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New soliton solutions with graphical analysis to the fractional Schrodinger–Hirota equation

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Abstract. The central objective of this study is to employ the generalized exponential rational function method in order to derive exact analytical solutions for the generalized nonlinear fractional Schrödinger–Hirota equation. By applying various ansatz techniques with time-dependent coefficients, both bright and dark optical soliton solutions of the proposed model are systematically constructed and analyzed. These soliton structures highlight the rich dynamical behavior of the equation and demonstrate the effectiveness of the adopted analytical approach. Furthermore, a detailed graphical investigation of the obtained solutions is carried out using Mathematica software. This visual analysis provides deeper insight into the evolution, stability, and fluctuation characteristics of the solutions under different parameter settings, thereby enhancing the physical interpretation of the results. The outcomes of this research have potential applications in the development of advanced theoretical models in plasma physics, condensed matter physics, optical fiber communications, and various industrial processes.

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1. Introduction

Finding exact solution methods for partial differential equations remains a fundamental challenge across many scientific disciplines, including mathematics, physics, and engineering. In many practical situations, these equations exhibit strong nonlinearity or complex boundary conditions, making classical solution techniques ineffective or entirely inapplicable. As a result, developing systematic approaches that can yield exact or closed-form solutions is of great theoretical and practical significance.

Partial differential equations play a central role in modeling a wide range of natural and physical phenomena such as fluid flow, heat transfer, wave propagation, and electromagnetic fields. Accurate analytical solutions not only provide a deeper understanding of the underlying physical processes but also serve as reliable benchmarks for validating numerical and approximate methods. Moreover, exact solutions can reveal qualitative properties of the system, including stability, symmetry, and long-term behavior, which are often difficult to detect through numerical simulations alone.

Given the importance of these equations, numerous analytical techniques have been proposed and refined over the years, including transformation methods, symmetry analysis, perturbation techniques, and variational approaches. These methods have proven effective for specific classes of equations and have significantly contributed to the advancement of mathematical modeling in science and engineering. Consequently, continued research into innovative analytical strategies remains essential for expanding the range of solvable partial differential equations and improving our understanding of complex systems. Due to the importance of the subject, several analytical methods have been successfully applied to obtain the exact solution of such equations. Some of these methods [1-22]. In the following, we consider the definitions and basic concepts for fractional derivatives.

1.1 we assume$f : [0,\infty) \to \mathbb{R}$, the conformable derivative of a function $f(t)$ of order α, is defined as

$$D_t^{\alpha} f(t) = \lim_{\to 0} \frac{f(t + t^{1-\alpha}) - f(t)}{}, \quad \alpha \in (0,1], \quad t > 0. \tag{1.1}$$

This new definition satisfies the following properties.

1.2 if that $c \geq 0$ and $t \ \geq \ c$, let h be a function defined on $(c, \ t]$ as well as $\alpha \in R$. Then, the $\alpha-$fractional integral of $h$is given by

$$ {}_{t}I_{c}^{\alpha}h\left(t\right)=\int\limits_{c}^{\alpha}\frac{h\left(x\right)}{x^{1-\alpha}}dx, $$

if the Riemann improper integral exists.

1.3 Theorem. for $\alpha \in (0,1]$, f, g be α-differentiable at a point t, then
$D_t^{\alpha}(af+bg)=aD_t^{\alpha}(f)+bD_t^{\alpha}(g)$, for $a, b \in \mathbb{R}$.
$D_t^{\alpha}(t^{\mu})=\mu t^{\mu-\alpha}$, for $\mu \in \mathbb{R}$.

$$ D_t^{\alpha}(fg)=fD_t^{\alpha}(g)+gD_t^{\alpha}(f). $$

$$ D_t^{\alpha}(\frac{g}{g})=\frac{gD_t^{\alpha}(f)-fD_t^{\alpha}(g)}{g^2}. $$

$$ D_t^{\alpha}(fog)\left(t\right)=t^{1-\alpha}g(t)^{\alpha-1}g'\left(t\right)D_t^{\alpha}\left(f\left(t\right)\right)_{t=g(t)}, $$

where "prime" is the classical derivatives with respect to t.

