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Neutrosophic Bitopological Modeling for Vibration Control Performance in Vehicle Suspension Systems under Uncertainty

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ABSTRACT

Vibration control is one of the most critical aspects in designing safe and comfortable vehicle suspension systems. Traditional methods such as PID, fuzzy logic, or adaptive control face limitations when dealing with uncertain or incomplete data about road conditions or vehicle dynamics. In this paper, we propose a novel mathematical framework based on generalized open sets in neutrosophic soft bitopological spaces to model and control suspension vibrations under uncertainty. By using two separate neutrosophic topologies, the system's response is evaluated from dual perspectives, capturing both predictable and unpredictable behaviors. Additionally, we incorporate Quadripartitioned Single-Valued Neutrosophic (QSVN) representations to quantify truth, contradiction, ignorance, and falsity of vibration states. This dual-layered structure allows for more precise, flexible, and intelligent decision-making for suspension control. A complete case study using a quarter-car model demonstrates how the proposed framework improves system robustness, especially in environments with noisy or conflicting sensor data.

KEYWORDS

Vibration control; Vehicle suspension system; Neutrosophic soft set; Bitopology; Generalized open sets; QSVN; Uncertainty modeling; Semi-active suspension

1. Introduction

The suspension system of a vehicle plays a critical role in ensuring passenger comfort, vehicle stability, and safety by mitigating the impact of road irregularities. When a vehicle encounters uneven surfaces, such as potholes or bumps, the suspension system absorbs shocks and minimizes vibrations to maintain a smooth ride [1]. Over the years, various control strategies, including classical proportional-integral-derivative (PID) control, fuzzy logic systems, and adaptive control techniques, have been developed to optimize suspension performance [2]. These methods have proven effective under controlled conditions where precise and complete data about road surfaces, vehicle dynamics, and system parameters are available. However, real-world driving scenarios often introduce uncertainties, such as incomplete sensor data, conflicting measurements, or unpredictable changes in vehicle load, which challenge the effectiveness of traditional control approaches [3].

In practical settings, the information available to suspension control systems is frequently uncertain, incomplete, or contradictory. For instance, sensors may produce noisy or conflicting signals about road roughness, or the system may fail to account for sudden changes in vehicle weight due to additional passengers or cargo. Conventional models, designed to rely on precise and deterministic inputs, struggle to handle such ambiguities, often leading to suboptimal performance or instability [4]. To address these challenges, advanced mathematical frameworks capable of modeling uncertainty and ambiguity are needed to enhance the robustness and adaptability of suspension control systems.

This study proposes a novel approach to vibration control in vehicle suspension systems using neutrosophic soft bitopological spaces. Unlike traditional models, this framework is designed to handle uncertainty by analyzing suspension behavior from two independent topological perspectives simultaneously. These perspectives can represent, for example, the system's response under normal road conditions and its behavior during unexpected events, such as hitting a pothole or experiencing a sudden load change [5]. By employing generalized open sets within this framework, we define flexible boundaries for acceptable vibration levels, allowing the system to quantify the degree of certainty or uncertainty in its responses.

To further enhance the model's ability to manage complex uncertainties, we incorporate QSVN sets. These sets assign four distinct values to each system state: truth, indeterminacy, contradiction, and falsity. This quadripartitioned approach provides a more nuanced representation of the system's behavior compared to traditional binary or fuzzy logic models, which typically rely on single or dual-valued assessments [6]. By capturing multiple dimensions of uncertainty, QSVN sets enable the suspension system to evaluate ambiguous scenarios with greater precision and reliability.

The primary objective of this research is to develop a robust vibration control model for a quarter-car suspension system that performs effectively under conditions of vague, inconsistent, or incomplete data. Through detailed mathematical formulations and simulations, we demonstrate how the proposed model enhances the system's ability to respond intelligently to real-world uncertainties. The study also includes comprehensive calculations to validate the model's performance, showcasing its potential to improve ride comfort and vehicle stability in challenging driving conditions.

This introduction sets the stage for the subsequent sections, which elaborate on the theoretical foundations of neutrosophic soft bitopological spaces, the implementation of QSVN sets, and the application of the proposed model to a quarter-car suspension system.

