Research Article

A Newton Linearized Crank-Nicolson Method for the Nonlinear Space Fractional Sobolev Equation

Yifan Qin,¹ Xiaocheng Yang,² Yunzhu Ren,¹ Yinghong Xu,¹ and Wahidullah Niazi¹

¹Department of Mathematics, Zhejiang Sci-Tech University, Hangzhou 310018, China
²School of Information Science and Technology, Zhejiang Sci-Tech University, Hangzhou 310018, China

Correspondence should be addressed to Xiaocheng Yang; yangxiaoch209@163.com

Received 16 March 2021; Accepted 10 April 2021; Published 27 April 2021

Abstract

This paper is to construct one class of numerical methods for the nonlinear space fractional Sobolev equation based on the CN method. Firstly, a fractional centered finite difference method in space and the CN method in time are utilized to discretize the original equation. Next, the existence, uniqueness, stability, and convergence of the numerical method are analyzed at length, and the convergence orders are proved to be $O(h^2 + \tau^2)$ in the sense of $L^2$-norm, $H^{\alpha/2}$-norm, and $H^\infty$-norm. Finally, the extensive numerical examples are carried out to verify our theoretical results and show the effectiveness of our algorithm in simulating spatial fractional Sobolev equation.

1. Introduction

The main propose of this paper is to construct one class of the Newton linearized finite difference method based on CN discretization in temporal direction to efficiently solve the following spatial fractional Sobolev equation:

$$\begin{aligned}
\partial_t u - \mu \partial_x \partial_t u &= \kappa \partial_x^\beta u + f(u), & \text{in } \mathbb{R} \times (0, T], \\
u(x, 0) &= u_0(x), & \text{in } \mathbb{R} \times \{0\},
\end{aligned}$$

where $1 < \alpha, \beta \leq 2$, and $\mu$ are positive constants, $u_0(x)$ and $f(u)$ are known sufficiently smooth functions. $\partial_x^\alpha$ in (1) denotes the Riesz fractional derivative operator for $1 < \alpha \leq 2$ and is defined in [1] as follows:

$$\partial_x^\alpha u(x, t) = -\frac{1}{2 \cos(\pi \alpha / 2) \Gamma(2 - \alpha)} \frac{\partial^2}{\partial x^{2-\alpha}} \int_{-\infty}^{\infty} |x - \xi|^{1-\alpha} u(\xi, t) d\xi.$$

(2)

This type of equation is widely used as a mathematical model for fluid flow through thermodynamics [2], shear in second-order fluids [3], consolidation of clay [4], and so on. Note that some special forms of equation (1) are frequently encountered in many fields. For example, taking $\alpha, \beta = 2$, (1) reduces to a one-dimensional integral-order Sobolev equation in the bounded domain [5]. When $f(u) = \sum_{i=1}^p \gamma_i u^i$ with integer $p$ and given constants $\gamma_i (i = 1, 2, \ldots, p)$, then the equation is called a semiconductor equation [6]. When $f(u) = 0$, it is reduced to a homogeneous space fractional Sobolev equation. When $\mu = 0$, (1) is reduced to the classical nonlinear reaction-diffusion equations. Recently, many scholars are dedicated to the numerical investigation on fractional diffusion equations and Sobolev equations based on finite difference or finite element methods in the literature. For example, Çelik and Duman [7] investigated the CN method to approximate the fractional diffusion equation with the Riesz fractional derivative in a finite domain. Wang et al. [8] studied the finite difference method for the space fractional Schrödinger equations under the framework of the fractional Sobolev space. Ran and He [9] investigated the nonlinear multidelay fractional diffusion equation based on the CN method in time and the fractional centered difference in space. Chen et al. [5] proposed a Newton linearized compact finite difference scheme to numerically solve a class of Sobolev equations based on the CN method and proved the unique solvability, convergence, and stability of the proposed scheme. Wang and Huang [10] constructed a conservative...
linear difference scheme for the nonlinear fractional Schrödinger equation. Zhang et al. [11] established the numerical asymptotic stability result of the compact \( \theta \)-method for the generalized delay diffusion equation. More researches on delay fractional problems can be referred to [12, 13] and the references therein.

The main work in this paper is to develop an efficient Newton linearized CN method to solve the nonlinear space fractional Sobolev problem (1). The existence, uniqueness, stability, and convergence of the proposed numerical scheme are demonstrated, and the convergent orders are obtained in the sense of \( L^2 \)-norm, \( H^{\alpha/2} \)-norm, and \( F^{\alpha} \)-norm. Besides, we also prove that the convergence orders of the constructed linearized numerical scheme are \( O(t^2+h^2) \) under three types of norms. The extensive numerical examples are proposed to argue a second-order accuracy in both temporal and spatial dimensions.

The organization of this paper is as follows. In Section 2, we define the fractional Sobolev norm and introduce the second-order centered finite difference approximation for the space Riesz derivative. In Section 3, we construct a CN finite difference scheme for the space fractional Sobolev equation. The existence, uniqueness, stability, and convergence of the proposed scheme in three classes of conventional norms are proved. Finally, the theoretical results are verified by several numerical examples.

2. Preliminaries

Firstly, we present some notations and lemmas which will be used to construct and analyze our numerical scheme.

