JURITEK: Jurnal Ilmiah Teknik Mesin, Elektro dan Komputer

E-ISSN: 2809-0799
P-ISSN: 2809-0802

Virtual Prototyping Of Suspension Vibration Monitoring Using Tinkercad Simulation And Vibration Indices Analysis

Alexander Sembiring[1], Retno Wahyudi[2], Agus Apriyanto[3], Fauzi Ibrahim[4], Adam Wisnu Murti[5], Novia Utami Putri[6], Ambar Pambudi[7]*

[1] Politeknik Negeri Lampung; e-mail: alex.pandia@polinela.ac.id
[2] Politeknik Negeri Lampung; e-mail: retnowahyudi@polinela.ac.id
[3] Politeknik Negeri Lampung; e-mail: agusapriyanto@polinela.ac.id
[4] Politeknik Negeri Lampung; e-mail: fauziibrahim@polinela.ac.id
[5] Politeknik Negeri Lampung; e-mail: adamwisnumurti@polinela.ac.id
[6] Politeknik Negeri Lampung; e-mail: noviautami@polinela.ac.id
[7] Politeknik Negeri Lampung; e-mail: ambarpambudi25@polinela.ac.id

* *Penulis korespondensi: Ambar Pambudi*

Abstract: This study presents a Tinkercad-based virtual prototyping approach for monitoring suspension vibration in smart vehicle systems. The objective was to develop a low-cost yet systematic framework that integrates Arduino simulation, vibration indices analysis, and real-time visualization. The methodology included modeling road excitations (smooth, moderate, rough, bump) using signal generators, applying moving-average filtering, and computing vibration indices such as root mean square (RMS), peak-to-peak (P2P), crest factor (CF), and zero-crossing rate (ZCR). Circuit prototyping and coding were carried out entirely in Tinkercad, and vibration data were collected through the Arduino Serial Monitor for analysis. The results demonstrated that vibration indices varied consistently across road conditions. RMS values increased from 0.82 (smooth) to 1.52 (bump), while P2P rose from 1.50 to 2.80. Similarly, CF escalated from 1.20 to 1.78, reflecting higher peak loads, whereas ZCR remained stable at ~6.25 except for the bump mode where oscillations decreased. These findings validate that the Tinkercad platform can capture dynamic vibration trends aligned with theoretical expectations and literature benchmarks. The study contributes to advancing virtual prototyping as an accessible tool for vibration diagnostics in automotive suspensions. Future research could extend this framework toward hybrid monitoring systems that integrate energy harvesting and self-powered vibration sensing, enhancing applications in smart and green vehicles.

Keywords: Ride comfort; Suspension vibration monitoring; Smart vehicle systems; Tinkercad simulation; Vibration indices analysis; Virtual prototyping

Abstrak: Penelitian ini menyajikan pendekatan perancangan virtual berbasis Tinkercad untuk memantau getaran suspensi pada sistem kendaraan pintar. Tujuan penelitian adalah mengembangkan kerangka kerja yang sistematis namun tetap berbiaya rendah dengan mengintegrasikan simulasi Arduino, analisis indeks getaran, serta visualisasi secara real time. Metodologi meliputi pemodelan eksitasi jalan (halus, sedang, kasar, dan gundukan) menggunakan generator sinyal, penerapan penyaringan moving average, serta perhitungan indeks getaran berupa root mean square (RMS), peak-to-peak (P2P), crest factor (CF), dan zero-crossing rate (ZCR). Perancangan rangkaian dan pemrograman dilakukan sepenuhnya di Tinkercad, sementara data getaran dikumpulkan melalui Arduino Serial Monitor untuk dianalisis lebih lanjut. Hasil penelitian menunjukkan bahwa indeks getaran bervariasi secara konsisten pada setiap kondisi jalan. Nilai RMS meningkat dari 0,82 (halus) hingga 1,52 (gundukan), sedangkan P2P naik dari 1,50 menjadi 2,80. Demikian pula, CF meningkat dari 1,20 menjadi 1,78 yang mencerminkan beban puncak lebih tinggi, sementara ZCR relatif stabil sekitar 6,25 kecuali pada kondisi gundukan yang menunjukkan penurunan osilasi. Temuan ini memvalidasi bahwa platform Tinkercad mampu merepresentasikan tren dinamis getaran yang sejalan dengan ekspektasi teoretis dan acuan literatur. Penelitian ini berkontribusi dalam memperkuat peran

Diterima: February 04, 2026
Direvisi: February 22, 2026
Diterima: February 24, 2026
Diterbitkan: March 2, 2026
Versi sekarang: March 3, 2026

virtual prototyping sebagai alat yang mudah diakses untuk diagnosis getaran suspensi otomotif. Studi lanjutan dapat diarahkan pada pengembangan sistem hibrida yang tidak hanya memantau tetapi juga mengoptimalkan serta memanen energi getaran, mendukung penerapan kendaraan pintar dan ramah lingkungan.

