \rangle = 0$;
- a complex-conjugate pair of eigenvalues $\lambda$.

The following result shows that the second option from the list above is true if $\alpha > \alpha_1$ and $c \geq 1$.

**Lemma 3.2.** For every $c \geq 1$ and $\alpha > \alpha_1$, the generalized eigenvalue problem (1.7) admits

- a simple positive eigenvalue $\lambda$ with the eigenfunction $v$ for which the sign of $\langle L_{c,\alpha} v, v \rangle$ and $\langle H_{c,\alpha} v, v \rangle$ are negative;
- a simple negative eigenvalue $\lambda$ with the eigenfunction $v$ for which the sign of $\langle L_{c,\alpha} v, v \rangle$ is negative;
- a simple zero eigenvalue with the eigenfunction $v$ for which the sign of $\langle L_{c,\alpha} v, v \rangle$ is negative.

The eigenfunction $v$ for all other eigenvalues corresponds to positive values of $\langle L_{c,\alpha} v, v \rangle$ and $\langle H_{c,\alpha} v, v \rangle$.

**Proof.** We utilize the perturbative expansions in the proof of Lemma 3.1. For the even expansion (3.18), we obtain

$$L_{c,\alpha} v = -\frac{a}{\lambda - 1} \left[ 1 + \cos(2x) \right] + \frac{(3 - \lambda)a^2}{2(2^\alpha - 1)(\lambda - 1)^2} \cos(3x) - \left( 1 - \frac{1}{2(2^\alpha - 1)} \right) a^2 \cos(x) + O(a^3).$$

By evaluating elementary integrals, we obtain

$$\langle L_{c,\alpha} v, v \rangle = -\frac{\pi a^2(2^{\alpha+1} - 3)}{2(\lambda - 1)^2(2^\alpha - 1)} \left[ 2 + (\lambda - 1)^2 \right] + O(a^3).$$

If $\alpha > \alpha_0$, then $\langle L_{c,\alpha} v, v \rangle$ is negative for both roots $\{-1, 2\}$ of the quadratic equation $\lambda(\lambda - 1) = 2$. Since $\langle H_{c,\alpha} v, v \rangle = \lambda \langle L_{c,\alpha} v, v \rangle$, the eigenvalue at $\lambda = 2 + O(a^2)$ corresponds to the simple positive eigenvalue, for which both quadratic forms are negative, whereas the eigenvalue $\lambda = -1$ corresponds to the negative eigenvalue, for which only $\langle L_{c,\alpha} v, v \rangle$ is negative and $\langle H_{c,\alpha} v, v \rangle$ is positive.

For the odd expansion (3.21), we obtain

$$L_{c,\alpha} v = -\frac{a}{\lambda - 1} \sin(2x) + \frac{(3 - \lambda)a^2}{2(2^\alpha - 1)(\lambda - 1)^2} \sin(3x) - \left( 1 - \frac{1}{2(2^\alpha - 1)} \right) a^2 \sin(x) + O(a^3).$$

By evaluating elementary integrals, we obtain

$$\langle L_{c,\alpha} v, v \rangle = \frac{\pi a^2}{2(2^\alpha - 1)(\lambda - 1)^2} \left[ 2 - (2^{\alpha+1} - 3)(\lambda - 1)^2 \right] + O(a^3),$$

The sign of the quadratic forms depends on the value of $\alpha$ for the two roots $\{0, \frac{2^{\alpha+1} - 5}{2^{\alpha+1} - 3}\}$ of the quadratic equation $\lambda[(2^{\alpha+1} - 3)\lambda + (5 - 2^{\alpha+1})] = 0$. If $\alpha > \alpha_1$, then $\langle L_{c,\alpha} v, v \rangle$ is negative for the eigenvalue $\lambda = 0$, for which $\langle H_{c,\alpha} v, v \rangle$ is zero, and positive for the eigenvalue $\lambda = \frac{2^{\alpha+1} - 5}{2^{\alpha+1} - 3} + O(a^2)$, for which $\langle H_{c,\alpha} v, v \rangle$ is also positive.