2.1. Fractional Sobolev Norm. Firstly, we define the fractional Sobolev norm (cf. [14]). Let \( h\mathbb{Z} \) be denoted by the infinite grid with grid points \( x_j = jh \) \((j \in \mathbb{Z})\). For arbitrary grid functions \( u = \{u_j\} \) and \( v = \{v_j\} \) on \( h\mathbb{Z} \), we define the discrete inner products and the corresponding \( L^2 \)-norm and \( F^{\alpha} \)-norm

\[
(u, v) = h \sum_{j \in \mathbb{Z}} u_j v_j, \quad \|u\|^2 = (u, u), \quad \|u\|_{F^{\alpha}} = \sup_{j \in \mathbb{Z}} |u_j|.
\]

(3)

Denote \( \tilde{L}^2 = \{u \mid u = \{u_j\}, \|u\|^2 < \infty\} \). For \( u \in \tilde{L}^2 \), the semidiscrete Fourier transformation \( \tilde{u} \) is written as

\[
\tilde{u}(k) = \frac{1}{\sqrt{2\pi}} h \sum_{j \in \mathbb{Z}} u_j e^{-ikx_j}.
\]

(4)

It is easy to get \( \tilde{u} \in L^2[-\pi/h, \pi/h] \) due to \( u \in \tilde{L}^2 \). The inversion formula is defined by

\[
u_j = \frac{1}{\sqrt{2\pi}} \int_{-\pi/h}^{\pi/h} \tilde{u}(k) e^{ikx_j} dk,
\]

(5) then we can easily check that Parseval’s equality

\[
(u, v) = \int_{-\pi/h}^{\pi/h} \tilde{u}(k) \tilde{v}(k) dk,
\]

(6) holds. Moreover, for the given constant \( 0 \leq \sigma \leq 1 \), the fractional Sobolev norm \( \|u\|_{F^{\sigma}} \) and seminorm \( |u|_{F^{\sigma}} \) are defined as follows:

\[
\|u\|_{F^{\sigma}}^2 = \int_{-\pi/h}^{\pi/h} \left( 1 + |k|^{2\alpha} \right) |u(k)|^2 dk, \quad |u|_{F^{\sigma}}^2 = \int_{-\pi/h}^{\pi/h} |k|^{2\alpha} |u(k)|^2 dk.
\]

(7)

Obviously, \( \|u\|_{F^{\sigma}} = \|u\| + |u|^2 \).

2.2. Second-Order Approximation of Spatial Riesz Fractional Derivative. In this section, we will review a second-order approximation for the Riesz fractional derivative. Introduce

\[
\mathcal{G}^{\alpha/\sigma}(R) = \left\{ \tilde{f} \left( \int_{-\infty}^{\infty} (1+|\omega|^\sigma) |\tilde{f}(\omega)| d\omega \right) f \in L^1(R) \right\},
\]

(8)

where \( \tilde{f}(\omega) = \int_{-\infty}^{\infty} e^{i\omega t} f(t) dt \) denotes the Fourier transformation of \( f(x) \).

Lemma 1. (cf. [7]). Suppose the function \( f(\cdot) \in \mathcal{G}^{2+\alpha}(R) \) and the fractional central difference is defined as follows:

\[
\delta^n f(x) = -h^{-\alpha} \sum_{k=-\infty}^{\infty} g_k^{(n)} f(x-kh).
\]

(9)

Then, it holds

\[
\delta^n f(x) = \delta^n f(x) + O(h^2).
\]

(10)

\( g_k^{(n)} \) is defined as

\[
g_k^{(n)} = \frac{(-1)^k \Gamma(\alpha + 1)}{\Gamma(\alpha/2 - k + 1) \Gamma(\alpha/2 + 1 + k)} k \in \mathbb{Z}.
\]

(11)

This is consistently established for arbitrary \( x \in \mathbb{R} \).

Remark 2. (cf. [15, 16]). If we define \( f^* \) by

\[
f^*(x) = \begin{cases} f(x), & x \in [a, b], \\ 0, & x \notin [a, b], \end{cases}
\]

(12) such that \( f^*(x) \in \mathcal{G}^{2+\alpha}(R) \). We get

\[
\delta^n f(x) = -h^{-\alpha} \sum_{k=-\|x-a\|/h}^{\|x-b\|/h} g_k^{(n)} f(x-kh) + O(h^2).
\]

(13)

For any \( t \in [0, T] \), we define

\[
u^*(x) = \begin{cases} u(x), & x \in [a, b], \\ 0, & x \notin [a, b], \end{cases}
\]

(14) and suppose \( u^*(x) \in \mathcal{G}^{2+\alpha}(R) \).
3. Second-Order CN Method and Theoretical Analysis

In this section, we are concentrated on the derivation and theoretical analysis of the finite different scheme. In practical computation, it is necessary to truncate the whole space problem onto a finite interval (boundaries are usually chosen sufficient large such that the truncation error is negligible or the exact solution has compact support in the bounded domain [17]). Here, we will truncate (1) on the interval \( \Omega = (a, b) \) as follows:

\[
\partial_t u - \mu \partial_x^2 u = \kappa \partial_t u + f(u), \quad \text{in } \Omega \times (0, T],
\]

(15)

\[
u(x, 0) = u_0(x), \quad \text{in } \mathbb{R} \times \{0\},
\]

(16)

\[
u(x, t) = 0, \quad \text{on } \mathbb{R} \setminus \Omega \times [0, T].
\]

(17)

3.1. The Derivation of the Linearized Numerical Scheme. Take positive integers \( M, N \) and let \( \tau = T/N, h = (b - a)/M \) be the temporal and spatial step sizes, respectively. Denote \( x_i = a + ih, 0 \leq i \leq M; t_j = kr, 0 \leq k \leq N; t_{k+1/2} = (k + 1/2)r, 0 \leq k \leq N - 1; \Omega_h = \{x_i \mid 0 \leq i \leq M\}, \Omega = \{x_k \mid 0 \leq k \leq N\}. \) Define \( \omega = (j \mid j = 1, 2, \ldots, M - 1\}, \partial \omega = \partial \omega \setminus \omega. \) Let \( V_h = \{u \mid u = u_i^h \mid 0 \leq i \leq M, 0 \leq k \leq N, u_0^h = u_0^M = 0\} \) be grid function space defined on \( \Omega_h \times \Omega_h \). Then, for a given grid function \( u \in V_h \), we introduce the following notations:

\[
u_i^{k+1}(1) = \frac{1}{2} (u_i^{k+1} + u_i^k), \quad \delta_t u_i^{k+1}(1) = \frac{1}{\tau} (u_i^{k+1} - u_i^k).
\]