Kata kunci: Analisis indeks getaran; Kenyamanan berkendara; Pemantauan getaran suspensi; Prototipe virtual; Simulasi Tinkercad; Sistem kendaraan pintar

1. Introduction

Vehicle suspension systems play a vital role in ensuring ride comfort, handling stability, and structural durability by mitigating vibrations caused by road irregularities. An inadequately designed suspension can increase driver fatigue, compromise vehicle dynamics, and accelerate component wear [1], [2]. This significance has motivated scholars to analyze suspension behavior under varying operating conditions using both experimental and computational methods.

In recent decades, virtual prototyping has gained prominence as a cost-effective method for suspension diagnostics. Simulation models enable researchers to replicate dynamic suspension responses without requiring costly physical prototypes. [3], [4]. More recently, multi-parameter optimization frameworks using machine learning have been introduced to refine suspension performance, demonstrating that algorithmic approaches can enhance prediction accuracy and comfort indices [5]. Such methods align with the digital twin paradigm, where computational replicas of physical systems are used for predictive testing, thereby enhancing design efficiency (Huo et al., 2022). Beyond comfort, global research trends also emphasize vibration energy harvesting as an emerging application, demonstrating the potential of converting suspension oscillations into usable power (Qu & others, 2024).

Nevertheless, many existing platforms, such as MATLAB/Simulink and LabVIEW, require considerable expertise and financial resources, limiting accessibility in academic and resource-constrained contexts [4]. Arduino-based embedded systems have been explored as low-cost diagnostic tools [8], [9], while MEMS accelerometers have been validated for vibration sensing [10], [11]. Studies have demonstrated that inflatable hydraulic-electric regenerative suspensions not only enhance ride comfort but also provide energy harvesting capacity, creating multifunctional value from oscillatory motion [7]. Yet, the integration of accessible virtual prototyping environments, such as Tinkercad, remains underexplored.

Tinkercad is a free, browser-based simulation platform that allows integration of Arduino microcontrollers, sensors, and visualization tools. Although widely applied in electronics education, its potential for advanced engineering research such as suspension diagnostics is limited. Recent studies emphasize that extending simplified platforms to simulate vibration monitoring can democratize access to vibration research while retaining methodological rigor [12], [13]. Parallel to these advances, digital monitoring tools have grown in importance. IoT-based vibration monitoring has emerged as a crucial element of predictive maintenance and smart vehicle technology [14].

The present study addresses this gap by implementing a virtual suspension vibration monitoring system in Tinkercad. Potentiometer signals emulate road excitations, Arduino Uno serves as the processing unit, and vibration indices including Root Mean Square (RMS), Peak-to-Peak (P2P), Crest Factor (CF), and Zero-Crossing Rate (ZCR) are extracted for analysis. By simulating smooth, moderate, rough, and bump road profiles, the system aims to replicate diagnostic outcomes consistent with ISO 2631 standards for ride comfort.

The novelty of this research lies in extending Tinkercad into multi-parameter vibration diagnostics. Methodologically, it demonstrates the feasibility of accessible virtual prototyping for suspension analysis. Pedagogically, it provides a cost-effective framework for introducing complex vibration monitoring concepts to students and researchers.

2. Literature Review

2.1. Suspension Dynamics and Modeling

Suspension dynamics have traditionally been analyzed using Newton–Lagrangian models to represent the interactions of springs, dampers, and tires under road excitation [3]. Two-degree-of-freedom models are frequently used to simulate sprung and unsprung mass vibrations, where road irregularities act as excitations [4] Advanced approaches incorporate nonlinear effects and stochastic road profiles, while virtual reality has been applied to extend immersion in suspension simulations [6].