2. Basic structure for GERF method

From the GERFM we consider the following nonlinear PDE

$$ \mathcal{L}(\psi,\psi_x,\psi_t,\psi_{xx},\ldots)=0. \tag{2.1} $$

Using the transformations $\psi=\psi(\xi)$ and $\xi=\sigma x-lt$, we reduce the nonlinear partial differential equation to the following ordinary differential equation:

$$ \mathcal{L}(\psi,\psi',\psi'',\ldots)=0, \tag{2.2} $$

Where σ and l will be found later. Now we consider that Eq. (2.2) has solution of the form

$$ \psi(\xi)=A_0+\sum_{k=1}^{M}A_k\Psi(\xi)^k+\sum_{k=1}^{M}B_k\Psi(\xi)^{-k}, \tag{2.3} $$

Where

$$ \Psi(\xi)=\frac{p_1e^{q_1\xi}+p_2e^{q_2\xi}}{p_3e^{q_3\xi}+p_4e^{q_4\xi}}. \tag{2.4} $$

The values of constants$p_i, q_i (1 \leq i \leq 4)$, A_0, A_k and $B_k (1 \leq k \leq M)$ are determined, in such a way that solution (2.3) always persuade Eq. (2.2). By considering the homogenous balance principle the value of M is determined .

3. Results

The generalized nonlinear fractional Schrödinger–Hirota system considered as following form

$$\begin{aligned} &iD_t^{\alpha}u + a_2 D_x^{2\alpha}u + ia_3 D_x^{3\alpha}u + a_4 D_x^{4\alpha} + ibD_x^{\alpha}\left(|u|^2 u\right) + \\ &i\sigma |u|^2 D_x^{\alpha}u + i\lambda D_x^{\alpha}\left(|u|^2\right) = c_1 |u|^2 u + c_2 |u|^4, \end{aligned} \tag{3.1}$$

We look for solution of Eq. (3.1) in the form

$$u(x,t) = \varphi(\xi)\, e^{i\left(k\frac{x^{\alpha}}{\alpha} - w\frac{t^{\alpha}}{\alpha} - \theta_0\right)}, \xi = \frac{x^{\alpha}}{\alpha} - v\frac{t^{\alpha}}{\alpha} \tag{3.2}$$

By replacing (3.2) into (3.1) we have

$$\begin{aligned} &(a_3 + 4a_4 k)\varphi_{\xi\xi\xi} + (\lambda + 2\sigma + 3b)\varphi^2\varphi_{\xi} - \\ &\left(v - 2a_2 k + 3a_3 k^2 + 4a_4 k^3\right)\varphi_{\xi} = 0 \end{aligned} \tag{3.3}$$

And

$$\begin{aligned} &a_4\varphi_{\xi\xi\xi\xi} + \left(a_2 - 3a_3 k - 6a_4 k^2\right)\varphi_{\xi\xi} + \left(a_4 k^4 + a_3 k^3 - a_2 k^2 - w\right)\varphi - \\ &(c_1 + k\lambda + bk)\varphi^3 - c_2\varphi^5 = 0 \end{aligned} \tag{3.4}$$

Considering that we have two equations for$\varphi(\xi)$, we must consider the compatibility conditions for one of these equations, for example, for the imaginary state. So we have

$$a_3 = -4a_4 k, \qquad \lambda = -2\sigma - 3b, \qquad v = 2a_2 k - 3a_3 k^2 - 4a_4 k^3 \tag{3.5}$$

3.1 Analytical solutions corresponding to the real part

In the following at first by applying (3.5) into (3.4) we obtain

$$\begin{aligned} &a_4\varphi_{\xi\xi\xi\xi} + \left(a_2 + 6a_4 k^2\right)\varphi_{\xi\xi} + \left(a_4 k^4 + a_3 k^3 - a_2 k^2 - w\right)\varphi - \\ &(c_1 - 2\sigma k - 2bk)\varphi^3 - c_2\varphi^5 = 0 \end{aligned} \tag{3.6}$$