(18)

Define the grid function

\[
u^h = u(x, t_k), \quad i \in \omega, 0 \leq k \leq N.
\]

(19)

Then, consider (15) at the point \( (x_i, t_{k+1/2}) \) and have

\[
\partial_t u_i(x_i, t_{k+1/2}) - \mu \partial_x^2 u_i(x_i, t_{k+1/2}) = \kappa \partial_t u_i + f(u_i(x_i, t_{k+1/2})), \quad i \in \omega, 0 \leq k \leq N - 1.
\]

(20)

Utilizing the Taylor expansion, the first term on the left hand side (LHS) in (20) can be estimated as

\[
\partial_t u_i(x_i, t_{k+1/2}) = \delta_t u_i^{k+1/2} + O(\tau^2).
\]

(21)

Noticing Lemma 1, for the second term on LHS in (20), we have

\[
\partial_x^2 \partial_t u_i(x_i, t_{k+1/2}) = \frac{1}{h^2} \sum_{j=0}^{M} g_{j-1}^{(a)}(\omega) \partial_j u_i^{k+1/2} + O(\tau^2 + h^2).
\]

(22)

For the first term on the right hand side (RHS) in (20), it yields

\[
\partial_t^2 u_i(x_i, t_{k+1/2}) = -\frac{1}{h^2} \sum_{j=0}^{M} g_{j-1}^{(a)}(\omega) u_i^{k+1/2} + O(\tau^2 + h^2)
\]

(23)

\[
= \delta_t u_i^{k+1/2} + O(\tau^2 + h^2).
\]

Moreover, we have

\[
u_i(x, t_{k+1/2}) = \frac{1}{2} (u_i^{k+1} + u_i^k) + O(\tau^2),
\]

(24)

\[
u_i(x, t_k) - \nu_i(x, t_{k+1}) = O(\tau) \leq c_0 \tau,
\]

where \( c_0 \) is a positive constant.

Applying the Newton linearized method to the nonlinear term \( f \) on RHS in (20) and using Taylor expansion at the point \( u_i^k \), it yields

\[
f(u_i(x, t_{k+1/2})) = f(u_i^k) + f(u_i^k) + f'(u_i^k) + O(\tau^2)
\]

(25)

\[
= f(u_i^k) + \frac{1}{2} (u_i^{k+1} - u_i^k) + O(\tau^2),
\]

where \( f'(u_i^k) = \partial_{u_i^k} f(\cdot) \). Plugging (21)–(23) and substituting (25) into (20), we have

\[
\delta_t u_i^{k+1/2} - \mu \delta_x \partial_x u_i^{k+1/2} = \kappa \partial_t u_i^{k+1/2} + f(u_i^k) + \frac{1}{2} f'(u_i^k) (u_i^{k+1} - u_i^k) + R_i^k, \quad i \in \omega, 0 \leq k \leq N - 1.
\]

(26)

There exists a positive constant \( c_1 > 0 \) such that

\[
\left|R_i^k\right| \leq c_1 (\tau^2 + h^2), \quad i \in \omega, 0 \leq k \leq N - 1.
\]

(27)

Omitting \( R_i^k \) in (26), replacing \( u_i^{k+1/2} \) with \( u_i^{k+1/2} \) in (26), then the finite difference scheme reads

\[
\delta_t u_i^{k+1/2} - \mu \delta_x \partial_x u_i^{k+1/2} = \kappa \partial_t u_i^{k+1/2} + f(u_i^k) + \frac{1}{2} f'(u_i^k) (u_i^{k+1} - u_i^k), \quad i \in \omega, 0 \leq k \leq N - 1.
\]

(28)

\[
u_i^0 = u_i^0(x_i), \quad i \in \omega,
\]

(29)

\[
u_i^k = 0, \quad i \in \partial \omega, \quad 1 \leq k \leq N.
\]

(30)

3.2. The Unique Solvability of Finite Difference Scheme. This section is concerned with the solvability of scheme (28)–(30). Now, we give some lemmas which will be used in the demonstration of solvability.
Lemma 3. (cf. [7]). Let

\[ A^a = \begin{pmatrix} g_0^{(a)} & g_1^{(a)} & \cdots & g_{M-1}^{(a)} \\ g_1^{(a)} & g_0^{(a)} & \cdots & g_{M-2}^{(a)} \\ \vdots & \vdots & \ddots & \vdots \\ g_{M-2}^{(a)} & g_{M-3}^{(a)} & \cdots & g_0^{(a)} \end{pmatrix}, \]

It holds

\[ g_0^{(a)} = \frac{\Gamma(a + 1)}{\Gamma^2(a/2 + 1)} \leq 0, \quad \sum_{j=-\infty}^{\infty} g_j^{(a)} = 0, \quad g_{-n}^{(a)} = 0, \quad \text{for any } n \leq 0, \]

where for any \( j \leq 1 \), and \( 0 < \lambda_j < 2g_0^{(a)} (i \in \omega) \), \( \lambda_i \) is the \( i \)th symmetric positive eigenvalue of matrix \( A^a \). \( A^\beta \) is given in a similar way. It implies that the matrices \( A^a \) and \( A^\beta \) are nonzero symmetric positive definite matrices.

Lemma 4. (discrete Sobolev inequality (cf. [14])). For every \( 2<\sigma \leq 1 \) there exists a constant \( C_\sigma = C(\sigma) > 0 \), independent of \( h > 0 \), such that

\[ \|v\|_{H^\sigma} \leq C_\sigma \|v\|_{L^2}. \]

Lemma 5. (cf. [8]). For any \( 1 < a \leq 2 \) and any grid function \( v \in V_h \), we have

\[ C_a \|v\|_{H^a}^2 \leq \| -\delta_x^{a/2} v \|_{L^2} \leq \|v\|_{H^2}^2, \]

where \( C_a = (\pi/2)^a \).

