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LETTER

Real-time road testing and analysis of adjustable passive suspension system with variable spring stiffness

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Abstract

This research paper investigates the importance of adjustable passive suspension systems, with a particular emphasis on a novel variant employing variable spring stiffness. The study examines the implications of variable stiffness on ride comfort and handling across diverse road conditions through real-world trials conducted on a designated test vehicle. Utilizing sophisticated data analysis methodologies, the optimal stiffness configurations tailored to distinct road conditions are discerned, aiming to ascertain the efficacy of the system in augmenting overall vehicle performance and adaptability. Acknowledging potential challenges inherent in real-time adjustments and system intricacies, the paper aims to showcase the tangible benefits of variable spring stiffness technology. In the experimental findings, the first setting demonstrates optimal ride comfort and vehicle stability at low speed, while at medium speed, the second setting excels in both aspects. Conversely, at high speed, the fourth setting offers the best ride comfort and vehicle stability.

Keywords Adjustable suspension · Variable spring stiffness · Real-time road testing · Experimental analysis · Vehicle performance · Ride comfort · Road handling/stability

1 Introduction

Ride comfort and stability are paramount for maintaining the physical well-being and safety of individuals during transportation. Smooth and stable rides minimize physical stress, reducing the risk of musculoskeletal issues and discomfort. They also alleviate motion sickness symptoms, promoting a more pleasant travel experience and ensuring passengers' mental well-being. Furthermore, stability is crucial for safety, as it enhances vehicle control and reduces the risk of accidents. Long-term exposure to poor ride conditions can have adverse health effects, emphasizing the importance of prioritizing comfort and stability. In commercial settings, these factors also impact productivity and performance. Ultimately, ensuring a comfortable and stable ride fosters a safer, healthier, and more enjoyable transportation experience for all passengers.

The passive suspension system in a motorcycle is indispensable, serving as a crucial component that directly influences performance, safety, and rider comfort. It plays a vital role in maintaining traction, stability, and control by absorbing bumps, vibrations, and other road irregularities, ensuring the wheels stay in contact with the ground during maneuvers. This not only enhances handling and maneuverability but also contributes to safer riding conditions by reducing the risk of accidents caused by loss of control or inadequate braking. Moreover, a well-designed passive suspension system enhances ride comfort by minimizing fatigue and musculoskeletal strain, particularly during long journeys. With customizable options available in modern motorcycles, riders can fine-tune suspension settings to their preferences, optimizing performance for various riding conditions. In essence, the passive suspension system is integral to the overall riding experience, providing a delicate balance between comfort, control, and safety.

Motorcycles undergo vibrational phenomena of diverse frequencies, emanating from both inherent natural oscillations and extraneous perturbations. The inherent structure of a motorcycle encompasses a multitude of natural frequencies, the confluence of which with external disturbances can induce resonance phenomena. [1, 2]. The spectrum

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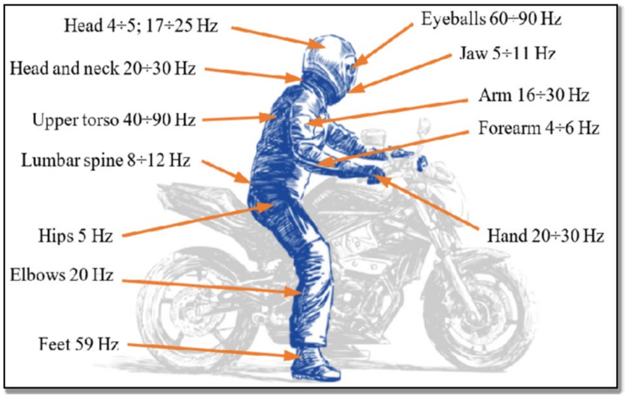


Fig. 1 Natural frequencies of selected organs and parts of the human body [1]

of vibrations spans from 0.1 to 100 Hz, exerting a notable influence on human physiology. This stems from the distinct natural frequencies inherent to our bodily organs and tissues, rendering them susceptible to such vibrational stimuli. Prolonged exposure, even over journeys spanning multiple hours, may induce symptoms such as limb numbness and diminished sensory perception, persisting for days. These frequency parameters are derived from empirical data, as illustrated in Fig. 1. A thorough investigation into the underlying causes of vibrations and the implementation of effective mitigation strategies are imperative to alleviate potential physiological repercussions. Consequently, it is paramount to scrutinize the origins of vibrations, deploy mitigation methodologies, and evaluate their physiological ramifications [3]. Recent research findings underscore the detrimental effects of vibration exposure on drivers' health, even during short durations. This underscores the profound physiological repercussions of vibrational stimuli on the human body [4]. The vehicle’s passive suspension system holds significant importance in mitigating undesirable vibrations. Serving as a pivotal component, it is instrumental in safeguarding the vehicle frame against the rigors of uneven road surfaces and adverse driving conditions [5].