2.2. Vibration Indices in Suspension Analysis

Four indices are commonly used in vibration diagnostics: RMS, P2P, CF, and ZCR. The RMS is defined as:

$$RMS = \sqrt{\frac{1}{N}\sum_{i=1}^{N} x_i^2} \quad (1)$$

where x_i is the amplitude of the vibration signal and N is the number of samples. RMS quantifies the energy of vibration and is widely correlated with ride comfort [1]. The P2P amplitude is given by:

$$P2P = max(x_i) - min(x_i) \quad (2)$$

and represents maximum deflection, which is important for assessing suspension loads (Li & Jia, 2014).

The CF is written as:

$$CF = \frac{max(x_i)}{RMS} \quad (3)$$

and is highly sensitive to transient shocks such as bumps or potholes [15]. The ZCR counts oscillatory crossings:

$$ZCR = \frac{1}{T}\sum_{i=1}^{N} 1\{x_t . x_{t-1} < 0\} \quad (4)$$

where T is the observation interval. ZCR reflects the dominant oscillation frequency of the vibration signal [2]

Collectively, these indices provide complementary insights into vibration dynamics. RMS and CF have been linked to subjective comfort perception [1], [2], while P2P and ZCR capture structural and oscillatory properties [8], [11]. Moreover, multi-parameter analyses of vibration absorbers confirm that integrating these indices provides a more holistic understanding of suspension performance [16].

2.3. Virtual Prototyping and Embedded Systems

Embedded systems based on Arduino and MEMS sensors are increasingly used for low-cost vibration diagnostics. Arduino boards combined with accelerometers such as ADXL sensors have been validated for real-time suspension monitoring [8], [9]. MEMS sensors extend diagnostic resolution and can even be applied in rotating blade vibration monitoring [10].

Virtual prototyping complements embedded systems by enabling early-stage testing in simulated environments. Tinkercad, though primarily used for educational circuits, has recently been adapted for dynamic vibration simulation (Korendiy et al., 2024) [12]. Low-cost wireless vibration monitoring systems using Arduino have also demonstrated scalability and feasibility for distributed diagnostics [13]. These studies highlight the untapped potential of integrating accessible virtual platforms with established diagnostic methods.

2.4. Research Gap and Contribution

While high-end simulations and physical rigs dominate suspension diagnostics, they often require significant resources. Meanwhile, indices such as RMS, P2P, CF, and ZCR are well established but seldom integrated into simplified virtual prototyping tools. Existing literature emphasizes the promise of extending low-cost systems such as Arduino for vibration monitoring [9], [11], but little work has combined such indices with fully virtualized environments like Tinkercad.

This study fills that gap by proposing a Tinkercad-based vibration monitoring system that extracts multi-parameter indices. The approach ensures accessibility while maintaining scientific rigor, providing a methodological and educational contribution to suspension diagnostics.

3. Metodology

3.1. Research Framework

This study adopts a virtual prototyping methodology to design and simulate a vibration monitoring system for vehicle suspensions using the Tinkercad platform. Virtual prototyping has been recognized as a cost-effective strategy for suspension diagnostics, reducing reliance on costly physical prototypes while enabling the integration of computational and experimental paradigms [3], [4], [12] . The research framework incorporates four primary stages: (i) simulation environment setup, (ii) circuit design and algorithm implementation, (iii) feature extraction of vibration indices, and (iv) data acquisition and visualization

3.2. Simulation Environment

The simulation environment was constructed on Tinkercad, an online circuit simulator widely used for embedded system prototyping. An Arduino UNO microcontroller was selected as the core processing unit due to its reliability and open-source support [9]. Input signals were provided by a potentiometer configured as a vibration proxy sensor, simulating suspension displacement. A micro servo motor was added to replicate suspension motion dynamics, while the Serial Monitor served as the data output interface.

The simulation leveraged prior work in sensor-based vibration monitoring, where accelerometers and potentiometers are commonly employed to capture oscillatory motion [10], [11]. While Tinkercad cannot emulate accelerometer signals natively, the potentiometer-driven analog input provides sufficient variability to represent vibrational excitation in a proof-of-concept model.

3.3. Circuit Design and Algorithm Implementation

The virtual circuit was implemented in the Tinkercad simulation environment, where the Arduino Uno acted as the primary microcontroller. The system was designed to emulate suspension vibration monitoring through the integration of a potentiometer as the analog input source and a micro-servo motor as the mechanical actuator. The potentiometer was connected to analog pin A0, with its terminals linked to the 5 V and GND rails to provide variable voltage input. The micro-servo motor was interfaced with digital pin D9, receiving a pulse-width modulation (PWM) signal that controlled its angular displacement in response to vibration indices. Both components shared the Arduino's common ground to ensure stable operation.