Lemma 6. (cf. [17]). For any grid function \( v \in V_h \), there exists a fractional symmetric positive quotient operator \( \delta_x^{a/2} \), such that

\[ (-\delta_x^{a/2} v, v) = \left( \delta_x^{a/2} v, \delta_x^{a/2} v \right). \]

Lemma 7. (cf. [18]) (discrete uniform Sobolev inequality). For every \( 1/2 < \sigma \leq 1 \), there exists a constant \( C_\sigma = C(\sigma) > 0 \) independent of \( h > 0 \) such that

\[ \|u\|_{H^\sigma} \leq \|u\|_{L^2}. \]

Lemma 8. (cf. [19]). Suppose \( \{F^k\}_{k=0}^{\infty} \) be nonnegative sequence and satisfy

\[ F^k \leq c \sum_{l=0}^{k-1} F^l + g, \quad k = 0, 1, 2, \ldots, \]

Then, we have

\[ F^k \leq ge^{ckr}, \quad k = 0, 1, 2, \ldots, \]

where \( c \) and \( g \) are nonnegative constants.

Theorem 9. The linearized finite difference scheme (28)–(30) is uniquely solvable.

Proof. Denote \( u^k = (u^k_1, u^k_2, \ldots, u^k_{M-1})^T \). We will prove the above result by the mathematical induction. Obviously, (29) is true for \( k = 0 \). Now, suppose \( u^l(0 \leq k \leq l \leq N - 1) \) has been uniquely determined; then, we only need to prove that \( u^{l+1} \) is uniquely determined by (28). We can rewrite (28) in the following matrix form:

\[ \left( I + \frac{\mu}{h^a} A^a + \frac{\tau K}{2h^a} A^\beta - \frac{\tau}{2} \text{diag} \left( f \left( u^l \right) \right) \right) u^{l+1} \]

\[ = \left( I + \frac{\mu}{h^a} A^a - \frac{\tau K}{2h^a} A^\beta - \frac{\tau}{2} \text{diag} \left( f \left( u^l \right) \right) \right) u^l + \tau f \left( u^l \right) + \tilde{G}^{l+1}, \]

where \( \tilde{G}^{l+1} \) is a vector which depends only on the boundary value. By using Lemma 3, when \( h \) is sufficiently small, it is easy to verify that the coefficient matrix of (39) is strictly diagonally dominant, which implies that there exists a unique solution \( u^{l+1} \). This completes the proof.

3.3. The Convergence and Stability of the Finite Difference Scheme. Firstly, we easily have the estimation of the local truncation error, according to (27).

Lemma 10. Let \( u(x, \cdot) \in C^{(2+a)}(x, \cdot) \) be the solution of the problem (15)–(17). Then, we have

\[ \|R^k\|^2 \leq (b-a)c_1^2 (\tau^2 + h^2)^2, \quad 0 \leq k \leq N - 1, \]

where \( c_1 \) is a positive constant independent of \( \tau \) and \( h \).

Denote

\[ c_i^k = U_i^k - u_i, \quad i \in \omega, \quad 0 \leq k \leq N. \]

We will obtain the main convergence result.

Theorem 11. Let \( u(x, \cdot) \in C^{(2+a)}(x, \cdot) \) be the solution of the problem (15)–(17). Then, there exist positive constants \( \tau_0 \) and \( h_0 \), when \( \tau < \tau_0 \) and \( h < h_0 \), for \( 0 \leq k \leq N \), we have

\[ \|\delta_i^k\|_{L^2} \leq C_1 (\tau^2 + h^2), \quad \|\delta_i^k\|_{H^{a/2}} \leq C_2 (\tau^2 + h^2), \quad \|\delta_i^k\|_{L^\infty} \leq C_3 (\tau^2 + h^2), \]

where \( C_1, C_2, C_3 > 0 \) are positive constants dependent of \( \tau \) and \( h \).
Proof. The mathematical induction will be employed. Firstly, it is obvious (42) is true for \( k = 0 \), via (29). Then, it assumes that (42) is true for \( 1 \leq k \leq m \leq N - 1 \). We will discuss that (42) holds for \( k = m + 1 \). According to the hypothesis, we can obtain the following estimation:

\[
\|u^k\|_{p_0} \leq \|u^{\hat{k}}\|_{p_0} + \|U^k\|_{p_0} \leq C_3 (r^2 + h^2) + \tilde{c}_0 \leq 1 + \tilde{c}_0, 1 \leq k \leq m, \tag{43}
\]

where \( \tau < \tau_0 = (2C_3)^{-1/2}, \ h < h_0 = (2C_3)^{-1/2} \), and \( \tilde{c}_0 = \max_{(x,t) \in \Omega \times [0,T]} \|U(x,t)\| \).

In the view of Lipschitz condition, we have

\[
|f\left(U^k\right) - f\left(U_i^k\right)| \leq c_2 \|\epsilon_i^k\|, i \in \sigma, 0 \leq k \leq N, \tag{44}
\]

\[
|f'\left(U^k\right) - f'\left(U_i^k\right)| \leq c_3 \|\epsilon_i^k\|, i \in \sigma, 0 \leq k \leq N, \tag{45}
\]

\[
\left|f'\left(U_i^k\right)\right| \leq c_4, i \in \sigma, 0 \leq k \leq N, \tag{46}
\]

where \( c_2, c_3, \) and \( c_4 \) are positive constants independent of \( \tau \) and \( h \).

