

Article

Analyzing Dynamics: Lie Symmetry Approach to Bifurcation, Chaos, Multistability, and Solitons in Extended $(3 + 1)$ -Dimensional Wave Equation

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Abstract: The examination of new $(3 + 1)$ -dimensional wave equations is undertaken in this study. Initially, the identification of the Lie symmetries of the model is carried out through the utilization of the Lie symmetry approach. The commutator and adjoint table of the symmetries are presented. Subsequently, the model under discussion is transformed into an ordinary differential equation using these symmetries. The construction of several bright, kink, and dark solitons for the suggested equation is then achieved through the utilization of the new auxiliary equation method. Subsequently, an analysis of the dynamical nature of the model is conducted, encompassing various angles such as bifurcation, chaos, and sensitivity. Bifurcation occurs at critical points within a dynamical system, accompanied by the application of an outward force, which unveils the emergence of chaotic phenomena. Two-dimensional plots, time plots, multistability, and Lyapunov exponents are presented to illustrate these chaotic behaviors. Furthermore, the sensitivity of the investigated model is executed utilizing the Runge–Kutta method. This analysis confirms that the stability of the solution is minimally affected by small changes in initial conditions. The attained outcomes show the effectiveness of the presented methods in evaluating solitons of multiple nonlinear models.

Keywords: extended $(3 + 1)$ -dimensional wave equation; Lie symmetry method; soliton solutions; bifurcation; chaos; multistability; sensitivity



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1. Introduction

In the present age of technological advancements, significant progress has been analyzed on the subject of solitons. They play a key role in transferring data over extended distances through fiber optics. Solitons also matter significantly as they are pivotal for the advancement of computer systems' computing power, while they present a wide variety of applications. Such applications cover image processing, data analysis, neurology, and fluids, among other fields [1–3]. As a result, experts have actively explored the evolution of soliton solutions for nonlinear partial differential equations (NLPDEs). Various effective methods have been employed to obtain soliton solutions for NLPDEs, including the Darboux transform [4], Hirota's approach [5], the Painlevé test [6], the sub-equation method [7], the unified approach [8], the bilinear approach [9], and multiple techniques discussed in [10].

Among these approaches, Lie analysis stands out as one of the systematic approaches for deriving closed-form solutions to NLPDEs. In recent decades, the application of Lie symmetries has been widespread, extending to numerous instances in both mathematics and engineering [11]. Upon conducting Lie analysis on nonlinear models, symmetry reductions and group-invariant solutions become accessible. These resultant symmetries frequently

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