Every other eigenvalue bifurcating from $\lambda = 1$ corresponds to the positive eigenvalues, for which both quadratic forms $\langle L_{c,\alpha} v, v \rangle$ and $\langle H_{c,\alpha} v, v \rangle$ are positive. \qed
3.2. Case $c > 2^\alpha$. The first resonance occurs at $c = 2^\alpha$, when a double eigenvalue of the operator $L_{c,\alpha}$ crosses zero and becomes a negative eigenvalue for $c > 2^\alpha$. Some eigenvalues of the operator $L_{c,\alpha}^{-1}H_{c,\alpha}$ may diverge as $c \to 2^\alpha$ and the conclusion on convergence of the iterative method (1.6) may change after the resonance. Here we prove that the iterative method (1.6) diverges for every $c > 2^\alpha$ and $\alpha \in (a_0, 2]$, where $L_{c,\alpha}^{-1}$ exists. Compared to the perturbative results in Section 3.1, the restriction $\alpha \leq 2$ is necessary to apply the results of [24] in the proof of Lemma 2.3. The following lemma specifies the number of negative eigenvalues of $L_{c,\alpha}^{-1}H_{c,\alpha}$ in $L_{\text{per}}^2(\pi, \pi)$.

Lemma 3.3. For every $c > 2^\alpha$ and $\alpha \in (a_0, 2]$, for which $L_{c,\alpha}^{-1}$ exists, $\sigma(L_{c,\alpha}^{-1}H_{c,\alpha})$ in $L_{\text{per}}^2(\pi, \pi)$ includes $N$ negative eigenvalues (counting with their algebraic multiplicities) with $N \geq 1$ in addition to the simple negative eigenvalue $-1$.

Proof. It follows from (2.10) that for $c > 2^\alpha$, $\sigma(L_{c,\alpha})$ in $L_{\text{per}}^2(\pi, \pi)$ admits $n$ negative eigenvalues (counting with their algebraic multiplicities) with $n \geq 5$. By Lemma 2.3, $\sigma(H_{c,\alpha})$ in $L_{\text{per}}^2(\pi, \pi)$ admits only one simple negative eigenvalue and the simple zero eigenvalue with an odd eigenfunction $\phi'$. In the space of even functions, $H_{c,\alpha}$ has only one simple negative eigenvalue and is invertible, whereas $L_{c,\alpha}$ has $n_{\text{ev}}$ negative eigenvalues with $n_{\text{ev}} \geq 3$. Both $H_{c,\alpha}$ and $L_{c,\alpha}$ are self-adjoint in $L_{\text{per}}^2(\pi, \pi)$ with the domain in $H_{\text{per}}^0(\pi, \pi)$, as well as in the corresponding subspaces of even functions. By Theorem 4.1 in [34], the constraints in $L_c^2$ may only reduce one negative eigenvalue in either $L_{c,\alpha}$ or $H_{c,\alpha}$ (the choice between the two operators depends on the sign of $\int_\pi^\pi \phi^3(x)dx$). In either case, by Theorem 1 in [22], there exist at least $N \geq 1$ negative eigenvalues $\lambda$ of the generalized eigenvalue problem (1.7) in $L_c^2$.

Corollary 3.2. Assume $\int_\pi^\pi \phi^3dx \neq 0$. The iterative method (1.6) diverges from $\phi$ for every $c > 2^\alpha$ and $\alpha \in (a_0, 2]$.

Proof. It follows from Lemma 3.3 and the representation (3.3) that $\sigma(L_T)$ in $L_c^2$ includes $N \geq 1$ positive eigenvalues larger than 1. These eigenvalues of $L_T$ outside the unit disk correspond to the eigenfunctions in the constrained subspace (3.3), which satisfy the orthogonality conditions

$\langle L_{c,\alpha}\phi, \alpha \rangle = \langle L_{c,\alpha}\phi', \alpha \rangle = 0$.

Divergence of the iterative method (1.6) follows by Theorem 3.1.

Remark 3.4. It follows from the proof of Lemma 3.3 that the divergence of the iterative method (1.6) for $c > 2^\alpha$ and $\alpha \in (a_0, 2]$ is observed if the initial guess $w_0 \in H_{\text{per}}^0(\pi, \pi)$ is even.

3.3. Case $c \in (1, 2^\alpha)$. Here we address numerically convergence of the iterative method (1.6) near the single-lobe periodic wave for $c \in (1, 2^\alpha)$. For simplicity of computations, we only consider the classical KdV and BO equations.