Considering the homogeneous balance between $\varphi^5$and φ'''' in (3.6) we have$M = 1$. So we have

$$\varphi(\xi) = A_0 + A_1\Psi(\xi) + B_1\Psi(\xi)^{-1}, \tag{3.7}$$

Set 1: for $p = [i, i, 1, -1]$and $q = [i, i, 1, -1]$ we have

$$\Psi(\xi) = \frac{\cos(\xi)}{\sin(\xi)} \tag{3.8}$$

Applying (3.8) into (3.7) then into (3.6) we obtain

$$\begin{aligned} &A_0 = 0, B_1 = c_2^{-1}\left(24a_4 c_2^3\right)^{\frac{1}{4}}, v = 2a_2 k - 3a_3 k^2 - 4a_4 k^3, \\ &A_1 = \frac{24^{\frac{1}{4}}}{120}\left(a_4 c_2^3\right)^{-\frac{3}{4}}\left(12a_4 k^2 c_2^2 + \sqrt{24a_4 c_2^3}\,(2bk + 2k\sigma - c_1) + 40a_4 c_2^2 + 2a_2 c_2^2\right), \\ &w = \frac{1}{30a_4 c_2^2}\left(-12\left((b+\sigma)k - \frac{c_1}{2}\right)\left(k^2 + \frac{10}{3}\right)a_4 + \frac{a_2}{6}\right)\sqrt{6a_4 c_2^3} + \\ &\frac{4}{5a_4 c_2}\left(c_2\left(-\frac{7}{4}k^4 - 5k^2 - \frac{40}{3}\right)a_4^2 + \left(\frac{5}{4}a_3 k^3 - \frac{9}{4}k^2 a_2 - \frac{5}{6}a_2\right)c\right) + \\ &\frac{4}{5a_4 c_2}\left((b+\sigma)k - \frac{c_1}{2}\right)^2 a_4 - \frac{4a_2^2}{5a_4} \end{aligned}$$

So final solution of equation (3.6) will be obtained as follows

$$u_1(x,t) = \frac{24^{\frac{1}{4}}}{120}\left(a_4c_2^3\right)^{-\frac{3}{4}}\left(12a_4k^2c_2^2+\sqrt{24a_4c_2^3}\,(2bk+2k\sigma-c_1)+40a_4c_2^2+2a_2c_2^2\right)\times \left[\frac{\cos\left(\frac{x^\alpha}{\alpha}-\left(2a_2k-3a_3k^2-4a_4k^3\right)\frac{t^\alpha}{\alpha}\right)}{\sin\left(\frac{x^\alpha}{\alpha}-(2a_2k-3a_3k^2-4a_4k^3)\frac{t^\alpha}{\alpha}\right)}\right]e^{i\left(k\frac{x^\alpha}{\alpha}-w\frac{t^\alpha}{\alpha}-\theta_0\right)}+ c_2^{-1}\left(24a_4c_2^3\right)^{\frac{1}{4}}\frac{\sin\left(\frac{x^\alpha}{\alpha}-\left(2a_2k-3a_3k^2-4a_4k^3\right)\frac{t^\alpha}{\alpha}\right)}{\cos\left(\frac{x^\alpha}{\alpha}-(2a_2k-3a_3k^2-4a_4k^3)\frac{t^\alpha}{\alpha}\right)}e^{i\left(k\frac{x^\alpha}{\alpha}-w\frac{t^\alpha}{\alpha}-\theta_0\right)},$$