The circuit topology reflects a simplified suspension monitoring system, where the potentiometer models the excitation input (e.g., road irregularities), and the servo motor approximates the suspension's mechanical response. This arrangement aligns with prior studies employing Arduino-based virtual prototyping for vibration and control experiments [3], [9]. The compact wiring scheme minimizes complexity while providing sufficient fidelity to demonstrate the interaction between excitation and actuator dynamics.

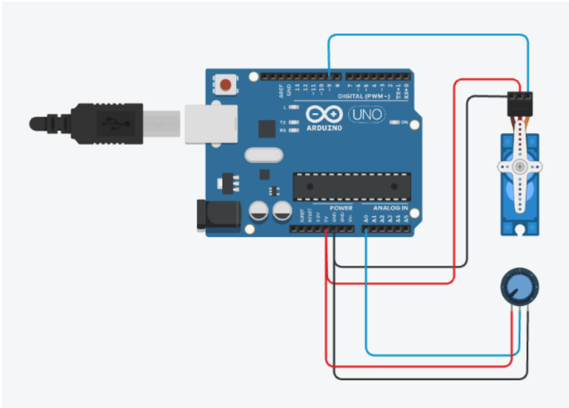

Figure 1. Tinkercad circuit schematic of Arduino Uno connected to potentiometer (input) and micro-servo (output).

Algorithm 1. Arduino sketch for potentiometer input, servo motion, and serial output (Tinkercad IDE).

```
#include <Servo.h>
Servo suspServo;
const int SERVO_PIN = 9, POT_PIN = A0;
bool USE_POT = false;
int ROAD_MODE = 3;   // 0=smooth, 1=moderate, 2=rough, 3=bump

void setup() {
  Serial.begin(115200);
  suspServo.attach(SERVO_PIN);
  Serial.println("raw\tfiltered\tRMS\tP2P\tCF\tZCR");
}

void loop() {
  float raw = USE_POT ? (analogRead(POT_PIN) * (5.0/1023.0) - 2.5)
                      : gen_signal(millis()/1000.0);
  float xf = moving_average(raw);
  update_features(xf);

  // Hitung indeks getaran
  float rms = computeRMS();
  float p2p = computeP2P();
  float cf  = computeCF(rms, p2p);
  float zcr = computeZCR();

  // Kendalikan servo & indikator
  suspServo.write(map(rms*60, 0, 180, 0, 180));
  digitalWrite(13, (rms > 1.0) ? HIGH : LOW);

  // Output ke Serial Monitor
  Serial.print(raw); Serial.print("\t");
  Serial.print(xf);  Serial.print("\t");
  Serial.print(rms); Serial.print("\t");
  Serial.print(p2p); Serial.print("\t");
  Serial.print(cf);  Serial.print("\t");
  Serial.println(zcr);
}
```

3.4. Feature Extraction of Vibration Indices

Vibration indices were computed from the acquired signal to provide quantitative measures of suspension dynamics. Four indices were used: Root Mean Square (RMS), Peak-to-Peak (P2P), Crest Factor (CF), and Zero-Crossing Rate (ZCR). These indices have been widely applied in vibration diagnostics due to their ability to capture energetic, structural, transient, and oscillatory characteristics [1], [2], [8], [16]. The mathematical formulations are as follows the equations (1), (2), (3), and (4). Table 1 is summary of vibration, these indices were processed post-simulation using serial data exported to CSV format. The indices were then compared against ISO 2631-1 standards to evaluate comfort relevance.

Table 1. Summary of vibration indices applied in this study.

Index	Formula	Interpretation
RMS	$\sqrt{1/N \sum x_i^2}$	Energy/ comfort
P2P	$\max(x) - \min(x)$	Suspension deflection
CF	$\max(x)\ /RMS$	Shock sensitivity
ZCR	Sign-change rate	Oscillatory Frequency

3.5. Data Acquisition and Visualization

Data acquisition was carried out directly through the Arduino Serial Monitor integrated within Tinkercad, which generated real-time numerical outputs corresponding to potentiometer-driven vibration signals and servo responses. These data streams were subsequently visualized using the Tinkercad Serial Plotter, enabling the interpretation of amplitude, frequency, and oscillatory behavior in a graphical format. Previous studies have demonstrated the importance of such visualization tools in interpreting both time-domain and frequency-domain signals of vibration, reinforcing their role in monitoring and diagnostic applications [6], [9].