For the KdV equation with $\alpha = 2$, we show that the method converges for $c \geq 1$ in agreement with Corollary 3.1. On the other hand, we illustrate transition to instability at $c \approx 2.3$ and divergence of the method for $c \geq 2.3$, which persists until $c = 2^2 = 4$.

Figure 3 shows eigenvalues of the generalized eigenvalue problem (1.7) computed numerically with the Fourier method for $c \in (1, 4)$. Five largest and five smallest eigenvalues of the operator
$L_{c,\alpha}^{-1}H_{c,\alpha}$ are shown on the left panel. In agreement with the result of Lemma 3.1 we observe eigenvalues $\lambda$ near points $\{-1, 0, \frac{2}{5}, 2\}$ in addition to a countable sequence of eigenvalues near 1. The right panel zooms in eigenvalues near $c = 1$ and shows the asymptotic approximation of the eigenvalue near 2 given by (3.24) and (3.25) with $\alpha = 2$.

For $c_s \approx 1.2$, two real eigenvalues coalesce to create a pair of complex eigenvalues that exist for every $c > c_s$. This transformation of eigenvalues compared to the result of Lemma 3.2 for $c \gtrsim 1$ does not contradict to the count of eigenvalues in Theorem 1 of [12]. Figure 4 shows that $|1-\lambda|$ for the eigenvalues of $L_T$ remains inside the unit disk for $c \in (c_s, 4)$. Therefore, the complex eigenvalue pair does not introduce additional instability to the iterative method.

![Figure 3](image1)

**Figure 3.** Left: Eigenvalues of the operator $L_{c,\alpha}^{-1}H_{c,\alpha}$ for $\alpha = 2$. Right: Zoom in with the asymptotic dependence given by (3.24) and (3.25).

![Figure 4](image2)

**Figure 4.** The plot of $|1-\lambda|$ for the complex eigenvalues $\lambda$. The insert shows that the complex eigenvalues do not reach the boundary of the unit disk.

For $c \in (1, c_{ss})$ with $c_{ss} \approx 2.3$, the spectrum of $L_T$ in $L^2$ remain inside the unit disk for $c \in (1, c_{ss})$. However, the largest eigenvalue of $L_{c,\alpha}^{-1}H_{c,\alpha}$ crosses the level 2 for $c = c_{ss}$ and the corresponding eigenvalue of $L_T$ is smaller than $-1$ for $c \in (c_{ss}, 4)$. This numerical result suggests
that the iterative method (1.6) converges for \( c \in (1, c^{**}) \) and diverge for \( c \in (c^{**}, 4) \). Moreover, for \( c^{***} \approx 2.7 \), the second largest eigenvalue of \( \mathcal{L}^{-1}_{c,0} \mathcal{H}_{c,0} \) crosses the level 2, hence the iterative method (1.6) diverges with two unstable eigenvalues for \( c \in (c^{***}, 4) \).

To illustrate convergence of the iterative method (1.6) for \( \alpha = 2 \), we use the initial function

\[
(3.27) \quad u_0(x) = a \cos(x) + \frac{1}{2} a^2 (\cos(2x) - 3) + \varepsilon \sin(x),
\]

where \( a > 0 \) and \( \varepsilon \in \mathbb{R} \) are small parameters to our disposal. Notice that we include the \( O(a^2) \) correction term of the Stokes expansion (2.1) in the initial function (3.27) to avoid vanishing denominator in the Petviashvili quotient \( M \) defined by (1.5). Indeed, \( \int_{-\pi}^{\pi} \phi^3 dx = 0 \), whereas \( \int_{-\pi}^{\pi} \phi^3 dx < 0 \) for every \( c > 1 \) and \( \alpha = 2 \) by Lemma 2.4. Computations reported below correspond to \( a = 0.4 \) and \( \varepsilon = 0 \); we have checked that computations for other small values of \( a \) and \( \varepsilon \) return similar results.

We measure the computational errors in three ways: the quantity \( |1 - M_n| \), where \( M_n = M(u_n) \), the distance between two successive approximations \( \|u_{n+1} - u_n\|_{L^\infty} \), and the residual error \( \|cu_n + u'' + u_n^2\|_{L^\infty} \). If iterations do not converge, we stop the algorithm after 500 iterations.