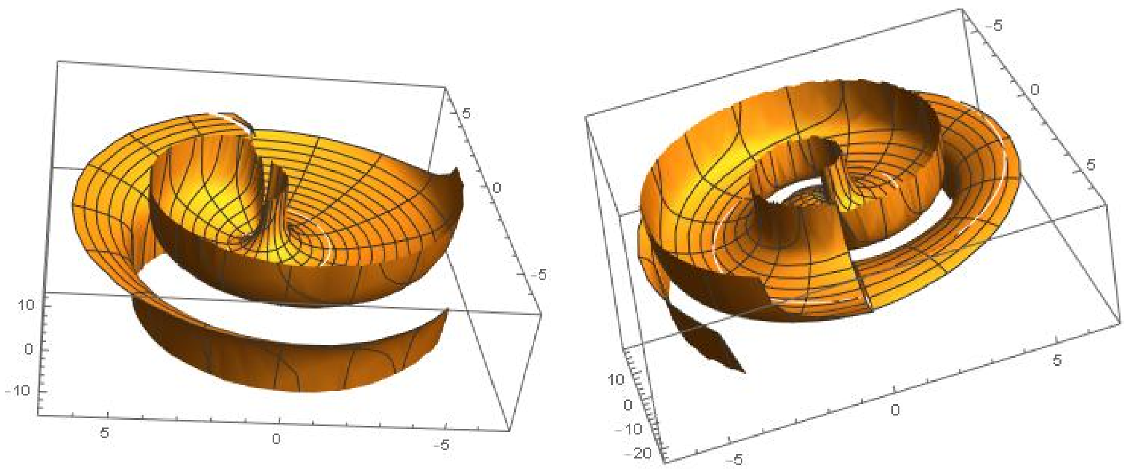


Image1: RevolutionPlot3D for $u_1(x,t)$with$\alpha = 0.3$, $\alpha = 0.9$ respectively and $x = 0..2\pi, t = 0..2\pi$.

Set 2: for $p = [-1,0,0,1]$and $q = [0,0,0,1]$ we have

$$\Psi(\xi) = -\frac{1}{1+e^{\xi}} \tag{3.9}$$

Applying (3.9) into (3.7) then into (3.6) we obtain

$$A_0 = \frac{2\sqrt{-5c_2(2kb+2k\sigma-c_1)}}{5c_2}, A_1 = 0,$$
$$B_1 = \frac{\sqrt{-5c_2(2kb+2k\sigma-c_1)}}{5c_2}, k = k,$$
$$v = 2a_2k-3a_3k^2-4a_4k^3$$

So final solution of equation (3.6) will be obtained as follows

$$u_2(x,t) = \left(\frac{2\sqrt{-5c_2(2kb+2k\sigma-c_1)}}{5c_2}\right)e^{i\left(k\frac{x^\alpha}{\alpha}-w\frac{t^\alpha}{\alpha}-\theta_0\right)}- \frac{\sqrt{-5c_2(2kb+2k\sigma-c_1)}}{5c_2}\left(1+e^{\frac{x^\alpha}{\alpha}-\left(2a_2k-3a_3k^2-4a_4k^3\right)\frac{t^\alpha}{\alpha}}\right)e^{i\left(k\frac{x^\alpha}{\alpha}-w\frac{t^\alpha}{\alpha}-\theta_0\right)},$$