In the realm of automotive engineering, a passive suspension system constitutes a sophisticated assembly of diverse components interlinking a vehicle's chassis with its wheels. Its paramount objective is to ensure passenger comfort by mitigating the effects of irregular road surfaces, while also facilitating stable vehicle maneuverability and control. The passive suspension system serves to physically isolate the vehicle's body from its wheels, thereby absorbing the shock generated by the un-sprung mass and attenuating its transmission to passengers, thereby enhancing ride comfort. Historically, the design of automotive passive suspension systems has revolved around a delicate equilibrium among three pivotal factors: road handling, load-bearing capacity, and passenger comfort. Consequently, traditional suspension configurations typically integrate a spring element for energy storage and a damper mechanism for energy dissipation [6].

To evaluate ride quality, a simplified car model depicted in Fig. 2 serves as the basis. Critical parameters under scrutiny encompass the mass characteristics, namely the sprung mass (ms) and un-sprung mass (mu), quantified in kilograms. Additionally, constants pertinent to the passive suspension system, such as the spring stiffness (Ks) and damping coefficient (Cs), are assumed to remain constant, indicative of a passive suspension configuration. Further, the tire stiffness (Kt), expressed in Newtons per meter, assumes significance in the analysis. The model also accounts for vertical displacements, denoted as Zs for the sprung mass, Zu for the un-sprung mass, and Zf for the road surface, thus enabling a comprehensive assessment of the vehicle's dynamic response and ride comfort [7]. The fundamental constituents of a passive suspension system comprise the spring and damper configured in parallel. Unquestionably, the efficacy of a passive suspension system is contingent upon the precise attributes of these components, notably the stiffness of the spring and the damping coefficient. Although semi-active and active suspension systems afford the benefit of adjustable damping, it is pertinent to acknowledge that attaining variable stiffness necessitates intricate mechanisms. Hence, the predominant reliance on the fixed stiffness of springs persists across the majority of vehicles. [8]. This paper aims to investigate the influence of spring stiffness on both the overall ride comfort and the handling characteristics of vehicles. In doing so, Reichart delves into the etymology

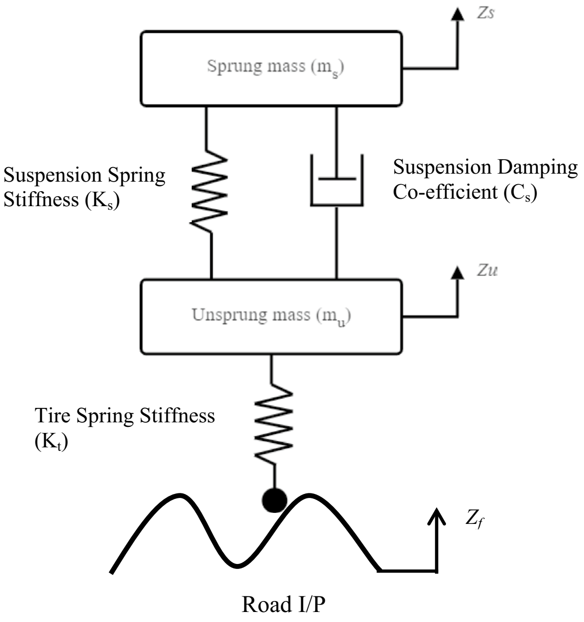


Fig. 2 Motorcycle suspension

of the term "comfort," elucidating its origins in the Latin word "confortare." [9]. A smooth and comfortable ride (Rc) is defined by the absence or minimal influence of road-induced vibrations experienced by the passenger. As stipulated by the ISO 2631–1-1997 standard, the degree of comfort in the ride is positively correlated with a lower acceleration of the sprung mass [10]. Road holding (Rh) denotes the capacity of a vehicle to leverage road friction for the efficient transmission of forces between the wheels and the road surface. The efficacy of this capability is contingent upon a confluence of factors, encompassing both the prevailing road conditions and the intrinsic characteristics of the vehicle itself [11]. In India, speed regulations vary according to geographical region and vehicle classification. As of 2018, the central government standardized speed limits for distinct categories of roadways: highways set at 120 km/h, national highways at 110 km/h, and urban roads at 70 km/h, specifically applicable to M1 vehicles, primarily encompassing passenger cars with a seating capacity of fewer than 8 individuals. It is noteworthy that individual states and local governing bodies possess the jurisdiction to stipulate speed restrictions below the national directives.