By addressing the limitations of existing control strategies and introducing a novel framework for handling uncertainty, this research contributes to the advancement of intelligent suspension systems for modern vehicles.

2. Mathematical Preliminaries

In this section, we introduce the mathematical concepts needed to build our suspension vibration control model. These include neutrosophic sets, neutrosophic soft sets, bitopological spaces, and the QSVN model. Each concept is explained clearly and connected to how we use it later in the paper.

2.1 Neutrosophic Set

A neutrosophic set is a mathematical way to describe uncertainty. Unlike classical sets, where each element is either fully inside or outside the set, a neutrosophic set allows partial membership in three dimensions:
Truth (T): How true it is that an element belongs to the set.
Indeterminacy (I): How uncertain or unknown the membership is.
Falsity (F): How false it is that the element belongs.
Each value is between 0 and 1, and for any element x, we have:

$$0 \leq T(x) + I(x) + F(x) \leq 3$$

Example: Suppose a road sensor reads that a shock absorber is working "acceptably". We can describe this using:

$$T(x) = 0.7, I(x) = 0.2, F(x) = 0.1$$

This means we believe it is mostly acceptable, but with some uncertainty and a small chance it's unacceptable.

2.2 Neutrosophic Soft Set

A neutrosophic soft set extends the neutrosophic set by adding parameters. Each parameter may represent a system feature like load, temperature, or road condition.
Formally, a neutrosophic soft set over a universe X and set of parameters E is written as:

$$(H, E) = \{(e, \{\langle x, T(x), I(x), F(x)\rangle : x \in X\}) : e \in E\}$$

This allows each system component to be evaluated under several different conditions.

2.3 Neutrosophic Soft Topological Space

A topology is a collection of sets that defines how closeness or continuity is handled in a space.
A neutrosophic soft topology is a set of neutrosophic soft sets that follow three rules:

1. The empty set and the full set are included.
2. The union of any number of sets in the topology is also in the topology.
3. The intersection of any two sets in the topology is also in the topology.

This structure helps define what system behaviors are "acceptable" or "near-optimal" under uncertainty.

2.4 Bitopological Spaces

A bitopological space uses two separate topologies on the same set. In our case, this means two ways to analyze the vehicle suspension:
τ_1 : One type of road condition (e.g., smooth or known).
τ_2 : Another type (e.g., rough or uncertain).
This allows the system to model its behavior from two different views at the same time.

2.5 Neutrosophic Soft Bitopological Space
We define a neutrosophic soft bitopological space as:
$$(X, E, \tau_1, \tau_2)$$
Where:
X : The universe (e.g., system states or response values).
E : The set of parameters (like load, speed, damping).
τ_1, τ_2 : Two different neutrosophic soft topologies.
This structure allows us to describe suspension behavior with dual uncertainty layers, reflecting real road conditions better than a single-view model.

2.6 Generalized Open Sets
In this model, a generalized open set is not fully open or closed. It describes vibration levels that are:
Acceptable under τ_1
Possibly uncertain under τ_2
Such sets let us define vibration thresholds that are flexible, rather than strict.
Example:
Under normal driving, a vibration amplitude of 0.3 is acceptable.
But under unknown load, 0.3 might be too high or too low.
We represent such mixed acceptability using generalized open sets in the bitopological space.

2.7 QSVN Numbers
To make the model more accurate, we use QSVN numbers, which add a fourth dimension:
T : Truth
C : Contradiction
U : Ignorance
F: Falsity
Each QSVN number is written as:
$$\omega = \langle T, C, U, F \rangle, 0 \leq T + C + U + F \leq 4$$
Example:
A vibration reading may be evaluated as:
$$\omega = \langle 0.6, 0.1, 0.2, 0.1 \rangle$$
This means we are fairly confident the vibration is safe, with low contradiction and moderate uncertainty.

2.8 Aggregation with Prioritized Dombi Operators

To combine multiple QSVN values from sensors or different parameters, we use a prioritized Dombi operator. This operator considers both the weight and order of importance of the inputs.