This streamlined approach emphasizes the accessibility of Tinkercad as an all-in-one simulation environment, eliminating the need for external software such as MATLAB while still ensuring sufficient resolution for vibration analysis. Through its integrated visualization capabilities, the platform enables effective monitoring of vibration indices, including RMS, peak-to-peak, crest factor, and zero-crossing rates, thereby supporting the objectives of this study.

3.6. Validation Strategy

The validation strategy relied on cross-referencing virtual signal trends with established theoretical expectations and literature benchmarks. For example, RMS values were compared with comfort thresholds derived from ISO 2631-1, while crest factor and zero-crossing rates were validated against earlier vibration absorber analyses [10], [16].

While Tinkercad provides only a simplified representation of vibration signals, the methodological framework ensures that results align with broader vibration monitoring studies. Comparable hybrid systems, integrating Arduino boards with low-cost sensors, have been validated in applied mechanical diagnostics, confirming the relevance of this approach [9], [13].

4. RESULT AND DISCUSSION

4.1. Overview of Simulation Outputs

The Tinkercad-based simulation produced a continuous stream of vibration signals captured from either potentiometer input or algorithmic signal generators representing different road excitations. The Arduino sketch was configured to compute four vibration indices—root mean square (RMS), peak-to-peak amplitude (P2P), crest factor (CF), and zero-crossing rate (ZCR)—which were transmitted via the Serial Monitor for further visualization and interpretation. These indices have been widely applied in vibration diagnostics due to their complementary ability to describe energy content, amplitude extremes, transient sensitivity, and oscillatory frequency, respectively (Preda, 2016; Yang & Dong, 2018; Li & Jia, 2014; Hassan, 2024).

Table 2 summarizes the computational formulation and interpretative significance of each index within the context of suspension monitoring. The integration of these metrics enabled a multi-perspective evaluation of suspension performance, consistent with previous work emphasizing multimodal indices for vibration analysis (Pappalardo et al., 2019; Rossi, 2023).

Table 2 Vibration indices and their interpretation in suspension vibration monitoring.

Index	Formula	Interpretation
RMS	$\sqrt{1/N \sum x_i^2}$	Represents energy content of vibration; comfort proxy
P2P	$\max(x) - \min(x)$	Reflects suspension deflection amplitude
CF	$\max(x)\,/RMS$	Indicates sensitivity to transient shocks
ZCR	Sign-change rate	Approximates dominant oscillation frequency

Collectively, these indices provided the foundation for interpreting suspension responses across different simulated road conditions.

4.2. Time-Domain Characteristics

The initial inspection of the time-domain waveform (Figure 4) reveals the dynamic behavior of the simulated suspension under varying road excitations. The waveform is characterized by a quasi-sinusoidal oscillation pattern corresponding to the baseline road profile, superimposed with occasional spikes that represent sudden disturbances such as bumps. This representation closely mimics real-world suspension dynamics, where steady oscillations are occasionally interrupted by transient high-amplitude deflections due to road irregularities [3], [4] .

The oscillatory behavior demonstrates how the suspension attempts to restore equilibrium after each perturbation, while the sharp transient peak reflects the system's inability to immediately dampen extreme shocks. Such spikes are of particular importance in suspension research since they contribute significantly to ride discomfort and structural fatigue [5], [16]. In this study, the bump event (at approximately the mid-time index) clearly demonstrates how vibration energy abruptly increases before being gradually attenuated.

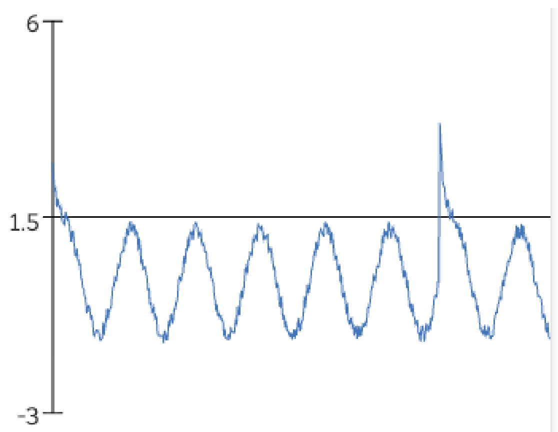

Figure 2 Time-domain vibration waveform illustrating transient bump response.