Figure 5 shows the profile of the last iteration and the three computational errors versus the number of iterations in the case \( c = 2 \). It is seen that the iterative method (1.6) converges to the single-lobe periodic wave, in agreement with Corollary 3.1. Since the exact periodic wave is known in (2.12)–(2.13), we can also compute the distance between the last iteration and the exact solution, in which case we find \( \|u - \phi\|_{L^\infty} \approx 2 \cdot 10^{-11} \). If \( \varepsilon \neq 0 \) in the initial function (3.27), the convergence to the periodic wave is still observed but the last iteration is shifted from \( x = 0 \), in agreement with Theorem 3.2.

![Figure 5](image-url)  
Figure 5. Iterations for \( c = 2 \) and \( \alpha = 2 \). (a) The last iteration versus \( x \). (b) Computational errors versus \( n \).

Figure 6 illustrates the case \( c = 2.3 \). Since the largest eigenvalue of \( \mathcal{L}^{-1}_{c,0} \mathcal{H}_{c,0} \) crosses the level 2 at this value of \( c \), see Figure 3, this case is marginal for convergence of iterations. As we can see from Figure 6, iterations still converge to a single-lobe periodic wave but the convergence is slow.

Figure 7 illustrates the case \( c = 3 \). The iterative method (1.6) diverges from the single-lobe periodic wave. The instability is related to the eigenvalue of \( \mathcal{L}_T \) which is smaller than \( -1 \), hence the period-doubling instability leads to an alternating sequence which oscillates between two double-lobe profile shown on the left panel. The right panel shows that the factor \( M \) no longer converges to 1 but to \(-4.3737\) and the residual errors does not converge to 0 but remains strictly positive with
the number of iterations. Therefore, the two limiting states of the iterative method (1.6) in the 2-periodic orbit are not a periodic wave of the boundary-value problem (1.3).

For the BO equation with $\alpha = 1$, we show that the method diverges for $c \gtrsim 1$ in agreement with Corollary 3.1. Figure 8 shows the eigenvalues of the generalized eigenvalue problem (1.7) for $\alpha = 1$. The eigenvalue $\lambda_1 = \frac{2\alpha + 1 - 5}{2\alpha + 1 + 3}$ in Lemma 3.1 yields $\lambda_1 = -1$ for $\alpha = 1$ in addition to the other eigenvalue $-1$ in $\{-1, 0, \lambda_1, \lambda_2\}$. Hence, $\lambda = -1$ is a double eigenvalue and the left panel shows that this double eigenvalue is preserved in $c$. The right panel zooms in eigenvalues near $c = 1$ and shows the asymptotic approximation of the eigenvalue near 2 given by (3.24) and (3.25) with $\alpha = 1$.

To illustrate convergence of the iterative method (1.6) for $\alpha = 1$, we use the initial function

$$u_0(x) = a \cos(x) + \frac{1}{2}a^2(\cos(2x) - 1) + \varepsilon \sin(x),$$

where $a > 0$ and $\varepsilon \in \mathbb{R}$. Again, we have verified that $\int_{-\pi}^{\pi} \phi^2 dx < 0$ for every $c > 1$ and $\alpha = 1$ by the explicit computations in (2.16), therefore, we included the second term of the Stokes expansion (2.9) in the initial function (3.28). In computations below, we take $a = 0.4$.

As predicted by Corollary 3.1 for $\alpha = 1$, the iterative method (1.6) diverges for the BO equation and this divergence for $c \gtrsim 1$ is due to an odd eigenfunction of the generalized eigenvalue problem (1.7) for the eigenvalue $\lambda_1 = -1$. 

Figure 6. Iterations for $c = 2.3$ and $\alpha = 2$. (a) The last iteration versus $x$. (b) Computational errors versus $n$.

Figure 7. Iterations for $c = 3$ and $\alpha = 2$. (a) The last two iterations versus $x$. (b) Computational errors versus $n$. 

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Figure 8. Left: Eigenvalues of the operator $L_{c,\alpha}^{-1}H_{c,\alpha}$ for $\alpha = 1$. Right: Zoom in with the asymptotic dependence given by (3.24) and (3.25).

Figure 9. Iterations for $c = 1.1$ and $\alpha = 1$. (a) The last four iterations versus $x$. (b) Computational errors versus $n$.

Figure 10. Iterations for $c = 1.3$ and $\alpha = 1$. (a) The last four iterations versus $x$. (b) Computational errors versus $n$.