Now, subtracting (28) from (26), we can obtain the error equation

\[
\delta_i e^{k+1/2} - \mu \delta_i e_{i}^{k+1/2} = \kappa \delta_i e_{i}^{k+1/2} + P_i^k + R_i^k, i \in \sigma, 0 \leq k \leq N - 1, \tag{47}
\]

where

\[
P_i^k = f\left(U_i^k\right) - f\left(U_i^k\right) U_i^{k+1/2} - U_i^{k+1} U_i^{k+1} - U_i^k U_i^{k+1} \right). \tag{48}
\]

Firstly, we establish \( L^2 \)-error estimation. Taking the discrete inner product of (47) with \( e^{k+1/2} \), we have

\[
\left(\delta_i e^{k+1/2}, e^{k+1/2}\right) - \mu \left(\delta_i e^{k+1/2}, e^{k+1/2}\right) = \kappa \left(\delta_i e^{k+1/2}, e^{k+1/2}\right) + \left(P_i^k, e^{k+1/2}\right) + \left(R_i^k, e^{k+1/2}\right). \tag{49}
\]

Now, we estimate each term in (49). The first term on LHS in (49) can be estimated as

\[
\left(\delta_i e^{k+1/2}, e^{k+1/2}\right) = \frac{1}{2\tau} \left(\|e^{k+1/2}\|^2 - \|e^{k+1/2}\|^2\right). \tag{50}
\]

Noticing Lemma 6, for the second term on the LHS in (49), we have

\[
\left(\delta_i e^{k+1/2}, e^{k+1/2}\right) = -\frac{1}{2\tau} \left(\|e^{k+1/2}\|^2 - \|e^{k+1/2}\|^2\right).
\]

Similarly, the first term on RHS in (49) can be obtained by

\[
\left(\delta_i e^{k+1/2}, e^{k+1/2}\right) = -\frac{1}{4\tau} \left(\|e^{k+1/2}\|^2 - \|e^{k+1/2}\|^2\right). \tag{51}
\]

According to (44)–(46), we have

\[
\|P_i^k\| = \left|f\left(U_i^k\right) - f\left(U_i^k\right) U_i^{k+1} U_i^k - U_i^{k+1} \right| \leq c_2 \|\epsilon_i^k\| + \frac{1}{2} \left(\|f'\left(U_i^k\right) - f'\left(U_i^k\right)\|\right) \leq c_2 \|\epsilon_i^k\| + \frac{1}{2} \left(\|f'\left(U_i^k\right) - f'\left(U_i^k\right)\|\right).
\]

Using the Cauchy-Schwarz inequality and Young inequality, the second term on the RHS in (49) becomes

\[
\left(P_i^k, e^{k+1/2}\right) \leq \frac{9}{4} \left(\|e^{k+1/2}\|^2 + \frac{1}{4} \left(\|e^{k+1/2}\|^2\right)\right) + \frac{1}{6} \left(\|e^{k+1/2}\|^2\right) \leq \frac{9c_2^2}{4} \left(\|e^{k+1/2}\|^2\right) + \frac{9c_2^2}{4} + \frac{1}{6} \left(\|e^{k+1/2}\|^2\right). \tag{52}
\]

The last term of RHS in (49) is estimated as

\[
\left(R_i^k, e^{k+1/2}\right) \leq \frac{3}{4} \left(\|e^{k+1/2}\|^2\right) + \frac{1}{3} \left(\|e^{k+1/2}\|^2\right) \leq \frac{3}{4} \left(\|e^{k+1/2}\|^2\right) + \frac{1}{6} \left(\|e^{k+1/2}\|^2\right). \tag{53}
\]

Substituting (50)–(55) into (49), we get

\[
\frac{\|e^{k+1/2}\|^2 - \|e^k\|^2}{2\tau} + \frac{\|\delta_i e^{k+1/2}\|^2 - \|\delta_i e^k\|^2}{2\tau} + \frac{\|\delta_i e^{k+1/2}\|^2 + \|\delta_i e^k\|^2}{2\tau} \leq c_2 \left(\|e^{k+1/2}\|^2 + \|e^k\|^2\right) + \frac{3}{4} \left(\|e^{k+1/2}\|^2\right).
\]

where \( c_2 = (9c_2^2/4) + (9c_2^2c_5^2r^2/16) + ((9/8)/9/c_2^2) + (1/3) \).
Summing for \( k \) from 0 to \( m \), we have
\[
\left\| e^{m+1} \right\|^2 + \mu \left\| \Delta_{x^2}^{\alpha} e^{m+1} \right\|^2 \leq \frac{\mu}{2} \left\| \Delta_t^{\alpha} e^0 \right\|^2 + \frac{k}{2} \sum_{k=0}^{m} \left( \left\| \Delta_{x^2}^{\alpha} e^{k+1} \right\|^2 + \left\| \Delta_t^{\alpha} e^{k} \right\|^2 \right).
\]
Noticing that \( e^0 = 0 \) and \( \kappa > 0 \), we have
\[
\left\| e^{m+1} \right\|^2 + \mu \left\| \Delta_{x^2}^{\alpha} e^{m+1} \right\|^2 \leq 4\epsilon_5 \sum_{k=0}^{m} \left\| \Delta_{x^2}^{\alpha} e^{k} \right\|^2 + 2\tau \epsilon_7 \left\| e^{m+1} \right\|^2 + \frac{3\tau}{2} \sum_{k=0}^{m} \left( \tau^2 + h^2 \right)^{2}.
\]
Therefore, we have
\[
\left\| e^{m+1} \right\| \leq C_1 \left( \tau^2 + h^2 \right),
\] where
\[
C_1 = \sqrt{(9(b-a)c_1^2T \exp(12\epsilon_5 T))/2}.
\]
Similarly, applying Lemma 5 yields
\[
\left\| e^{m+1} \right\|_{l^p} \leq C_2 \left( \tau^2 + h^2 \right),
\] where
\[
C_2 = \sqrt{(9(b-a)c_1^2T \exp(12\epsilon_5 T))/2C_{\alpha\mu}}.
\]
Finally, we can establish \( l^p \)-error estimate by combining (62) with (63). Denoting \( C_3 = C_1 \sqrt{C_1^2 + C_2^2} \), it follows from Lemma 7 that
\[
\left\| e^{m+1} \right\|_{l^p} \leq C_3 \left( \tau^2 + h^2 \right).
\]
We complete the proof.