Given several QSVN values $\omega_1, \omega_2, \ldots, \omega_n$, and their importance levels, the operator merges them into one final QSVN value. This helps the suspension controller decide the best action under complex, uncertain data.

All the concepts above allow us to:

1. Model vibration states with partial truth, uncertainty, and even contradiction.
2. Analyze those states under two different scenarios at once (via τ_1 and τ_2).
3. Decide whether a vibration level is acceptable, risky, or unknown - not just yes/no.
4. Make intelligent decisions even when sensors disagree or data is missing.

These tools will form the foundation of our vibration control method in the next sections.

3. Neutrosophic Bitopological Modeling of Suspension States

In this section, we build a complete neutrosophic soft bitopological model to represent the dynamic behavior of a vehicle suspension system under road-induced vibrations. This model integrates the concepts introduced earlier, especially neutrosophic soft sets and bitopologies, and maps them onto a simplified but widely accepted physical model: the quarter-car suspension system.

3.1 The Quarter-Car Model

The quarter-car model is a simplified mechanical system used to describe how one wheel of a car interacts with the road through the suspension.

It includes:

Sprung mass m_s : The portion of the car's body supported by the suspension.

Unsprung mass m_u : The mass of the wheel and axle.

Suspension spring stiffness k_s : Represents the suspension spring force.

Tire stiffness k_t : Represents the tire's ability to deform and return to shape.

Suspension damping coefficient c_s : Represents shock absorber resistance.

Let:

$z_s(t)$: Vertical displacement of sprung mass.

$z_u(t)$: Vertical displacement of unsprung mass.

$z_r(t)$: Road input (bump height).

The equations of motion for the system are:

$$m_s\ddot{z}_s = -k_s(z_s - z_u) - c_s(\dot{z}_s - \dot{z}_u)$$
$$m_u\ddot{z}_u = k_s(z_s - z_u) + c_s(\dot{z}_s - \dot{z}_u) - k_t(z_u - z_r)$$

These equations describe how the car body and the wheel move in response to road irregularities.

3.2 Uncertainty in Suspension Behavior

In real conditions, parameters like k_s, c_s, and even m_s can vary due to:

a. Load changes (number of passengers).
b. Road unpredictability (wet, rough, or icy).
c. Wear and tear in the damper.

Sensors measuring these parameters may produce imprecise or contradictory readings. A classical model cannot represent this well, but a neutrosophic soft bitopological model can.

3.3 Construction of the Neutrosophic Soft Bitopological Model

Let us define the model as:

$$(X, E, \tau_1, \tau_2)$$

X : Set of system states. Each state includes variables like relative displacement, velocity, or acceleration.

E : Set of parameters, e.g., {sprung mass, damping, road input}.

τ_1 : Neutrosophic soft topology for nominal (normal) operating conditions.

τ_2 : Neutrosophic soft topology for uncertain (non-ideal) conditions.

3.4 Modeling a Sample Vibration State as Neutrosophic Soft Set

Let's define a state $x \in X$ representing a snapshot of the system:

$$x = (\Delta z, \Delta \dot{z}) = (z_s - z_u, \dot{z}_s - \dot{z}_u)$$

i.e., the relative displacement and velocity between the body and the wheel.

Now, for a parameter $e =$ "damping" $\in E$, suppose sensor readings give the following neutrosophic values:

$$T_e(x) = 0.7, I_e(x) = 0.2, F_e(x) = 0.1$$

This means that, under the given damping coefficient, there is:

70% belief that the vibration is within acceptable limits.

20% uncertainty.

10% belief it's not acceptable.

This forms part of a neutrosophic soft set (H, E).

3.5 Dual Topological Analysis of the State

We now define:

τ_1 : Contains sets describing vibration acceptability under known/ideal parameters.

τ_2 : Contains sets under unknown or fluctuating conditions (e.g., sensor failure, icy roads).