Figure 9 illustrates the case $c = 1.1$ showing the last four iterations in the left panel and the factor $M$ converging to 1.0107 and the residual error converging to 0.0826 in the right panel. In this computation, we take $\varepsilon = 0$. Although the residual error starts to decrease initially due to contracting properties of $L_T$ on the even subspace of $L^2_{\text{per}}(-\pi, \pi)$, round-off errors induce odd perturbations which result in slow instability. As a result, the periodic wave of amplitude 0.458
Lemma 4.1.\ The proof of Theorem 1.2.

\[ (4.3) \tilde{\psi} \text{ to method (1.6) in the 2-periodic orbit are not a periodic wave of the boundary-value problem (1.3).} \]

Similarly to the pattern of Figure 7. The right panel of Figure 11 shows that the factor formed much faster and the drifted periodic profile is drifted to the right if \( \varepsilon > 0 \) and to the left if \( \varepsilon < 0 \).

Figure 10 shows the marginal case \( c = 1.3 \) where another unstable eigenvalue of \( L_T \) related to the even eigenfunction crosses the level \(-1\). Although the instability pattern of Figure 9 is repeated on Figure 10, the periodic profile becomes more complicated and the instability process is accompanied by many intermediate oscillations. Here again we set \( \varepsilon = 0 \), if \( \varepsilon \neq 0 \), the drifted periodic profile is formed much faster and intermediate oscillations are reduced.

Figure 11 illustrates the case \( c = 1.6 \) when several eigenvalues of \( L_T \) are located below \(-1\). After short intermediate iterations, the iterative method starts to oscillate between two iterations, similarly to the pattern of Figure 7. The right panel of Figure 11 shows that the factor \( M \) converges to \(-5.1447\) and the residual error remains strictly positive. The two limiting states of the iterative method (1.6) in the 2-periodic orbit are not a periodic wave of the boundary-value problem (1.3).

4. Proof of Theorem 1.2

By linearizing \( \tilde{T}_{c,\alpha} \) at \( \psi \) with \( w_n = \psi + a_n \psi' + b_n \psi'' + \beta_n \), where \( \beta_n \in H_{\text{per}}^2(-\pi, \pi) \cap L^2_c \) satisfies the two constraints in

\[
L^2_c := \{ \omega \in L^2_{\text{per}}(-\pi, \pi) : \langle \psi', \omega \rangle = \langle \psi', 0 \rangle = 0 \},
\]

we obtain the linearized iterative rule:

\[
 a_{n+1} = 0, \quad b_{n+1} = b_n, \quad \beta_{n+1} = \tilde{L}_T \beta_n,
\]

where

\[
(4.3) \quad \tilde{L}_T := \tilde{L}^{-1}_{c,\alpha}(2\psi') = \text{Id} - \tilde{L}^{-1}_{c,\alpha} \tilde{H}_{c,\alpha} : H_{\text{per}}^2(-\pi, \pi) \cap L^2_c \rightarrow H_{\text{per}}^2(-\pi, \pi) \cap L^2_c
\]

with \( \tilde{L}_{c,\alpha} = c - D_{\alpha} \) and \( \tilde{H}_{c,\alpha} = \tilde{H}_{c,\alpha} \) given by (1.13). Hence Lemmas 2.2 and 2.3 apply to \( \tilde{H}_{c,\alpha} = \tilde{H}_{c,\alpha} \). In addition, Theorem 2.2 ensures positivity of \( \psi(x) > 0 \) for every \( x \in [-\pi, \pi] \).

The following lemma characterizes the spectrum of \( \tilde{L}^{-1}_{c,\alpha} \tilde{H}_{c,\alpha} \) in \( L^2_{\text{per}}(-\pi, \pi) \) for every \( c > 1 \) and \( \alpha \in (0, 2] \). Convergence of the iterative method (1.11) to the positive periodic wave \( \psi \in H_{\text{per}}^2(-\pi, \pi) \) of the boundary-value problem (1.2) follows from this lemma. This construction yields the proof of Theorem 1.2.