Next, we will analyze the stability of the scheme (28)–(30). Let \( \{ u_i \} \) be the solution of the fractional Sobolev equation
\[
E(h, \tau) = \frac{1}{h} \sum_{i=0}^{M} \left( U_i - u_i \right)^2, \quad E_{\alpha}(h, \tau) = \max_{0 \leq i \leq M, 0 \leq k \leq N} \left| U_i - u_i \right|.
\]
\[
\text{Ord}_2 = \log_2 \left( \frac{\left\| E(h, \tau) \right\|}{\left\| E(h/2, \tau/2) \right\|} \right),
\]
\[
\text{Ord}_{\alpha} = \log_2 \left( \frac{\left\| E(h, \tau) \right\|_{l^p}}{\left\| E(h/2, \tau/2) \right\|_{l^p}} \right).
\]

Table 1: $\ell^2$- and $\ell^\infty$-errors and their convergence orders of (28)–(30) for $1 < \alpha < 2$ in the spatial direction for (72) with fixed time step $\tau = 1/2000$ for Example 1.

| $(\alpha, \beta)$ | $h$   | $\|e\|$   | Ord$_2$ | $\|e\|_\infty$ | Ord$_\infty$ |
|-------------------|-------|-----------|---------|-----------------|--------------|
| (1.2,1.8)         | 1/10  | 7.5025e-4 | –       | 1.0862e-3       | –            |
|                   | 1/20  | 1.7359e-4 | 2.1117  | 2.5686e-4       | 2.0802       |
|                   | 1/40  | 4.0650e-5 | 2.0702  | 6.1167e-5       | 2.0702       |
| (1.5,1.5)         | 1/10  | 7.7557e-4 | –       | 1.1391e-3       | –            |
|                   | 1/20  | 1.7445e-4 | 2.1524  | 2.6326e-4       | 2.1133       |
|                   | 1/40  | 3.9827e-5 | 2.1310  | 6.1202e-5       | 2.1048       |
| (1.8,1.2)         | 1/10  | 1.1777e-3 | –       | 1.6525e-3       | –            |
|                   | 1/20  | 2.7908e-4 | 2.0733  | 3.9673e-4       | 2.0584       |
|                   | 1/40  | 6.6203e-5 | 2.0757  | 9.5326e-5       | 2.0572       |

Table 2: $\ell^2$- and $\ell^\infty$-errors and their convergence orders of (28)–(30) for $1 < \alpha < 2$ in the temporal direction for (72) with fixed spatial step $h = 1/2000$ for Example 1.

| $(\alpha, \beta)$ | $\tau$ | $\|e\|$   | Ord$_2$ | $\|e\|_\infty$ | Ord$_\infty$ |
|-------------------|--------|-----------|---------|-----------------|--------------|
| (1.2,1.8)         | 1/10   | 1.9481e-4 | –       | 3.1163e-4       | –            |
|                   | 1/20   | 4.8708e-5 | 1.9998  | 7.7916e-5       | 1.9998       |
|                   | 1/40   | 1.2169e-5 | 2.0010  | 1.9465e-5       | 2.0010       |
| (1.5,1.5)         | 1/10   | 1.5223e-4 | –       | 2.4163e-4       | –            |
|                   | 1/20   | 3.8057e-5 | 2.0000  | 6.0406e-5       | 2.0001       |
|                   | 1/40   | 9.5069e-6 | 2.0011  | 1.5088e-5       | 2.0013       |
| (1.8,1.2)         | 1/10   | 1.2416e-4 | –       | 1.9507e-4       | –            |
|                   | 1/20   | 3.1025e-5 | 2.0006  | 4.8747e-5       | 2.0006       |
|                   | 1/40   | 7.7412e-6 | 2.0028  | 1.2163e-5       | 2.0028       |

Table 3: $\ell^2$- and $\ell^\infty$-errors and their convergence orders of (28)–(30) for $1 < \alpha < 2$ in the spatial direction for (73) with $\tau = 1/2000$ for Example 2.

| $(\alpha, \beta)$ | $h$   | $\|e\|$   | Ord$_2$ | $\|e\|_\infty$ | Ord$_\infty$ |
|-------------------|-------|-----------|---------|-----------------|--------------|
| (1.1,1.9)         | 1/100 | 1.3736e-4 | –       | 2.9683e-4       | –            |
|                   | 1/200 | 4.9959e-5 | 1.4591  | 9.9718e-5       | 1.5737       |
|                   | 1/400 | 1.6497e-5 | 1.5985  | 3.1555e-5       | 1.6784       |
| (1.5,1.5)         | 1/100 | 4.6568e-4 | –       | 6.5750e-4       | –            |
|                   | 1/200 | 1.3983e-4 | 1.7357  | 2.0089e-4       | 1.7106       |
|                   | 1/400 | 4.0066e-5 | 1.8032  | 5.8340e-5       | 1.7839       |
| (1.9,1.1)         | 1/100 | 1.7483e-4 | –       | 2.1547e-4       | –            |
|                   | 1/200 | 4.6475e-5 | 1.9115  | 5.7682e-5       | 1.9013       |
|                   | 1/400 | 1.2052e-5 | 1.9471  | 1.5024e-5       | 1.9408       |

Example 1. We firstly consider the following fractional Sobolev equation as

\[
\partial_t u - \mu \partial_x^\alpha \partial_t \mu = \kappa \partial_x^\beta u + \sin (u) + g(x, t), \quad (x, t) \in (0, 1) \times (0, 1],
\]

(71)

The exact solution is

\[
u(x, t) = \tau^3 x^2 (1 - x)^2.
\]

(72)
Table 4: $L^2$- and $H^1$-errors and their convergence orders of (28)--(30) for $1 < \alpha < 2$ in the temporal direction for (73) with $h = 1/1000$ for Example 2.