Table 1 presents the prescribed speed thresholds for motorcycles and passenger cars within Maharashtra, India. Motorcycles are constrained to a maximum speed of 50 km per hour, whereas passenger vehicles are permitted to travel at speeds of up to 65 km per hour. Strict adherence to these speed regulations is paramount to ensure the safety of motorists and pedestrians alike. Speeding stands as a significant contributing factor to road accidents, often resulting in grave injuries or fatalities [12]. To comprehensively assess the efficacy of passive suspension systems in terms of ride comfort and stability, it becomes imperative to integrate specific hardware and software components for thorough analysis and evaluation.

In assessing the comfort attributes of a ride, a suite of components is deployed, encompassing the Data Acquisition System (DAQ), accelerometer, and NI LabVIEW software. Central to this process is the utilization of a data acquisition system (DAQ) to capture data stemming from diverse physical occurrences. The primary role of this system is to acquire critical signals, which are subsequently transmuted from their initial analog manifestation (electrical signals) into a digital format, thereafter meticulously overseen by a computer for further analysis and management. [13]. Accelerometers serve as instrumental devices employed in the assessment of vibrational dynamics or motion acceleration within structural entities. Functionally, they operate by transducing the force resultant from vibration or acceleration into an electrical charge. The magnitude of the electrical charge generated correlates directly with the force acting upon the accelerometer. Given a constant mass for the accelerometer, this electrical charge is also directly proportional to the acceleration experienced. NI LabVIEW, a sophisticated software solution, finds application in the realms of testing, automation, measurement, and system monitoring, providing comprehensive capabilities to facilitate these endeavors [14]. NI LabVIEW stands as a robust software solution employed for real-time data processing, enjoying widespread adoption across industries, particularly in the realm of process control. Its efficacy is augmented by a plethora of optional libraries and modules, thereby broadening its applicability across diverse domains [15]. Outputs generated by NI LabVIEW predominantly manifest in both the time and frequency domains, affording users comprehensive insights into data dynamics across temporal and spectral dimensions.

Table 1 Speed limit for vehicles in Maharashtra State

State	Motorcycle	Medium passenger vehicle
Maharashtra, India	50 km/h	65 km/h

In the realm of signal analysis, the time domain elucidates the behavior of mathematical functions and physical signals relative to time. It is recognized that these signals exhibit varying values across all real numbers in continuous-time or discrete instances in discrete-time settings. Visual representations in the time domain graphically illustrate the temporal evolution of signals over time intervals. Conversely, the frequency domain graphically portrays the distribution of signal energy across different frequency bands over a spectrum of frequencies. Through the examination of a function or signal's temporal evolution, the time domain affords insights into its dynamic behavior and inherent characteristics. Moreover, the frequency domain representation not only captures the amplitude, or strength, of individual frequency components but also encodes information pertaining to phase shifts associated with each sinusoidal component. This phase information facilitates the synthesis of frequency components to reconstruct the original time signal accurately [16]. The Fast Fourier Transform (FFT) has emerged as an indispensable tool, particularly in the realm of high-speed signal and image processing. Employing this transformative technique, signals can be seamlessly transitioned into the frequency domain, facilitating streamlined filtering and correlation processes with reduced computational overhead [17]. These time-domain signals exhibit variability in accordance with input vibrations and spring stiffness parameters.

In conventional passive suspension systems, springs exhibit a predetermined stiffness, maintaining consistent resistance to compression or extension across their operational range. The passive suspension system encompasses five distinct settings, designated from Setting no. 1 to Setting no. 5, facilitating customization in spring stiffness. Setting 1 signifies the lowest stiffness, while Setting 5 denotes the highest. With an ascending adjustment from Setting 1 to Setting 5, the spring stiffness intensifies, and conversely, diminishes when decreasing the setting. This dynamic presents a delicate equilibrium between ride comfort and handling characteristics: Elevated spring stiffness enhances handling prowess by curbing body roll, thereby bolstering vehicle stability during cornering and maneuvers. However, this enhancement comes at the expense of comfort, as stiffer springs attenuate the absorption of road irregularities, yielding a rougher ride quality. Conversely, softer springs augment comfort by effectively cushioning against road imperfections, culminating in a smoother ride experience. Nonetheless, this compromise may compromise handling dynamics, manifesting as an increased body roll that undermines stability and precision during maneuvers. Notably, the relationship between ride comfort and road holding is inversely proportional, necessitating a comprehensive evaluation of a vehicle's performance in comparison with the prevailing road conditions to ascertain its overall efficacy.

