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PAPER

Ginzburg Landau equation's Innovative Solution (GLEIS)

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Keywords: The sine-Gordon expansion method, 2D Ginzburg-Landau equation, traveling wave solutions

Abstract

A novel soliton solution of the famous 2D Ginzburg-Landau equation is obtained. A powerful Sine-Gordon expansion method is used for acquiring soliton solutions 2D Ginzburg-Landau equation. These solutions are obtained with the help of contemporary software (Maple) that allows computation of equations within the symbolic format. Some new solutions are depicted in the forms of figures. The Sine-Gordon method is applicable for solving various non-linear complex models such as, Quantum mechanics, plasma physics and biological science.

1. Introduction

Solution of the exact solutions of travelling wave with nonlinear evolution equations plays an important role. The utilization of these solutions are found in various nonlinear physical phenomenons. There are many complex models that are used in many fields of nonlinear sciences. Few of these models are described as biological sciences, quantum mechanics, plasma physics. Obviously, these non linear models requires nonlinear evolutionary equations to express some physical phenomena. Finding out solutions of these equations have direct implementations in the above said fields. For the past two decades, many direct method have been developed to have special solutions with reasonable efficiency. Few of these direct methods are unified Method [1, 2], tanh-sech method [3], Bäcklund transformation method [4–6], Jacobi elliptic function expansion method [7, 8], Hirotas direct method [9], modified auxiliary equation technique [10, 11], F-expansion method [12], improved Bernoulli sub-equation function method [13], new extended direct algebraic method [14, 15], many other methods are also reported in [1, 16–28].

In this paper, Ginzburg-Landau equation is presented [29] that appears as a class of nonlinear constant coefficients partial differential equation. As with the passage of time new and innovative solutions are appearing and the research activities in this area is still under voyage, it is proposed to have title matching with the on going train. So, Ginzburg Landau equation's Innovative Solution (GLEIS) is expresses the right title to present this research.

$$iu_t + \frac{1}{2}u_{xx} + \frac{1}{2}(e - if)u_{yy} + (1 - i\delta)|u|^2u = i\gamma u, \tag{1}$$

Where β, f, δ, γ are constants with real values.

A weakly nonlinear and dissipative systems having canonical model can be expressed with the complex Ginzburg-Landau equation. A variety of settings including chemical physics, condensed matter physics, fluid

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dynamics, mathematical biology, nonlinear optics, and statistical mechanics is available to discuss different behaviours for this equation. This equation can be used as a generic amplitude equation and researchers were using it since long. This equation can also generate the instabilities that can lead to chaotic dynamics. Various areas of physics fir phase transitions and superconductivity can take benefit from this equation in the theory. Broad range of physical systems that describes evolution phenomena such as physical systems or even extending from physics to optics was considered as remarkable success in past. More recently, a detailed research is carried out for turbulent dynamics as systems model with nonlinear partial differential equations [30]. Ginzburg-Landau equation also found its applications in fluid dynamics by many researchers, however, Poiseuille flow [31] played vital role in such studies. Similarly, the Rayleigh-Bénard problem and Taylor-Couette flow [32–35] are also explored for the nonlinear growth of convection rolls.

Complex Ginzburg-Landau equation were under extensive mathematical research for quite a long time [29, 30]. Many hard turbulence examples are provided in [29, 30]. Similarly, cubic-quintic complex Ginzburg-Landau equation [36] is originated by the researcher. Other studies extended the research for low-dimensional behavior [37], attractor bifurcation [38, 39], and even revolutionized research for traveling waves[40, 41].

In current research Powerful sine-Gordon expansion method (SGEM) [42–44] is explored for finding out new solutions to the complex Ginzburg-Landau equations. Many exact solutions were explored for this equation such as [14, 45–57]. Still there are lot of other solutions exist and can be found with literature review.

2. The Sine-Gordon expansion method

In this section the Sine-Gordon Expansion Method (SGEM) is explained to find out general facts.

Sine-Gordon equation can be considered as follows.

$$u_{xx} - u_{tt} = m^2 \sin(u), \tag{2}$$

Where $n \in \mathbb{R}\backslash\{0\}$ and $u = u(x, t)$.