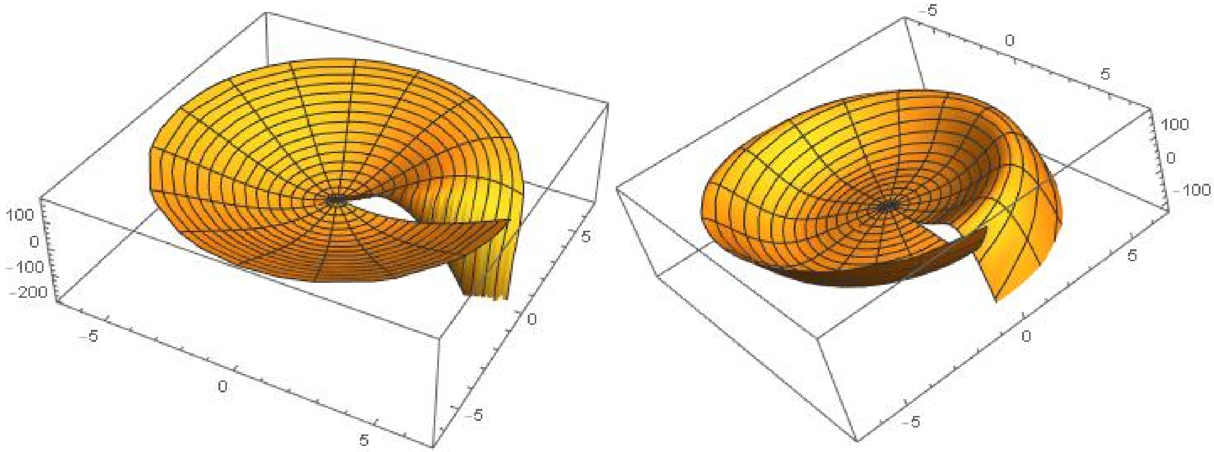


Image2: RevolutionPlot3D for $u_2\left(x,t\right)$with$\alpha=0.3$, $\alpha=0.9$ respectively and $x=0..2\pi, t=0..2\pi$.

Set 3: for $p=[2,3,1,1]$and $q=[0,1,0,1]$ we have

$$\Psi(\xi)=\frac{3e^{\xi}+2}{e^{\xi}+1} \tag{3.10}$$

Applying (3.10) into (3.7) then into (3.6) we obtain

$$A_0=\tfrac{-3\sqrt{2c_2}}{2c_2}\sqrt{2kb+2k\sigma+\sqrt{\left(4a_4k^4+4a_3k^3-4a_2k^2-4w\right)c_2+4\left(\left(b+\sigma\right)k-\tfrac{c_1}{2}\right)}-c_1},$$
$$A_1=\tfrac{\sqrt{2c_2}}{2c_2}\sqrt{2kb+2k\sigma+\sqrt{\left(4a_4k^4+4a_3k^3-4a_2k^2-4w\right)c_2+4\left(\left(b+\sigma\right)k-\tfrac{c_1}{2}\right)}-c_1},$$
$$B_1=0, v=2a_2k-3a_3k^2-4a_4k^3, w=a_4k^4+a_3k^3-a_2k^2$$

So final solution of equation (3.6) will be obtained as follows

$$u_3\left(x,t\right)=\tfrac{-3\sqrt{2c_2}}{2c_2}*$$
$$\sqrt{2kb+2k\sigma+\sqrt{\left(4a_4k^4+4a_3k^3-4a_2k^2-4w\right)c_2+4\left(\left(b+\sigma\right)k-\tfrac{c_1}{2}\right)}-c_1}\,e^{i\left(k\frac{x^\alpha}{\alpha}-w\frac{t^\alpha}{\alpha}-\theta_0\right)}+$$
$$\tfrac{\sqrt{2c_2}}{2c_2}\sqrt{2kb+2k\sigma+\sqrt{\left(4a_4k^4+4a_3k^3-4a_2k^2-4w\right)c_2+4\left(\left(b+\sigma\right)k-\tfrac{c_1}{2}\right)}-c_1}\left(\frac{3e^{\frac{x^\alpha}{\alpha}-v\frac{t^\alpha}{\alpha}}+2}{e^{\frac{x^\alpha}{\alpha}-v\frac{t^\alpha}{\alpha}}+1}\right)*$$
$$e^{i\left(k\frac{x^\alpha}{\alpha}-w\frac{t^\alpha}{\alpha}-\theta_0\right)},$$