In the evaluation of passive suspension systems, two primary road conditions are conventionally scrutinized: on-road and off-road terrains. These conditions serve as the basis for conducting real-time road assessments [18]. Within the automotive sector, the real-world testing of motorcycles holds significant importance. This methodological approach entails evaluating a motorcycle's performance and overall functionality within authentic riding environments. It serves as a practical complement to the extensive research and development endeavors, functioning as a validation platform for the motorcycle's design and engineering attributes. During the analysis phase, careful consideration is given to the selection of an appropriate road segment, ensuring the relevance and efficacy of the testing process.

Selecting an appropriate road segment is paramount to obtain precise and actionable suspension testing data. Several considerations should guide this selection process. Firstly, opt for a road patch resembling the surfaces where the suspension will undergo testing, encompassing variations such as smooth pavements, cobblestones, potholes, or irregular bumps. Additionally, ensure that the chosen test section offers sufficient length to conduct uninterrupted tests at the desired velocity, facilitating comprehensive evaluation of suspension performance across diverse conditions. Moreover, the designated road segment should possess adequate width to accommodate the vehicle comfortably and securely, allowing for seamless maneuverability and safe placement of testing apparatus. By adhering to these criteria, researchers can optimize the accuracy and utility of suspension testing endeavors. This paper provides a thorough analysis of the shock absorption behavior and vibration characteristics of a vehicle's passive suspension system under diverse operating conditions and configurations. The novelty of this study lies in its systematic approach to elucidating the intricate interactions between suspension setup, vehicle speed, and dynamic performance. Key contributions of this research include the identification of optimal shock absorption settings and a detailed examination of vibration frequencies and amplitudes. Section 2 delineates the experimental configuration and testing procedures, providing insight into the methodological approach. Subsequently, Sect. 3 offers a thorough exposition and analysis of the obtained results, emphasizing the benefits associated with different spring configurations. Finally, Sect. 4 encapsulates the research findings and offers conclusive remarks on the implications and potential avenues for further investigation.

2 Experimentation

To evaluate the performance of the adjustable passive suspension system, a comprehensive real-time road test was executed to assess the impact of road vibrations on human physiological response. This entailed the utilization of a data acquisition system (DAQ) integrated with NI LabVIEW software. Throughout the testing protocol, the parameters of spring mass, un-sprung mass, and road conditions remained constant. The examination was conducted across varying speeds, specifically 20, 40, and 60 km/h, with data readings recorded at each setting of the adjustable passive suspension system ranging from 1 to 5. Subsequently, the gathered data will undergo rigorous analysis to ascertain the optimal suspension setting conducive to enhancing ride comfort.

2.1 Motorcycle setup

Figure 3 depicts the motorcycle configuration utilized during testing procedures. The visual representation showcases a motorcycle arrangement employed for real-time road assessments, specifically focusing on the scrutiny of its passive suspension system. The Motorcycle Setup delineates the positioning of accelerometers and their connectivity to a laptop via a Data Acquisition System (DAQ), indicative of an investigative endeavor wherein engineers or researchers are endeavoring to juxtapose the efficacy of the passive suspension system in managing external forces and vibrations. The

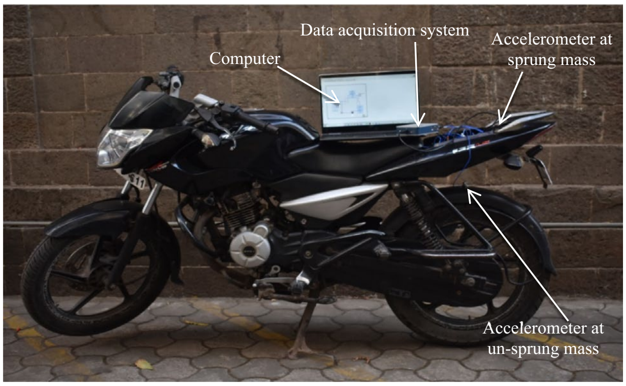


Fig. 3 Motorcycle setup for testing

Fig. 4 Accelerometer, DAQ Chassis and NI-9234 module

laptop serves as a central hub for data collection, storage, and analysis derived from the accelerometers. Accelerometers, instrumental devices utilized herein, are tasked with gauging vibrations and forces across distinct sections of the motorcycle. Within this context, the term "sprung" pertains to components upheld by the passive suspension system, whereas "un-sprung" denotes sections devoid of suspension support.