**Lemma 4.1.** For every \( c > 1 \) and \( \alpha \in (0, 2] \), \( \sigma(\tilde{L}^{-1}_{c,\alpha} \tilde{H}_{c,\alpha}) \in (0, 1) \) in \( L^2_c \).
Proof. We note that \( \tilde{L}_{c,\alpha} \) is positive for every \( c > 1 \) and \( \alpha > 0 \), whereas \( \tilde{H}_{c,\alpha} \) has one simple negative eigenvalue and a simple zero eigenvalue for every \( c > 1 \) and \( \alpha \in (\alpha_0, 2] \) by Lemma 2.3.

By Theorem 1 in [12], \( \sigma(\tilde{L}_{c,\alpha}^{-1}\tilde{H}_{c,\alpha}) \) in \( L^2_{\text{per}}(-\pi, \pi) \) is real and contains one simple negative eigenvalue and a simple zero eigenvalue, the rest of the spectrum is positive and bounded away from zero. The negative and zero eigenvalues correspond to the exact solutions:

\[
\tilde{L}_{c,\alpha}^{-1}\tilde{H}_{c,\alpha}\psi = -\psi \quad \text{and} \quad \tilde{L}_{c,\alpha}^{-1}\tilde{H}_{c,\alpha}\psi' = 0.
\]

These eigenvalues are removed by adding two constraints in the definition of \( L^2_c \) in (4.1). The positive eigenvalues are bounded from above by 1 because the operator \( \tilde{L}_{c,\alpha}\tilde{T} = \tilde{L}_{c,\alpha}^{-1}(2\psi) = \text{Id} - \tilde{L}_{c,\alpha}^{-1}\tilde{H}_{c,\alpha} \) is strictly positive due to positivity of \( \tilde{L}_{c,\alpha} \) and \( \psi \). Hence, \( \sigma(\tilde{L}_{c,\alpha}^{-1}\tilde{H}_{c,\alpha}) \in (0, 1) \) in \( L^2_c \).

Corollary 4.1. For every \( c > 1 \) and \( \alpha \in (\alpha_0, 2] \), the iterative method (1.11) converges to \( \psi \) in \( H^\alpha_{\text{per}}(-\pi, \pi) \).

Proof. Conditions \( \int_{-\pi}^\pi \psi^3 dx > 0 \) and \( \int_{-\pi}^\pi \psi'(\psi')^2 dx > 0 \) follow by positivity of \( \psi \) in Theorem 2.2.

By Lemma 4.1, the operator \( \tilde{L}_{T} = \tilde{L}_{c,\alpha}(2\psi) = \text{Id} - \tilde{L}_{c,\alpha}^{-1}\tilde{H}_{c,\alpha} \) is a strict contraction in \( L^2_c \) for every \( c > 1 \) and \( \alpha \in (\alpha_0, 2] \). Convergence of the iterative method (1.11) follows by Theorem 3.2.

\[ \square \]

The iterative method (1.11) diverges for \( c = 3 \) and \( \alpha = 2 \), as is seen from Figure 7. We can also compute the distance between the last iteration and the exact solution, in which case we find \( \|u - \phi\|_{L^\infty} \approx 1.3 \cdot 10^{-11} \).

Figure 12 shows the result of iterations for \( c = 3 \) and \( \alpha = 2 \). It is seen that iterations converge quickly to a positive, single-lobe periodic wave \( \psi \) in agreement with Corollary 4.1. Note that the iterative method (1.10) diverges for \( c = 3 \) and \( \alpha = 2 \), as is seen from Figure 7. We can also compute the distance between the last iteration and the exact solution, in which case we find \( \|u - \phi\|_{L^\infty} \approx 5.9 \cdot 10^{-11} \).

Figure 13 reports similar results for \( c = 1.6 \) and \( \alpha = 1 \). Again, the iterative method (1.6) diverges for these values of \( c \) and \( \alpha \), as is seen from Figure 11. We can also compute the distance between the last iteration and the exact solution, in which case we find \( \|u - \phi\|_{L^\infty} \approx 5.9 \cdot 10^{-11} \).
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Figure 13. Iterations for $c = 1.6$ and $\alpha = 1$. (a) The last iteration versus $x$. (b) Computational errors versus $n$.

Acknowledgements: DEP thanks D. Clamond for posing a problem on the lack of convergence of Petviashvili’s method for periodic waves in the KdV equation. The authors also thank H. Chen, A. Durán, M. Johnson, and P. Torres for discussion of various technical aspects of this manuscript.

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