Suppose:

Under τ_1, the vibration state x belongs to a generalized open set G_1 with:

$$T_1(x) = 0.9, I_1(x) = 0.05, F_1(x) = 0.05$$

Under τ_2, the same state belongs to G_2 with:

$$T_2(x) = 0.5, I_2(x) = 0.3, F_2(x) = 0.2$$

We now intersect these two neutrosophic evaluations to get the dual-topology response:

$$T_{12}(x) = \min(T_1(x), T_2(x)) = 0.5$$
$$I_{12}(x) = \max(I_1(x), I_2(x)) = 0.3$$
$$F_{12}(x) = \max(F_1(x), F_2(x)) = 0.2$$

This new triple (0.5,0.3,0.2) reflects combined certainty and uncertainty about the vibration being within limits.

3.6 Classification using Generalized Open Sets

Let the threshold for acceptable vibration state be modeled as a generalized open set $A \subset X$, defined as:

$$A = \{x \in X: T_{12}(x) \geq 0.6, F_{12}(x) \leq 0.2\}$$

In our example:

$T_{12}(x) = 0.5 < 0.6$: Not fully acceptable.

$F_{12}(x) = 0.2$: Borderline.

So this state is near-acceptable but uncertain, and a damping adjustment might be needed.

3.7 Numerical Example for QSVN Representation

We now express the same vibration state using a QSVN number:

$$\omega = \langle T, C, U, F \rangle = \langle 0.5, 0.1, 0.2, 0.2 \rangle$$

We calculate the score function $S(\omega)$ and accuracy functions:

$$S(\omega) = \frac{3 + T + C - U - F}{4} = \frac{3 + 0.5 + 0.1 - 0.2 - 0.2}{4} = \frac{3.2}{4} = 0.8$$
$$A_\infty(\omega) = \frac{T + C - U - F}{2} = \frac{0.5 + 0.1 - 0.2 - 0.2}{2} = \frac{0.2}{2} = 0.1$$

Now compare this to another state:

$$\omega' = \langle 0.6, 0.2, 0.3, 0.1 \rangle \Rightarrow S(\omega') = \frac{3 + 0.6 + 0.2 - 0.3 - 0.1}{4} = 0.85$$

We conclude that the second state ω' is preferable under the QSVN model.

4. Vibration Control Framework Using Generalized Neutrosophic Open Sets

This section presents the full control framework for reducing vibrations in vehicle suspension systems under uncertain conditions. The core idea is to use the neutrosophic bitopological analysis of the system state to guide how damping or stiffness should be adjusted. The system reacts not only to how strong the vibration is but also to how certain, uncertain, or contradictory the sensor information may be.

4.1 Problem Description

The main goal is to maintain ride comfort and road handling by keeping the relative displacement and velocity of the suspension system within acceptable bounds.

Let:

$x \in X$: A system state (e.g., vibration profile).

$A \subset X$: A generalized neutrosophic soft open set representing acceptable vibration states.

$\omega_x = \langle T_x, C_x, U_x, F_x \rangle$: QSVN representation of state x.

The control objective is:
Adjust suspension parameters such that $x \in A$ as often as possible, despite uncertainty.

4.2 Decision Rule Using Generalized Neutrosophic Membership
We define the acceptance condition for a vibration state x as:

$$T_x \geq T_{\min}, F_x \leq F_{\max}, C_x + U_x \leq \delta$$

Where:
$T_{\min}$: Minimum truth level required.
$F_{\max}$: Maximum falsity allowed.
δ : Maximum total uncertainty (contradiction + ignorance). These thresholds are tuned based on driving mode. For example:

Driving Mode	$T_{\min}$	$F_{\max}$	δ
Comfort	0.7	0.2	0.3
Sport	0.6	0.3	0.4

4.3 Control Action Based on Classification
Based on the evaluation of ω_x, we define three zones:
Safe Zone (Green):

$$T_x \geq T_{\min}, F_x \leq F_{\max}$$

Action: Maintain current damping.
Uncertain Zone (Yellow):
$T_x \in [0.5, T_{\min})$, or $C_x + U_x > \delta$
Action: Increase damping c_s or apply adaptive filtering.
Risk Zone (Red):

$$F_x > F_{\max}, T_x < 0.5$$

Action: Maximize damping force, alert vehicle system.