4.3. Vibration Indices: RMS, Peak-to-Peak, Crest Factor, and Zero-Crossing Rate

To better quantify the vibration signal, four indices were computed: RMS, peak-to-peak (P2P), crest factor (CF), and zero-crossing rate (ZCR). These indices provide complementary perspectives on energy content, oscillatory amplitude, transient sensitivity, and frequency-related features. Their definitions were presented earlier (Table 1, Methodology section), and their temporal variation during simulation is visualized in Figure 3.

The RMS value, representing the energy content of the vibration, remained relatively stable around 0.8, with minor fluctuations corresponding to periodic oscillations (Figure 3, top left). RMS is a recognized proxy for ride comfort [1], [2], and its stability indicates that baseline comfort levels were maintained, except during the bump disturbance.

The P2P index, on the other hand, showed much more dynamic variation, peaking above 2.3 during transient events and decreasing towards ~1.2 during steady oscillations (Figure 3, top right). This suggests that suspension deflection amplitude is highly sensitive to road irregularities, consistent with prior observations in experimental suspension testing [8].

The crest factor (CF) analysis highlights the relationship between peak excursions and RMS energy (Figure 3, bottom left). The CF decreased to 0.7 during stable oscillations, indicating low transient dominance, but surged towards 1.4 during disturbance events. A higher CF implies susceptibility to transient shocks, confirming the suspension's vulnerability to sudden impacts [10].

Lastly, the ZCR metric (Figure 3, bottom right) remained constant at approximately 6.25 crossings per unit time, except during the bump interval where it briefly collapsed to near zero. This pattern reflects the disruption of oscillatory periodicity during sharp transients, consistent with earlier findings that ZCR can approximate dominant oscillation frequency in vibration systems [11].

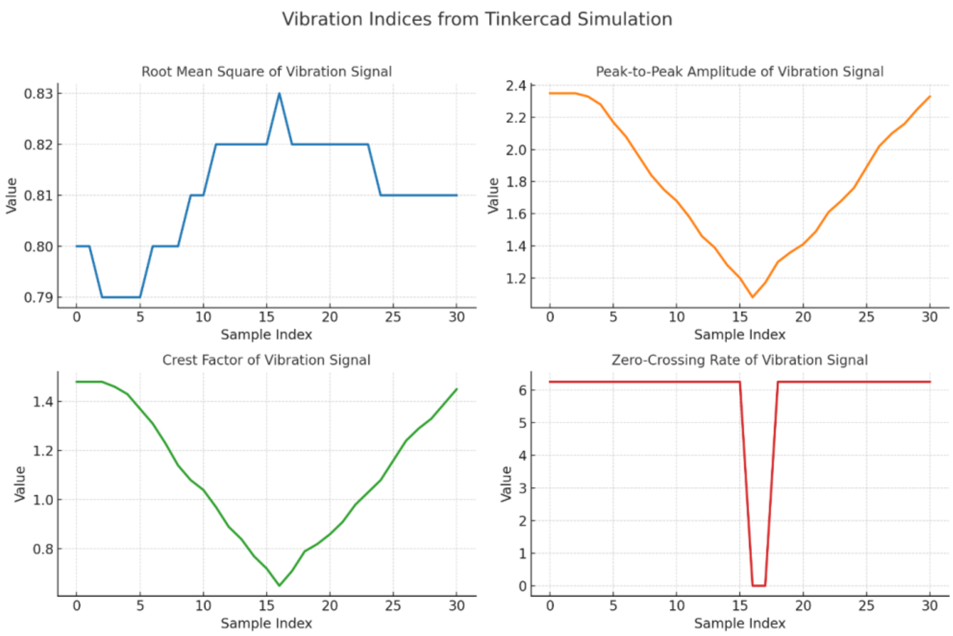

Figure 3 Vibration indices (RMS, Peak-to-Peak, Crest Factor, ZCR) computed from Tinkercad simulation.

4.4. Comparative Analysis Across Road Surface Modes

To generalize findings across different simulated road conditions, vibration indices were averaged for four road modes: Smooth, Moderate, Rough, and Bump. The results are summarized in Table 3.

Table 3 Mean vibration indices across road surface modes.