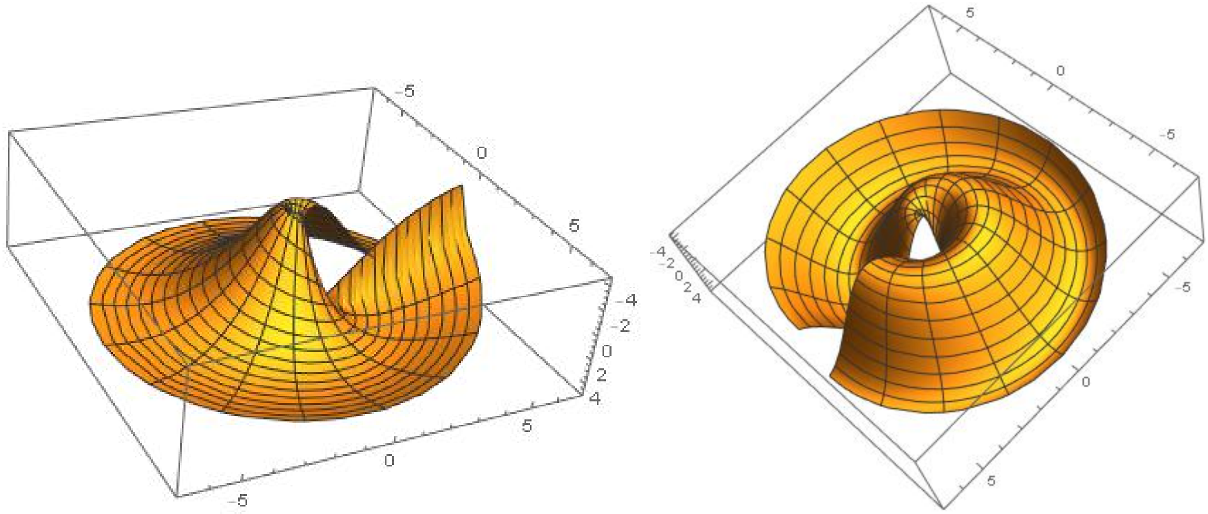


Image3: RevolutionPlot3D for $u_3\left(x,t\right)$with$\alpha=0.3$, $\alpha=0.9$ respectively and$x=0..2\pi, t=0..2\pi$**.**

Set 4: for $p=[0,1,1,1]$and $q=[0,1,0,1]$ we have

$$\Psi(\xi)=\frac{e^{\xi}}{e^{\xi}+1}, \tag{3.11}$$

Applying (3.11) into (3.7) then into (3.6) we obtain

$$A_1=\frac{\sqrt{10}\left(-bk-k\sigma+\frac{1}{2}c_1\right)}{5\sqrt{c_2(2bk+2k\sigma-c_1)}}, A_0=0,$$
$$B_1=\frac{\sqrt{10}\sqrt{c_2(2bk+2k\sigma-c_1)}}{10c_2}, v=2a_2k-3a_3k^2-4a_4k^3,$$
$$w=\frac{1}{150c_2}\left(150a_4k^4c_2+150a_3k^3c_2+348b^2k^2+696bk^2\sigma+348k^2\sigma^2-150k^2c_2a_2\right)+$$
$$5k^2a_2-\frac{1}{150c_2}\left(348bkc_1-348k\sigma c_1+125a_2c_2+125a_4c_2+87c_1^2\right)$$

So final solution of equation (3.6) will be obtained as follows

$$u_4\left(x,t\right)=\frac{\sqrt{10}\left(-bk-k\sigma+\frac{1}{2}c_1\right)}{5\sqrt{c_2(2bk+2k\sigma-c_1)}}\left(\frac{e^{\frac{x^{\alpha}}{\alpha}-\left(2a_2k-3a_3k^2-4a_4k^3\right)\frac{t^{\alpha}}{\alpha}}}{e^{\frac{x^{\alpha}}{\alpha}-\left(2a_2k-3a_3k^2-4a_4k^3\right)\frac{t^{\alpha}}{\alpha}}+1}\right)e^{i\left(k\frac{x^{\alpha}}{\alpha}-w\frac{t^{\alpha}}{\alpha}-\theta_0\right)}+$$
$$\frac{\sqrt{10}\sqrt{c_2(2bk+2k\sigma-c_1)}}{10c_2}\left(\frac{1+e^{\frac{x^{\alpha}}{\alpha}-\left(2a_2k-3a_3k^2-4a_4k^3\right)\frac{t^{\alpha}}{\alpha}}}{e^{\frac{x^{\alpha}}{\alpha}-\left(2a_2k-3a_3k^2-4a_4k^3\right)\frac{t^{\alpha}}{\alpha}}}\right)e^{i\left(k\frac{x^{\alpha}}{\alpha}-w\frac{t^{\alpha}}{\alpha}-\theta_0\right)},$$