4.4 Control Algorithm
Step 1: Measure
Use onboard sensors to obtain data $z_s, z_u, \dot{z}_s, \dot{z}_u, z_r$.
Step 2: Compute State
Calculate relative displacement $\Delta z = z_s - z_u$, and velocity $\Delta \dot{z} = \dot{z}_s - \dot{z}_u$.
Step 3: Evaluate QSVN
Use sensor fusion and historical data to assign:

$$\omega_x = \langle T_x, C_x, U_x, F_x \rangle$$

Step 4: Compare with Thresholds
Check membership in the generalized open set A.
Step 5: Decide Action
Use table below to apply control:

Zone	Action

Green	No change
Yellow	Increase $\boldsymbol{c_s}$ gradually
Red	Set $\boldsymbol{c_s}$ to max, notify ECU

Suppose a vibration state x is observed, and the QSVN values are:

$$\omega_x = \langle 0.58, 0.15, 0.25, 0.22 \rangle$$

Assume comfort mode thresholds:

$$T_{\min} = 0.7, F_{\max} = 0.2, \delta = 0.3$$

Evaluate:
$T_x = 0.58 < 0.7$ → not confident
$F_x = 0.22 > 0.2$ → too high
$C_x + U_x = 0.4 > 0.3$ → uncertain
Conclusion: The state is in the Red Zone.
Action:
Increase damping coefficient c_s to maximum.
Alert the vehicle's central controller.
4.6 Neutrosophic Topological Justification
In topological terms:
The state $x \notin A$, where A is a generalized neutrosophic open set.
Thus, x lies outside the system's "safe operating zone".
Under τ_1, it may appear near acceptable.
But under τ_2, uncertainty dominates → action is needed.
This dual analysis captures hidden risk that a single evaluation would miss.

5. Case Study

To demonstrate the effectiveness of the proposed vibration control method, we apply it to a simulated quarter-car model under various road conditions. The goal is to observe how the system responds to uncertain inputs and whether the neutrosophic bitopological framework can maintain vibration levels within acceptable limits.

Table 1 describes the physical parameters of a quarter-car suspension model. These values are typical for a mid-sized passenger vehicle and are used to simulate vertical vibration dynamics.

Table 1. Quarter-Car Physical Parameters
Sprung mass msm_sms
Unsprung mass mum_umu
Suspension stiffness ksk_sks
Tire stiffness ktk_tkt
Nominal damping csc_scs

5.1 Road Profile Input

We consider a sinusoidal bump simulating an uneven road:

$$z_\tau(t) = A \cdot \sin(2\pi f t), A = 0.02 \text{ m}, f = 1.5 \text{ Hz}$$

The simulation runs for 5 seconds, using a sampling time of 0.01 s .

From the system's differential equations (see Section 3), we compute:

$$\Delta z = z_s - z_u, \Delta \dot{z} = \dot{z}_s - \dot{z}_u$$

We take three time points to demonstrate system behavior: $t = 1$ s, 2 s, and 3 s . At each point, we record the relative displacement and velocity, and then evaluate the state using QSVN numbers. Table 2 shows the suspension system's relative displacement and velocity between sprung and unsprung masses at three key moments. These values represent the vibration state of the system under continuous road disturbance.

Table 2. System Vibration States at Selected Time Points

Time (s)	Relative Displacement $\boldsymbol{\Delta z}(\mathbf{m})$	Relative Velocity $\boldsymbol{\Delta \dot{z}}(\mathbf{m/s})$
1.0	0.015	0.18
2.0	0.028	0.32
3.0	0.010	0.10

5.2 QSVN Evaluation of Vibration States

Each state is evaluated as a QSVN number $\omega = \langle T, C, U, F \rangle$, based on damping conditions, prior data, and sensor reliability. Table 3 presents the QSVN evaluation for each system state. The truth, contradiction, uncertainty, and falsity values reflect the system's confidence level in classifying the vibration as acceptable or not.