2.2 Hardware

Figure 4 illustrates an accelerometer deployed for testing purposes. An accelerometer serves as a pivotal device for quantifying the vibration or acceleration of a moving object. Operating on the principle of mass-induced pressure on piezoelectric elements, it translates mechanical stimuli into electrical signals. These signals directly correlate with the applied force on the sensor. Additionally, Fig. 4 depicts a Data Acquisition (DAQ) system, an instrumental component facilitating the measurement of acceleration in conjunction with the accelerometer. Widely adopted in domains like vibration analysis and motion detection, the DAQ system plays a pivotal role in acquiring and processing crucial data points. Table 2 shows the accelerometer specifications. Table 3 shows the DAQ specifications and Table 4 present the NI 9234 acceleration module specifications.

2.3 Software

Figure 5 illustrates the LabVIEW code utilized in the testing process. LabVIEW, developed by National Instruments, stands as a robust programming tool specifically tailored for engineers and scientists. Renowned for its user-friendly interface and diverse capabilities, LabVIEW finds extensive utility across various domains, including data acquisition, instrument control, industrial automation, image processing, and scientific computations. The integration of LabVIEW facilitated the establishment of necessary hardware-software connections, enabling the direct transfer of acceleration data into Excel in a numerical format. Furthermore, it facilitates the visualization of data in both time and frequency domains.

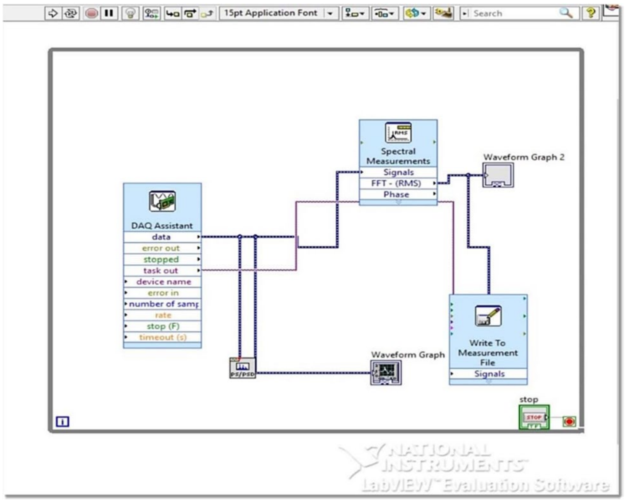


Fig. 5 NI LabVIEW coding

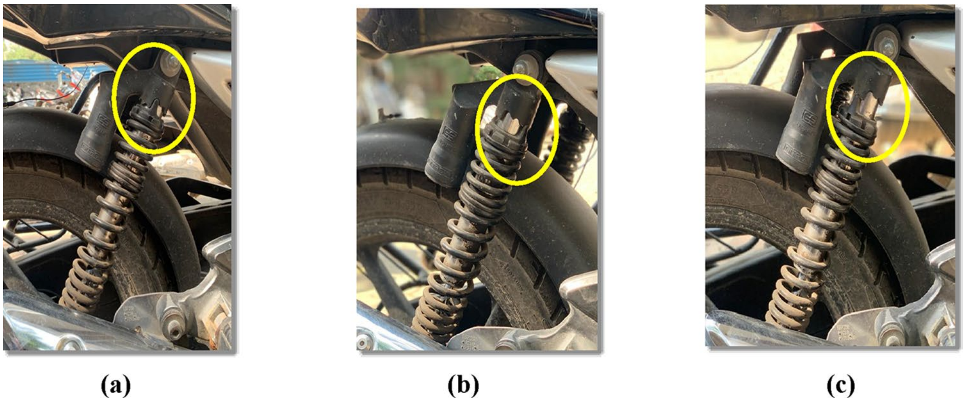
The depicted diagram exemplifies a LabVIEW application for data acquisition (DAQ), with key components such as the DAQ Assistant, a pivotal block responsible for configuring and managing DAQ tasks.