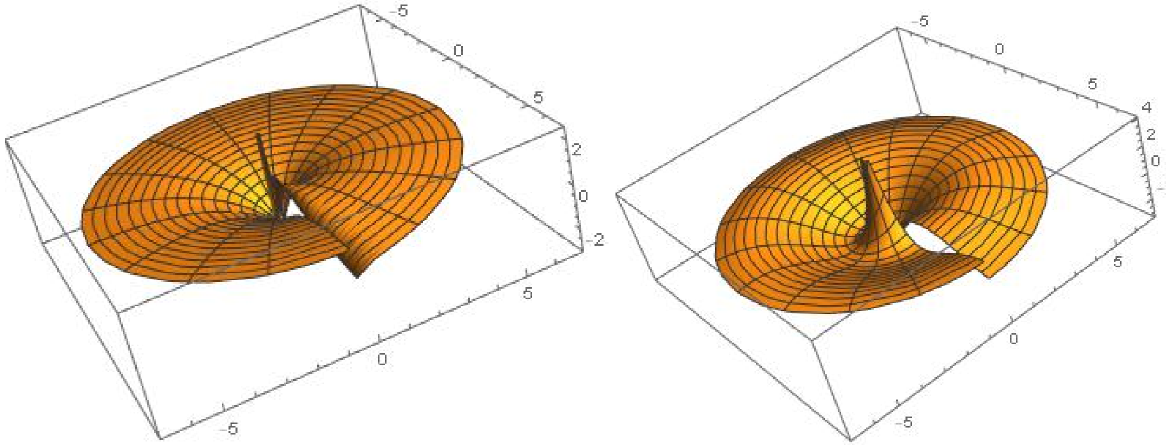


Image4: RevolutionPlot3D for $u_4\left(x,t\right)$with$\alpha=0.3$, $\alpha=0.9$ respectively and$x=0..2\pi, t=0..2\pi$**.**

Set 5: for $p=[1+i,1-i,1,1]$and $q=[-i,i,-i,i]$ we have

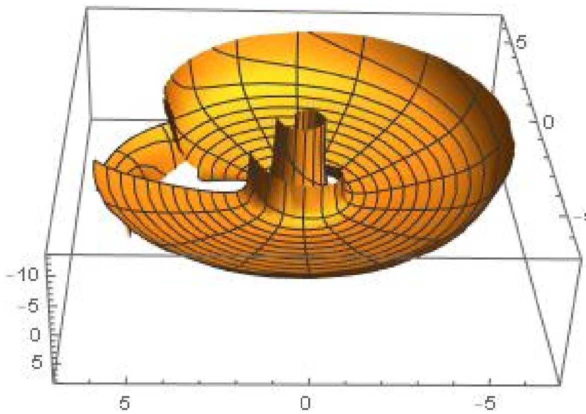
$$\Psi(\xi)=\frac{\sin\left(\xi\right)+\cos\left(\xi\right)}{\cos\left(\xi\right)} \tag{3.12}$$

Applying (3.12) into (3.7) then into (3.6) we obtain

$$A_1=\tfrac{12^{\frac{1}{4}}}{c_2}\left(a_4c_2^3\right)^{\frac{1}{4}}, A_0=0, v=2a_2k-3a_3k^2-4a_4k^3,$$
$$B_1=\tfrac{\sqrt{2}\left(3a_4c_2^3\right)^{\frac{1}{4}}}{15a_4c_2^3}\left(\sqrt{3}\left((b+\sigma)k-\tfrac{c_1}{2}\right)\sqrt{a_4c_2^3}+3\left(a_4k^2+\tfrac{1}{6}a_2-\tfrac{80}{3}a_4\right)c_2^2\right),$$
$$k=\tfrac{\sqrt{-6a_4((a_2-260a_4))}}{6a_4},$$