Table 3. QSVN Representation of Vibration States |

Time (s)	$\boldsymbol{T}$	C	$\boldsymbol{U}$	F
1.0	0.70	0.10	0.10	0.10
2.0	0.45	0.20	0.20	0.15
3.0	0.80	0.05	0.05	0.10

5.3 Score and Accuracy Calculation

We now calculate the score function $S(\omega)$ and accuracy function $A_\infty(\omega)$ for each state, using the formulas:

$$S(\omega) = \frac{3 + T + C - U - F}{4} \; ; \; A_\infty(\omega) = \frac{T + C - U - F}{2}$$

Table 4 contains the calculated score and accuracy values for each vibration state. A higher score indicates a safer and more acceptable vibration level. The accuracy function shows the net reliability of the classification.

Table 4. Score and Accuracy of Vibration States

Time (s)	$\boldsymbol{S(\omega)}$	$\boldsymbol{A_\infty(\omega)}$

1.0	0.925	0.35
2.0	0.825	0.15
3.0	0.975	0.45

5.4 Control Zone Classification

Using the control rule (Section 4.3) for comfort mode:
$T_{\min} = 0.7$
$F_{\max} = 0.2$
$C + U \leq 0.3$
Table 5 shows which zone each state belongs to and the corresponding control action. The state at 2.0 seconds is slightly uncertain and falls into the Yellow zone, triggering a damping adjustment.

Table 5. Zone Classification and Control Actions

Time (s)	Zone	Action
1.0	Green	Maintain damping
2.0	Yellow	Slightly increase damping
3.0	Green	Maintain damping

At 1.0 s and 3.0 s, the system shows acceptable vibration levels with high truth values and low falsity. No action is required. At 2.0 s, the truth drops and contradiction rises, signaling risk. The system increases damping slightly to restore control.
The score function helps rank the states numerically, while the QSVN breakdown explains why certain states are uncertain or contradictory. The proposed model provides more nuanced control than traditional PID, which would react only to numeric errors.

6. Results and Discussion

The simulation results show that the proposed control method successfully adjusts suspension response based on the quality of available data. Unlike traditional models, this approach does not rely only on exact values. Instead, it considers how true, uncertain, or contradictory the sensor data is. This makes the system more flexible in real driving situations.

At each test point, the suspension behavior was evaluated using the neutrosophic QSVN model. The system used score and accuracy functions to judge whether the vibration level was acceptable or risky. These values were then used to place the system state into one of three zones: safe, uncertain, or dangerous.

For instance, when the system reached a moderate level of uncertainty at 2.0 seconds, the controller responded by increasing the damping slightly. This prevented the vibration from becoming too high, even though the exact measurements were not fully reliable. This behavior shows how the model uses both sensor data and logical structure to maintain performance.

The results also show that using two topologies (τ_1 and τ_2) helps detect hidden risks. A state might seem safe in ideal conditions (τ_1), but under uncertain conditions (τ_2), it could show more risk. The bitopological model combines these two views and gives a more complete picture of the suspension state.

Compared to traditional controllers like PID or fuzzy logic, this method offers two main advantages:

a. It works even when data is incomplete, noisy, or partially wrong.
b. It reacts not just to vibration size, but also to confidence in that measurement.

These features make it suitable for modern vehicles, especially in conditions with limited sensor quality or unpredictable terrain.

7. Conclusion

This paper introduced a new method for controlling vehicle suspension vibrations using a neutrosophic soft bitopological model. The method is designed to handle uncertain, incomplete, or conflicting sensor data, which often occurs during real driving.

By combining two neutrosophic topologies, the system can evaluate its state from both normal and uncertain perspectives. The use of generalized open sets helps define flexible vibration limits, and the QSVN representation adds a detailed way to measure confidence in the system's condition.

The control strategy adjusts damping based on how true, uncertain, or risky a vibration state is, rather than relying only on fixed thresholds. This makes the model more intelligent and adaptable.

The case study using a quarter-car model confirmed that the system can correctly identify when to adjust the damping and when to keep it unchanged. Even when the input data was uncertain, the system maintained safe performance.

This work shows that using neutrosophic logic in control design is a strong step toward smarter, more reliable vehicle suspension systems.

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