| $(\alpha, \beta)$ | $\tau$ | $\|e\|$ | $\text{Ord}_2$ | $\|e\|_{L^\infty}$ | $\text{Ord}_{L^\infty}$ |
|-------------------|--------|--------|----------------|-----------------|----------------|
| $(1.1,1.9)$       | 1/100  | 2.0697e - 2 | –                | 5.6643e - 2     | –               |
|                   | 1/200  | 8.1358e - 3 | 1.3471          | 1.3366e - 2     | 2.0833          |
|                   | 1/400  | 2.0509e - 3 | 1.9880          | 2.9698e - 3     | 2.1701          |
| $(1.5,1.5)$       | 1/100  | 2.0526e - 2 | –                | 5.6522e - 2     | –               |
|                   | 1/200  | 8.1446e - 3 | 1.3336          | 1.3303e - 2     | 2.0871          |
|                   | 1/400  | 2.0523e - 3 | 1.9886          | 2.9423e - 3     | 2.1767          |
| $(1.9,1.1)$       | 1/100  | 2.0734e - 2 | –                | 5.6310e - 2     | –               |
|                   | 1/200  | 8.1558e - 3 | 1.3461          | 1.3202e - 2     | 2.0927          |
|                   | 1/400  | 2.0536e - 3 | 1.9897          | 2.9033e - 3     | 2.1850          |

Table 5: $L^2$- and $H^1$-errors and their convergence orders of (28)--(30) for $1 < \alpha < 2$ in the spatial direction for (75) with $\tau = 1/1000$ for Example 3.

| $(\alpha, \beta)$ | $h$ | $\|e\|$ | $\text{Ord}_2$ | $\|e\|_{L^\infty}$ | $\text{Ord}_{L^\infty}$ |
|-------------------|-----|--------|----------------|-----------------|----------------|
| $(1.3,1.7)$       | 1/10 | 1.4761e - 2 | –                | 1.6303e - 2     | –               |
|                   | 1/20 | 3.3659e - 3 | 2.1327          | 3.8460e - 3     | 2.0837          |
|                   | 1/40 | 8.0373e - 4 | 2.0662          | 9.0995e - 4     | 2.0795          |
| $(1.5,1.5)$       | 1/10 | 1.6167e - 2 | –                | 1.8043e - 2     | –               |
|                   | 1/20 | 3.6642e - 3 | 2.1414          | 4.2293e - 3     | 2.0930          |
|                   | 1/40 | 8.7053e - 4 | 2.0735          | 9.9262e - 4     | 2.0911          |
| $(1.7,1.3)$       | 1/10 | 2.0933e - 2 | –                | 2.2257e - 2     | –               |
|                   | 1/20 | 4.8190e - 3 | 2.1190          | 5.3128e - 3     | 2.0667          |
|                   | 1/40 | 1.1227e - 3 | 2.1018          | 1.2648e - 3     | 2.0705          |

Table 6: $L^2$- and $H^1$-errors and their convergence orders of (28)--(30) for $1 < \alpha < 2$ in the temporal direction for (75) with $h = 1/1000$ for Example 3.

| $(\alpha, \beta)$ | $\tau$ | $\|e\|$ | $\text{Ord}_2$ | $\|e\|_{L^\infty}$ | $\text{Ord}_{L^\infty}$ |
|-------------------|--------|--------|----------------|-----------------|----------------|
| $(1.3,1.7)$       | 1/10   | 9.1725e - 3 | –                | 1.0470e - 2     | –               |
|                   | 1/20   | 2.5218e - 3 | 1.8629          | 2.8729e - 3     | 1.8657          |
|                   | 1/40   | 6.6380e - 4 | 1.9256          | 7.5586e - 4     | 1.9263          |
| $(1.5,1.5)$       | 1/10   | 8.7813e - 3 | –                | 9.8734e - 3     | –               |
|                   | 1/20   | 2.4228e - 3 | 1.8578          | 2.7208e - 3     | 1.8595          |
|                   | 1/40   | 6.3844e - 4 | 1.9240          | 7.1689e - 4     | 1.9242          |
| $(1.7,1.3)$       | 1/10   | 8.2127e - 3 | –                | 9.1056e - 3     | –               |
|                   | 1/20   | 2.2771e - 3 | 1.8507          | 2.5228e - 3     | 1.8517          |
|                   | 1/40   | 6.0134e - 4 | 1.9209          | 6.6620e - 4     | 1.9210          |

Taking $\mu = 1$, $\kappa = 1$, the linearized numerical scheme (28)--(30) with $\tau = h$ is applied to solve the above Sobolev equation. The global numerical errors and convergence orders with respect to different $\alpha$ and $\beta$ are listed in the following tables. Table 1 lists the $L^2$-norm and $H^1$-norm errors and spatial convergence orders with fixed time step $\tau = 1/2000$. Table 2 tests the temporal convergence orders with fixed spatial step $h = 1/2000$. It demonstrates that the convergence orders of the scheme (28)--(30) is second-order accurate in both spatial and temporal directions which is consistent with Theorem 11.

All the data are referred to MATLAB codes in Example 1 in the supplementary files.
Example 2. Next, we consider the nonlinear fractional Sobolev equation as

\[ u(x, t) = \sin (t + 1) (2 + x)^2 (2 - x)^2 \]  

(73)

is oscillatory along with the temporal direction, where \( \mu = 1 \) and \( \kappa = 1 \). And the initial boundary conditions and \( g(x, t) \) are determined by (73).

In this example, we examine the spatial convergence orders with the fixed time step \( \tau = 1/2000 \) and the temporal convergence orders with the fixed spatial step \( h = 1/1000 \) in \( L^2 \)-norm and \( L^\infty \)-norm errors, respectively. All the numerical results in the example are listed in Tables 3 and 4. Similar results are observed. All the data are referred to MATLAB codes in Example 2 in the supplementary files.

Example 3. Then, we calculate the nonlinear fractional Sobolev equation as

\[ \partial_t u - \partial_x^\mu \partial_x u = \partial_x^\beta u + u^2 - u^4 + g(x, t), (x, t) \in (-1, 1) \times (0, 1). \]  

(74)

We choose the exact solution

\[ u(x, t) = (t + 1) (1 + x)^2 (1 - x)^2. \]  

(75)

The initial boundary conditions and \( g(x, t) \) are determined by (75).