Wave transformation can be utilized to form $u = u(x, t) = \phi(\zeta), \zeta = \alpha(x - kt)$ on equation (2), produces the following nonlinear ordinary differential equation (NODE):

$$\phi'' = \frac{n^2}{\alpha^2(1 - k^2)} \sin(\phi), \tag{3}$$

Where k is travelling wave speed representation and $\phi = \phi(\zeta)$, ζ is travelling wave amplitude. Integrating equation (3), can also be formulated as follows:

$$\left[\left(\frac{\phi}{2}\right)'\right]^2 = \frac{n^2}{\alpha^2(1 - k^2)} \sin^2\left(\frac{\phi}{2}\right) + Q, \tag{4}$$

Where the integration constant is represented by Q.

Substituting the value of $Q = 0$, $b^2 = \frac{n^2}{\alpha^2(1-k^2)}$ and $\omega(\zeta) = \frac{\phi}{2}$ in equation (4), gives:

$$\omega' = b \sin(\omega), \tag{5}$$

Inserting $b = 1$ into equation (5), produces:

$$\omega' = \sin(\omega), \tag{6}$$

Simplifying equation (6), and reformulating these equations can provide following set of equations

$$\sin(\omega) = \sin(\omega(\zeta)) = \left.\frac{2de^{\zeta}}{d^2e^{2\zeta} + 1}\right|_{d=1} = \operatorname{sech}(\zeta), \tag{7}$$

$$\cos(\omega) = \cos(\omega(\zeta)) = \left.\frac{d^2e^{2\zeta} - 1}{d^2e^{2\zeta} + 1}\right|_{d=1} = \tanh(\zeta), \tag{8}$$

Where d is the constant of integration.

There is dependency of many parameters for partial differential equation (9) and it also has non linearity;

$$P(u, \ uu_x, \ u^2u_t, \ \ldots), \tag{9}$$

Solving the above equation will produce the following equation:

$$\phi(\zeta) = \sum_{i=1}^{m} \tanh^{i-1}(\zeta)[B_i \operatorname{sech}(\zeta) + A_i \tanh(\zeta)] + A_0. \tag{10}$$

equation (10) may be given according to equation (7) and (8) as;

$$\phi(\omega) = \sum_{i=1}^{m} \cos^{i-1}(\omega)[B_i \sin(\omega) + A_i \cos(\omega)] + A_0. \tag{11}$$

Determining m is achieved by balancing the highest power of term having non linearity and adjusting the highest derivative in the transformed NODE. A new set of equations can be produced by considering each summation of the coefficients as zero for the equation $\sin^i(w)\cos^j(w), 0 \leqslant i, j \leqslant m$. So, we have a new set of equations and all these equations are symbolic in nature. We can solve these equations in symbolic manners by the use of modern available computational software. In this research one of these software is used i.e. Wolfram Mathematica 9. By the use of described software we can have values values of all unknown coefficients that appears in these non linear partial differential equations. These includes the unknown coefficients such as A_i, B_i, μ and c. substituting the values of m along with the other obtained values of coefficients in equation (10) leads to have a new travelling wave solutions which is presented in equation equation (9).

3. Applications of Sine-Gordon expansion method

In this section, it is described, how SGEM can be used in finding out new possible solution of equation (1).

We can always assume that equation (1) describes exact solution of SGEM. So holding this assumption and continuing with the other equations as function of exponential as described in equation (12)

$$u = \exp i(\eta)v(\xi), \quad \eta = (px + st), \tag{12}$$

Where p, s are some unknown constants and should be determined, $v(x, y, t)$ is a function having real values in it. Following new equation can be constructed by Substituting equation (12) into equation (1)

$$\begin{cases} iv_t + \frac{1}{2}(v_{xx} + ev_{yy}) - \frac{1}{2}ifv_{yy} + i(pv_x + ev_y), \\ -i\gamma v - \left[s + \frac{1}{2}(p^2\right]v + v^3 - i\delta v^3 = 0. \end{cases} \tag{13}$$