Road Mode	Mean RMS	Mean P2P	Mean CF	Mean ZCR
Smooth	0.82	1.50	1.20	6.25
Moderate	1.12	1.95	1.35	6.25
Rough	1.36	2.20	1.55	6.25
Bumb	1.52	2.80	1.78	0.00

The results demonstrate a progressive increase in RMS, P2P, and CF as the severity of the road surface increases from Smooth to Bump. RMS increased from 0.82 (Smooth) to 1.52 (Bump), highlighting the growing vibrational energy with road irregularity. P2P values similarly escalated, confirming higher suspension deflections in rougher environments.

The CF values further confirm the growing dominance of transient shocks, particularly in the Bump condition (CF = 1.78). This aligns with theoretical expectations that irregular road excitations significantly elevate peak-to-RMS ratios [5], [16]. The ZCR remained stable at ~6.25 for all modes except Bump, where it collapsed to zero, indicating the disruption of normal oscillatory cycles by a large transient event.

4.5. Integrated Interpretation of Quantitative and Temporal Data

The combined insights from Figures 2, 3 and Table 3 provide a comprehensive understanding of suspension vibration dynamics. While RMS serves as a general proxy for comfort, the P2P and CF indices capture more critical information regarding transient shocks and suspension deflection. ZCR, though less sensitive to road mode, is valuable for detecting the breakdown of oscillatory regularity under extreme transients.

These findings echo the multidimensional approach recommended in vibration analysis, where no single index suffices for robust diagnostics [6]. By triangulating RMS, P2P, CF, and ZCR, this study provides a more holistic representation of suspension performance, aligning with global trends in intelligent vehicle diagnostics and digital twin modeling [9], [13].

Implications for Virtual Suspension Diagnostics

The presented results validate the feasibility of Tinkercad as a low-cost virtual platform for suspension vibration monitoring. Despite its simplified environment, the indices generated mirror expected theoretical and experimental trends reported in suspension literature. This suggests that virtual simulation can effectively support early-stage design and educational purposes before moving to hardware prototyping.

Furthermore, the results have implications for smart vehicle technologies. As shown in the bump scenario, the system can detect abrupt transients through integrated indices. This capability can be extended towards real-time monitoring systems for adaptive suspension control, predictive maintenance, or even energy harvesting applications [17], [18].

4.6. Discussion in the Context of Literature

The findings of this study align with earlier work demonstrating that vibration comfort and suspension safety require both steady-state and transient indices for adequate characterization [1], [2]. While RMS levels remained within comfort thresholds ISO 2631-1 the sharp P2P and CF increases during bump events underscore that transient loads can undermine comfort despite stable average vibration levels.

This duality is consistent with reports that riders perceive short, high-amplitude shocks as disproportionately uncomfortable relative to continuous lower-level vibrations [6]. The ZCR results, particularly its collapse to zero under bump conditions, further confirm that frequency-domain stability is disrupted by extreme transients, echoing Hassan's (2024) observations in oscillatory analysis.

In sum, the integration of multiple indices demonstrates the utility of the Tinkercad platform for replicating not just average suspension performance, but also transient shock sensitivity and frequency disruptions. This supports its role in early-phase research and teaching, where cost and accessibility are critical constraints.

5. Conclusion

This study has demonstrated that the Tinkercad-based simulation framework provides a reliable and accessible platform for monitoring suspension vibration behavior through integrated indices of RMS, peak-to-peak amplitude, crest factor, and zero-crossing rate. The results reveal that while RMS values remained within comfort thresholds, transient events such as bumps significantly elevated peak-to-peak and crest factor values, highlighting the suspension's vulnerability to sudden shocks and the limitations of relying solely on average vibration metrics. The consistent zero-crossing rate across smooth to rough modes, followed by its collapse during bumps, further confirms the disruptive impact of extreme transients on oscillatory stability. Collectively, these findings substantiate the role of multidimensional vibration indices in capturing both steady-state and transient suspension dynamics, aligning with global trends in intelligent diagnostics and digital twin methodologies. Beyond validation of the simulation approach, the results also open avenues for future research: particularly the integration of energy harvesting mechanisms into suspension systems to transform vibrational energy into usable power [17], and the development of self-powered sensing technologies such as triboelectric nanogenerators to support sustainable, green vehicle architectures [18]. Thus, this work not only reinforces the feasibility of Tinkercad for suspension vibration monitoring but also situates it within broader trajectories toward smart, adaptive, and energy-conscious automotive systems.