Similar to above example, Tables 5 and 6 list the \( L^2 \)-norm and \( L^\infty \)-norm errors and corresponding spatial and temporal convergence orders of (28)–(30), respectively. To testify the spatial convergence orders, we fixed the time step \( \tau = 1/1000 \). Similarly, we take the fixed spatial step \( h = 1/1000 \) to obtain the temporal convergence orders. The numerical
results show that (28)–(30) is close to second-order accurate in spatial and temporal directions. All the data are referred to MATLAB codes in Example 3 in the supplementary files.

In the following model, the exact solution is unknown, we test convergence orders using the posterior error estimation

$$\text{Ord}_2 = \log_2 \left( \frac{\|u(h, \tau) - u(h, \tau/2)\|}{\|u(h, \tau/2) - u(h, \tau/4)\|} \right), \text{Ord}_\infty = \log_2 \left( \frac{\|u(h, \tau) - u(h, \tau/2)\|_{\infty}}{\|u(h, \tau/2) - u(h, \tau/4)\|_{\infty}} \right),$$

(76)

Example 4. We consider the following equation:

$$\partial_t u - \partial_x^2 \partial_t u = \partial_x^2 u + u - u^2, \quad (x, t) \in (-25, 25) \times (0, 0.1],$$

$$u(x, 0) = \sqrt{2}\text{sech}(x + 5) \cos (4/x), x \in [-25, 25],$$

$$u(-25, t) = u(25, t) = 0, t \in [0, 0.1],$$

(77)

with the exact solution is unknown.

In the computation, we take different spatial and temporal step sizes. The $l^2$, $l^\infty$-norm errors, and their convergence orders of (28)–(30) are listed in Table 7 with the fixed temporal step size $\tau = 1/1000$. Similarly, the spatial step size fixed at $h = 1/1000$ in Table 8. Tables 7 and 8 show that the numerical results have second-order accurate in spatial and temporal directions. Figure 1 presents curves of $u(x, t)$ with respect to $x$ at different time with the step sizes $h = 0.5$, $\tau = 0.02$ (a) and the evolutionary surfaces of $u(x, t)$ at $T = 0.1$ (b), $T = 1$ (c), and $T = 2$ (d) in Example 4.

5. Conclusion

In the article, we establish an efficient finite difference scheme for nonlinear spatial fractional Sobolev equation based on Newton linearized technique. We have proved that the numerical solution of the scheme is unique solvable, stable, and convergent. The pointwise error estimate is proved with the convergence order $O(\tau^2 + h^2)$. Extensive numerical examples are carried out to testify the numerical theoretical results. Extending the current work to high dimensional cases is possible, which will leave as our future work.
Data Availability

All the data are available and referred to the supplementary file.

Conflicts of Interest

The authors declare that they have no competing interests.

Acknowledgments

This work was supported by Zhejiang Provincial Natural Science Foundation of China under Grant LY18D060009.

References

[1] R. Gorenflo and F. Mainardi, “Random walk models for space-fractional diffusion processes,” *Fractional Calculus and Applied Analysis*, vol. 1, no. 2, pp. 167–191, 1998.

[2] R. E. Ewing, “A coupled non-linear hyperbolic-Sobolev system,” *Annali di Matematica Pura ed Applicata*, vol. 114, no. 1, pp. 331–349, 1977.

[3] T. W. Ting, “A cooling process according to two-temperature theory of heat conduction,” *Journal of Mathematical Analysis and Applications*, vol. 45, no. 1, pp. 23–31, 1974.

[4] D. W. Taylor, *Research on Consolidation of Clays*, Massachusetts Institute of Technology Press, Cambridge, 1942.

[5] X. Chen, J. Duan, and D. Li, “A Newton linearized compact finite difference scheme for one class of Sobolev equations,” *Numerical Methods for Partial Differential Equations*, vol. 34, no. 3, pp. 1093–1112, 2018.

[6] M. O. Korpusov and A. G. Sveshnikov, “Blow-up of solutions of abstract Cauchy problems for nonlinear operator differential equations,” *Doklady Akademii Nauk*, vol. 195, pp. 12–15, 2005.

[7] C. Çelik and M. Duman, “Crank-Nicolson method for the fractional diffusion equation with the Riesz fractional derivative,” *Journal of Computational Physics*, vol. 231, no. 4, pp. 1743–1750, 2012.

[8] D. Wang, A. Xiao, and W. Yang, “Maximum-norm error analysis of a difference scheme for the space fractional CNLS,” *Applied Mathematics and Computation*, vol. 257, pp. 241–251, 2015.

[9] M. Ran and Y. He, “Linearized Crank-Nicolson method for solving the nonlinear fractional diffusion equation with multi-delay,” *International Journal of Computer Mathematics*, vol. 95, pp. 1–14, 2017.

[10] P. Wang and C. Huang, “A conservative linearized difference scheme for the nonlinear fractional Schrödinger equation,” *Numerical Algorithms*, vol. 69, no. 3, pp. 625–641, 2015.

[11] Q. Zhang, M. Chen, Y. Xu, and D. Xu, “Compact $\theta$-method for the generalized delay diffusion equation,” *Applied Mathematics and Computation*, vol. 316, pp. 357–369, 2018.

[12] Q. Zhang, X. Lin, K. Pan, and Y. Ren, “Linearized ADI schemes for two-dimensional space-fractional nonlinear Ginzburg-Landau equation,” *Computers and Mathematics with Applications*, vol. 80, no. 5, pp. 1201–1220, 2020.

[13] Q. Zhang and T. Li, “Asymptotic stability of compact and linear $$\theta$$-methods for space fractional delay generalized diffusion equation,” *Journal of Scientific Computing*, vol. 81, no. 3, pp. 2413–2446, 2019.