Real and imaginary parts of the equation (13) can be separated and it is found that

$$\begin{cases} \dfrac{1}{2}(v_{xx} + ev_{yy}) + v^3 - \left[s + \frac{1}{2}p^2\right]v = 0, \\ v_t - \frac{1}{2}fv_{yy} + (pv_x + ev_y) - \delta v^3 - \gamma v = 0. \end{cases} \tag{14}$$

Consider the following equation

$$v(x, y, t) = \phi(\xi), \quad \xi = kx + ly + \nu t, \tag{15}$$

Where three constants are unknown i.e. k, l, ν. Ordinary differential equations can be obtained by substituting (15) into equations (14), $\phi(\xi)$

$$\begin{cases} \frac{1}{2}(k^2 + el^2)\phi'' + \phi^3 - \left[s + \frac{1}{2}p^2\right]\phi = 0, \\ -\frac{1}{2}fl^2\phi'' + (pk + \nu)\phi' - \delta\phi^3 + (-\gamma)\phi = 0. \end{cases} \tag{16}$$

Under the constrain conditions: $\nu = -pk$, $b = -\frac{2}{k^2 + el^2} = -\frac{2\delta}{fl^2}$, $c = 2\frac{s + \frac{1}{2}p^2}{k^2 + el^2} = \frac{-2\gamma}{fl^2}$, then equation (16) takes the form

$$2(k^2 + el^2)\phi''(\xi) - f^2l^4\phi(\xi) + 4\left(s + \frac{1}{2}p^2\right)\phi^3(\xi) = 0, \tag{17}$$

Now, ϕ'' and ϕ^3 in equation (17) can be balanced with the help of coefficient m, take the value $m = 1$ for balancing purpose in equation (17).

Following equation can be obtained by using equation (11) and considering $m = 1$;

$$\phi(\omega) = B_1 \sin(\omega) + A_1 \cos(\omega) + A_0, \tag{18}$$

Differentiating equation (18) twice, following result can be achieved:

$$\phi''(\omega) = B_1 \cos^2(\omega)\sin(\omega) - B_1 \sin^3(\omega) - 2A_1 \sin^2(\omega)\cos(\omega). \tag{19}$$

Putting equations (18) and (19) into equation (17), yields an equation in trigonometric functions. In the above equations, setting the value of zero to each summation for the functions having various coefficients but same powers, provides a collection of new algebraic equations. These equations are solvable and the Solution to these set of equations can be obtained by using any symbolic mathematical solver software like Mathematica or Maple. Values of these coefficients plays important role and different cases can be obtained using different values of these coefficients. Taking different values of the coefficients along with the value $m = 1$, in equation (10)

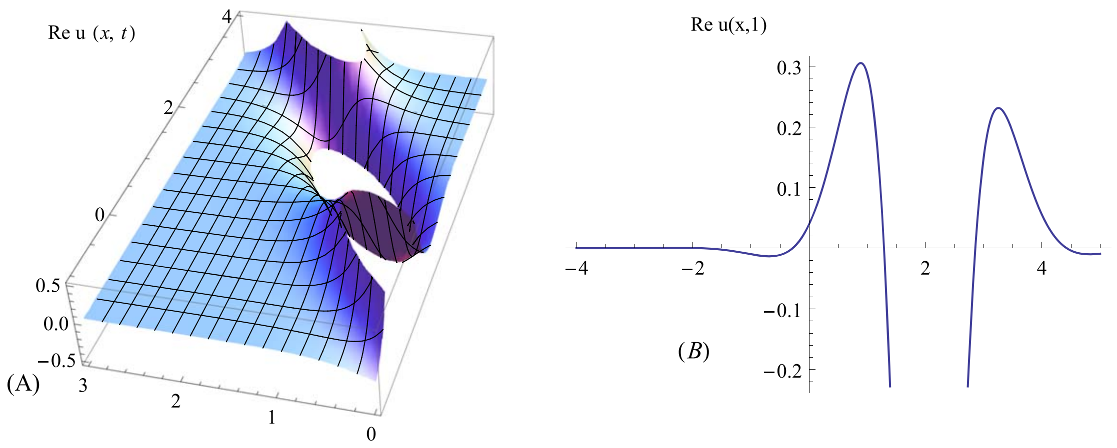

Figure 1. (A) The three dimensional (3D) surfaces of equation (21), (B) Two dimensional (2D) surfaces of equation (21) by considering the values $p = 2, s = -1, k = 2, y = 0, e = 0$.

generates a separate case and hence provides a new solution to equation (1). Each case is highlighted in the subsequent sections.