So final solution of equation (3.6) will be obtained as follows

$$u_5\left(x,t\right)=\tfrac{12^{\frac{1}{4}}}{c_2}\left(a_4c_2^3\right)^{\frac{1}{4}}\left(\frac{\sin\left(\frac{x^\alpha}{\alpha}-v\frac{t^\alpha}{\alpha}\right)+\cos\left(\frac{x^\alpha}{\alpha}-v\frac{t^\alpha}{\alpha}\right)}{\cos\left(\frac{x^\alpha}{\alpha}-v\frac{t^\alpha}{\alpha}\right)}\right)e^{i\left(\frac{\sqrt{-6a_4((a_2-260a_4))}}{6a_4}\frac{x^\alpha}{\alpha}-w\frac{t^\alpha}{\alpha}-\theta_0\right)}+$$
$$\tfrac{\sqrt{2}\left(3a_4c_2^3\right)^{\frac{1}{4}}}{15a_4c_2^3}\left(\sqrt{3}\left((b+\sigma)k-\tfrac{c_1}{2}\right)\sqrt{a_4c_2^3}+3\left(a_4k^2+\tfrac{1}{6}a_2-\tfrac{80}{3}a_4\right)c_2^2\right)\times$$
$$\left(\frac{\cos\left(\frac{x^\alpha}{\alpha}-v\frac{t^\alpha}{\alpha}\right)}{\sin\left(\frac{x^\alpha}{\alpha}-v\frac{t^\alpha}{\alpha}\right)+\cos\left(\frac{x^\alpha}{\alpha}-v\frac{t^\alpha}{\alpha}\right)}\right)e^{i\left(\frac{\sqrt{-6a_4((a_2-260a_4))}}{6a_4}\frac{x^\alpha}{\alpha}-w\frac{t^\alpha}{\alpha}-\theta_0\right)},$$



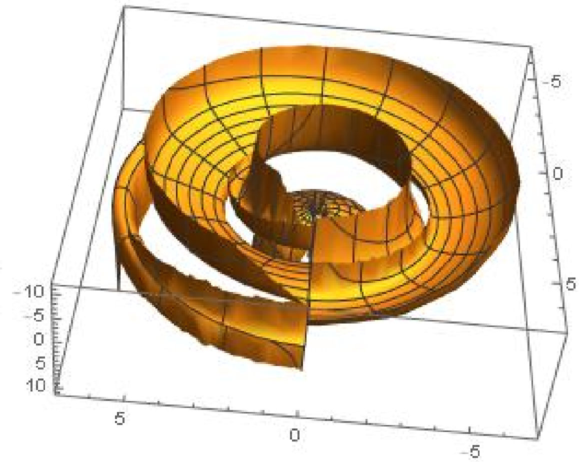


Image5: RevolutionPlot3D for $u_5\,(x,t)$with$\alpha = 0.3$, $\alpha = 0.9$ respectively and$x = 0..2\pi, t = 0..2\pi$**.**

4. Conclusion

The generalized exponential rational function method is a powerful approach with various solutions for solving non-linear differential equations. The solutions obtained in this study for the generalized nonlinear fractional Schrödinger–Hirota equation using this method are new and have not been observed in any other study. These types of solutions are named soliton and periodic solutions and play considerable roles in many directions of nonlinear physical sciences. Moreover, a graphical visualization including three-dimensional, contour, and two-dimensional profiles was displayed for some of the gained solutions with the chosen functions and parameters. The answers obtained in this study are more accurate compared to other methods proposed so far, and their most obvious feature is that they are much easier to obtain than other methods.

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