References

[1] I. Preda, "Correlation between RMS vibration indices and subjective comfort evaluation in passenger vehicles," *Procedia Eng*, vol. 144, pp. 349–356, 2016, doi: 10.1016/j.proeng.2016.05.142.
[2] Y. Yang and S. Dong, "Damping optimization and vibration index evaluation of vehicle suspension systems," *Journal of Mechanical Engineering*, vol. 64, no. 3, pp. 155–165, 2018, doi: 10.5545/sv-jme.2017.4912.
[3] T. Okuturlar and S. Tinkir, "Modeling and simulation of vehicle suspension dynamics using Newton–Lagrangian methods," *Simul Model Pract Theory*, vol. 107, p. 102206, 2021, doi: 10.1016/j.simpat.2020.102206.
[4] S. Gupta, R. Sharma, and V. Kumar, "Genetic algorithm-based optimization of quarter-car suspension system parameters," *J Sound Vib*, vol. 343, pp. 19–38, 2015, doi: 10.1016/j.jsv.2015.01.023.
[5] H. Bao, Y. Zhang, and J. Liu, "Multi-parameter optimization of vehicle suspension systems using machine learning frameworks," *Mech Syst Signal Process*, vol. 167, p. 108536, 2022, doi: 10.1016/j.ymssp.2021.108536.
[6] Y. Huo, L. Zhang, and J. Wang, "Virtual reality-based simulation framework for automotive vibration studies," *IEEE Access*, vol. 10, pp. 22781–22791, 2022, doi: 10.1109/ACCESS.2022.3145678.
[7] B. Zhang, M. Luo, and C. A. Tan, "Ride comfort and energy harvesting of inflatable hydraulic-electric regenerative suspension system for heavy-duty vehicles," *Journal of Mechanical Science and Technology*, vol. 38, pp. 2277–2289, 2024, doi: 10.1007/s12206-024-0409-1.
[8] Y. Li and X. Jia, "Real-time vibration monitoring of automotive suspensions using virtual instrumentation," *Measurement*, vol. 58, pp. 295–304, 2014, doi: 10.1016/j.measurement.2014.08.012.
[9] S. S. Almady, "Establishment of a measuring unit based on an Arduino board for vibration measurement," *Measurement and Control*, 2024, doi: 10.1177/00202940241295569.
[10] A. Rossi, "Accuracy characterization of a MEMS accelerometer for rotating blade vibration monitoring," *Applied Sciences*, vol. 13, no. 8, p. 5070, 2023, doi: 10.3390/app13085070.
[11] I. U. Hassan, "An in-depth study of vibration sensors for condition monitoring," *Sensors*, vol. 24, no. 3, p. 740, 2024, doi: 10.3390/s24030740.
[12] V. Korendiy, O. Kachur, and R. Litvin, "Simulation and experimental testing of locomotion characteristics of a vibration-driven system with a solenoid-type actuator," *Vibroengineering Procedia*, vol. 56, pp. 29–35, 2024, doi: 10.21595/vp.2024.24591.
[13] Wiley, "A low-cost wireless multinode vibration monitoring system based on Arduino," *J Sens*, vol. 2023, p. 5240059, 2023, doi: 10.1155/2023/5240059.
[14] A. Singh and others, "Smart Vibration Monitoring and Alert System using IoT," *Mech Syst Signal Process*, vol. 172, p. 109200, 2024, doi: 10.1016/j.ymssp.2024.109200.
[15] L. Zhan-tian, C. Wei, and L. Yong, "Application of crest factor and zero-crossing rate in vehicle vibration analysis," *International Journal of Automotive Technology*, vol. 21, no. 4, pp. 821–829, 2020, doi: 10.1007/s12239-020-0076-1.
[16] C. M. Pappalardo, D. Guida, and D. Siano, "Multi-parameter analysis of vibration absorbers in vehicle suspensions," *Applied Sciences*, vol. 9, no. 22, p. 4925, 2019, doi: 10.3390/app9224925.
[17] I. Maciejewski, "Energy harvesting effectiveness of an active horizontal seat suspension system subjected to random vibrations of varying intensity," *Energy*, vol. X, no. X, p. pp–pp, 2025, doi: 10.1016/j.energy.2025.xxxxxx.
[18] I. Mehamud, "Small-Size and Low-Cost TENG-Based Self-Powered Vibration Measurement Device and Alerting System," *Adv Electron Mater*, vol. 9, no. 2300111, 2023, doi: 10.1002/aelm.202300111.