Case-1: There could be many possible set of values for the constants used in equation (1). Each set of values for these constants will generate a different kind of result in form of the solution presented in this paper. One of the possible set of values for these constants is given below.

$$A_0 = 0,\ \ A_1 = 0,\ \ B_1 = \sqrt{\frac{(k^2 + el^2)}{\left(s + \frac{1}{2}p^2\right)}},\ \ f^2l^4 = 2(k^2 + el^2). \tag{20}$$

where $\frac{(k^2 + el^2)}{\left(s + \frac{1}{2}p^2\right)} \geqslant 0$ for all cases.

These coefficients can take different values and hence provides solution for equation (1) in the following format:

$$u_1(x,\ y,\ t) = e^{i((px+st)}\left[\sqrt{\frac{(k^2 + el^2)}{\left(s + \frac{1}{2}p^2\right)}}\ \mathrm{sech}(kx + ly - pkt)\right]. \tag{21}$$

There are other constants in the equation (21) and considering the values $p = 2; s = -1; k = 2; y = 0; e = 0$ for this equation, figure 1 can be obtained. While, figure 1(A) shows The three dimensional (3D) surfaces of equation (21), and figure 1(B) shows Two dimensional (2D) surfaces of equation (21). It can be observed that this solution is used for singular soliton surfaces as shown in figure 1 and valid for $3D$ and $2D$ surfaces of u_1.

Case-2: Interchanging the values of A_1 with B_1 and slight change in the values of f^2l^4 another possible set of constants is generated as follows:

$$A_0 = 0,\ \ A_1 = \sqrt{\frac{(k^2 + el^2)}{\left(s + \frac{1}{2}p^2\right)}},\ \ B_1 = 0,\ \ f^2l^4 = -4(k^2 + el^2). \tag{22}$$

Similarly, with the assumption of above coefficients provide solution to equation (1) in the following format:

$$u_2(x,\ y,\ t) = e^{i((px+st)}\left[\sqrt{\frac{(k^2 + el^2)}{\left(s + \frac{1}{2}p^2\right)}}\ \tanh(kx + ly - pkt)\right]. \tag{23}$$

Case-3: Similarly, figure 2 can be obtained using values of $p = 1, s = 0.5, k = 2, y = 0, e = 0$ for the constants given the equation (23). It can also be observed that this solution is extended version of previous solution. This solution can be used for the periodic $3D$ and $2D$ of u_1 surface.

$$A_0 = 0,\ \ A_1 = -\sqrt{\frac{(k^2 + el^2)}{4\left(s + \frac{1}{2}p^2\right)}}\,i,\ \ B_1 = -\sqrt{\frac{(k^2 + el^2)}{4\left(s + \frac{1}{2}p^2\right)}},\ \ f^2l^4 = -(k^2 + el^2). \tag{24}$$

As describes in case-1 and case-2, with the assumption of the above coefficients provide solution to equation (1) in the following format:

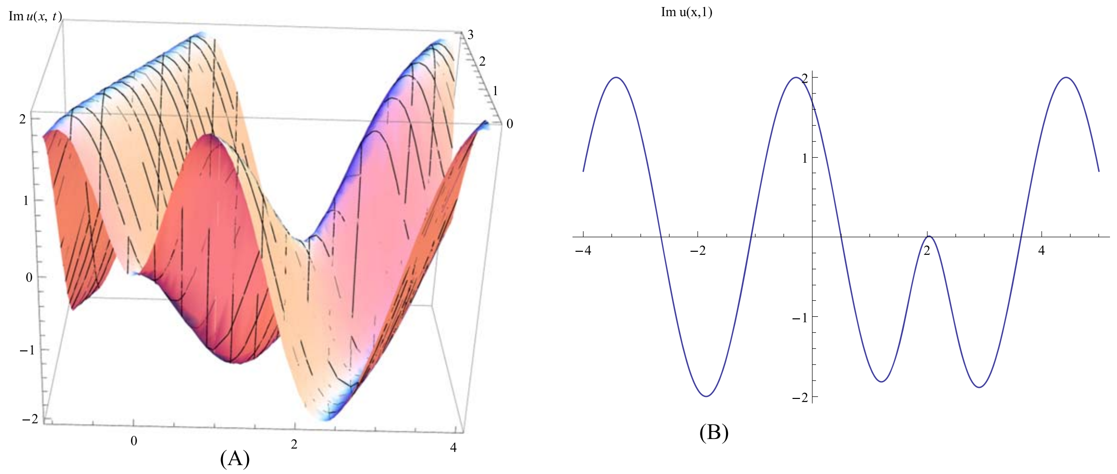

Figure 2. (A) The three dimensional surfaces of equation (23), (B) two dimensional surfaces of equation (23) by considering the values $p = 2, s = -1, k = 2, y = 0, e = 0$.

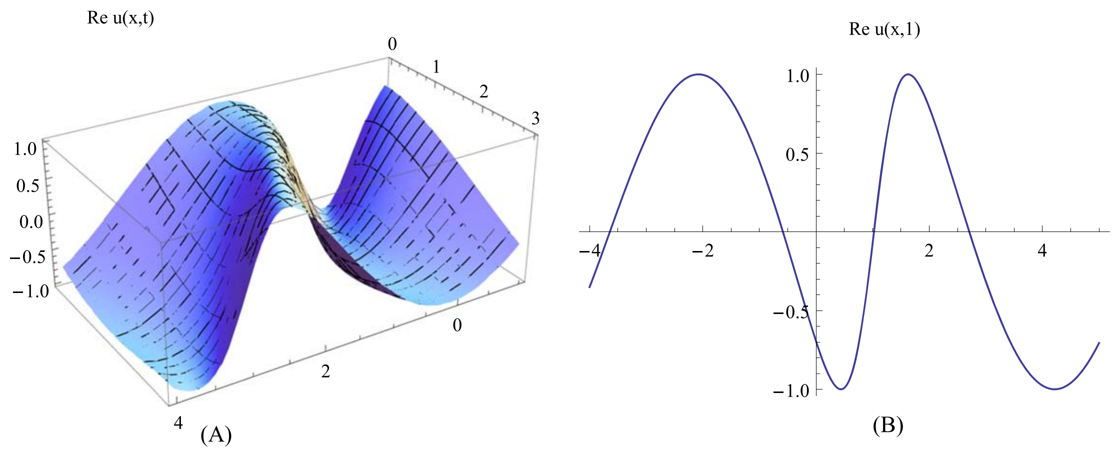

Figure 3. (A) The 3D surfaces of equation (25), (B) 2D surfaces of equation (25) by considering the values $p = 1, s = 0.5, k = 2, y = 0, e = 0$.

$$u_3(x, y, t) = e^{i((px+st)}\left[-\sqrt{\frac{(k^2 + el^2)}{4\left(s + \frac{1}{2}p^2\right)}}\operatorname{sech}(kx + ly - pkt) - \sqrt{\frac{(k^2 + el^2)}{4\left(s + \frac{1}{2}p^2\right)}}\, i\tanh(kx + ly - pkt)\right]. \tag{25}$$

Case-4: Considering the values for the constants as $p = 1; s = 0: 5; k = 2; y = 0; e = 0$ figure 3 can be obtained. The $3D$ surface of equation (25) is shown in figure 3(A), where as 2D surface of equation (25) is shown in figure 3(B). It is also described that figure 3 can only be generated with the assumption of following values of constants.

$$A_0 = 0,\ \ A_1 = 0,\ \ B_1 = \sqrt{\frac{f^2 l^4}{2\left(s + \frac{1}{2}p^2\right)}},\ \ f^2 l^4 = 2(k^2 + el^2). \tag{26}$$

The above coefficients provides a unique solution of (1) and given as below:

$$u_4(x, y, t) = e^{i((px+st)}\left[\sqrt{\frac{f^2 l^4}{2\left(s + \frac{1}{2}p^2\right)}}\operatorname{sech}(kx + ly - pkt)\right]. \tag{27}$$

Case-5: Similarly, another solution is possible in the form of u_5.

$$A_0 = 0,\ \ A_1 = \sqrt{\frac{f^2 l^4}{4\left(s + \frac{1}{2}p^2\right)}},\ \ B_1 = -\sqrt{\frac{f^2 l^4}{4\left(s + \frac{1}{2}p^2\right)}}\, i,\ \ -f^2 l^4 = (k^2 + el^2). \tag{28}$$

Where $\frac{f^2 l^4}{4(s + \frac{1}{2}p^2)} \geqslant 0$ for all case. The above coefficients provides a unique solution of (1) and given as below:

$$u_5(x, y, t) = e^{i((px+st)}\left[-\sqrt{\frac{f^2 l^4}{4\left(s + \frac{1}{2}p^2\right)}}\, i\, \mathrm{sech}(kx + ly - pkt) + \sqrt{\frac{f^2 l^4}{4\left(s + \frac{1}{2}p^2\right)}}\, \tanh(kx + ly - pkt)\right]. \tag{29}$$

All of the above solutions are possible with the help of considering different values of the constants used in the different equations. More solutions are still possible by considering another possible set of constant used in same equations. This ongoing research for finding out different solutions is still under way and getting a faster pace due to the available software available to solve the equations in the symbolic format and hence the title of this paper is suggested as Ginzburg Landau equation's Innovative Solution (GLEIS). The solutions obtained from these equations are directly applicable to different field of sciences like microscopic properties of superconductivity, phase transition in superconductivity, quantum field theory and event to string theory.

As a summary, it reiterated that similar solutions were obtained in the literature review and reported in this paper. The solutions obtained in this paper can be applied to the natural travel of waves. These solutions are not only applied to the waves but in general the similar nature real physical phenomena such as heat flow in single or multi-dimensional space. In general, there are three types of solutions for such problems. One soliton is the solution, which is high in the middle and decreasing asymptotically, on both sides. Other solution is known as kinks and this solution is ascending from one asymptotic state to the other asymptotic state. The third form of solution is descending from one asymptotic state to the other asymptotic state. However, the solutions extracted in this paper show entirely new manifestation. This type of solution is known as singular solution which was not obtained in the literature so far. This solutions is also shown pictorially in from of figure 1. Similar solutions are provided in various references such as [48]. The solution provided in [48] are in the form of exponential or exponential with *tan* functions, In our method the solutions are obtained in the form of exponential function or exponential function with *tanh* or *sech*. The proposed solutions manifest another form of traveling wave which was never found in literature.

4. Discussion

In [48] the first integral method was developed and been utilized in solving the 2D Ginzburg-Landau equation and various solutions in hyperbolic functions form were obtained. Secondly, the well-known $\left(\frac{G'}{G}\right)$ - Some exact hyperbolic and trigonometric function were obtained by using the method of expansion as given in [58]. It is also observed that same solution structures also exists in literature when these two methods are used. However, the results are new even when the structures are same. These solutions and implementation on waves are novel and different from the existing solutions. On the other hand, $3D$ and $2D$ surfaces of u_1 is singular soliton surfaces by observing figures 1. The solution can be extended in figures 2 for periodic $3D$ and $2D$ of u_1 surface.

5. Conclusion

It is evident from the simulation results that the existing solutions were not the only possible solutions. New solutions are possible that can find the applications in wave propagation of physical phenomenons. The singular solution obtained in figure 1 is novel.

The results extracted in this paper show that SGEM is effective tool which can provide various different solutions. These solutions have importance especially for nonlinear evolution equations. More interesting solutions are expected in future.

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