The subsequent phase in our data processing and visualization journey involves leveraging sophisticated tools tailored for comprehensive analysis. Within this framework, the Waveform Graph module emerges as a pivotal component, facilitating real-time visualizations of acquired data. Complementing this, the Spectral Measurements feature comprises specialized blocks specifically designed for frequency analysis of signals. Among these, the FFT (RMS) module stands out, harnessing the power of Fast Fourier Transform (FFT) algorithms to derive the frequency spectrum while potentially incorporating Root Mean Square (RMS) computations for amplitude assessment. Additionally, the PS/PSD functionality, offering Power Spectrum or Power Spectral Density analysis, enables advanced frequency scrutiny, while Phase analysis delves into the phase characteristics of signal components. These capabilities hold particular relevance in the realm of Vibration Monitoring, where our system may be tasked with assessing vibrations in machinery or structures. Through spectral measurements, we can pinpoint significant frequencies and identify potential sources of concern, facilitating proactive problem mitigation and enhanced operational efficiency.

2.4 Suspension setting

In Fig. 6, five suspension notches delineate the stiffness of the spring, with the first notch representing the least stiffness and the fifth notch denoting the highest stiffness. This configuration plays a pivotal role in defining the comfort level of the ride. To comprehensively assess the impact of distinct

Fig. 6 Adjustable suspension settings (**a**-setting 1, **b**-setting 3, **c**-setting 5)



suspension settings, a sequence of tests was conducted under constant velocities of 20, 40, and 60 km per hour (km/h). Across each velocity setting, uniform parameters such as the sprung mass of the vehicle's supported components, the unsprung mass of the vehicle's unsupported components, and the conditions of the road patch remained consistent. The overarching objective of this experimental endeavor was to ascertain an optimal suspension setting conducive to urban road conditions. Such an approach facilitated a detailed examination of suspension dynamics across diverse operational scenarios.

2.5 Road-test patch

Road patches serve as controlled simulations replicating common road hazards such as bumps, potholes, and uneven terrain, enabling researchers to scrutinize passive suspension system responses under controlled conditions. Figure 11 delineates the designated section of the road utilized for all tests and experiments. In the context of passive suspension system evaluation, the term "road test patch" does not denote a physical alteration to the road surface; rather, it refers to a specific segment engineered to rigorously assess the system's performance under varied conditions. This purpose-built testing track incorporates features such as bumps, potholes, rugged terrain, sharp turns, and gradients By traversing this patch, specialists can analyze how the suspension mitigates shocks, sustains tire traction, dampens vibrations, manages lateral forces, and distributes weight effectively, ensuring a comfortable, controlled, and stable ride. The configuration of five suspension notches in Fig. 7 delineates spring stiffness levels, ranging from least to highest stiffness, significantly impacting ride comfort. To comprehensively evaluate distinct suspension settings, a series of tests were conducted at constant velocities of 20, 40, and 60 km per hour (km/h), maintaining uniform parameters such as vehicle sprung and un-sprung masses, and consistent road patch conditions.

The overarching objective of these experiments was to identify optimal suspension configurations suited for urban road conditions, enabling detailed analysis of suspension dynamics across diverse driving environments. While road patches play a specific role in motorcycle testing, offering insights into suspension responses to various road conditions and low-speed handling, a diversified route incorporating different terrain features remains invaluable for comprehensive testing. Such an approach allows for a thorough assessment of motorcycle performance, complemented by closed-course settings and data-logging tools to ensure safety and efficacy in testing environments.

Fig. 7 Road patch

Table 2 Accelerometer specifications

Sensitivity	(± 10%)100 mV/g
Measurement range	± 50 g pk
Broadband resolution	(1 to 10,000 Hz) 0.00015 g rms
Frequency range	(± 5%) 0.5 to 10,000 Hz
Sensing element	Ceramic

3 Results and discussion

3.1 Output

Table 5 presents the outcomes of vibration assessments conducted on diverse segments of a machine or vehicle's suspension infrastructure. Figure 8 delineates the graphical representation of vibrational data, with the horizontal axis (X-axis) denoting frequency in Hertz (Hz), elucidating the frequency of vibrational occurrences per second. Concurrently, the vertical axis (Y-axis) portrays RMS acceleration in meters per second squared (m/sec^2), serving as a measure of the average intensity of vibrations sustained over time.

Table 6 presents the outcomes of an examination conducted at the peak of acceleration for a spring-mass system. It encompasses five configurations (1, 2, 3, 4, and 5) and three distinct velocities (20, 40, and 60 km/h).

Table 3 DAQ specifications

Name	CDAQ-SV1101 bundle
Slot	1
No. of channel	4 (51.2 kS/s/channel)
Sound and vibration capacity	± 5 V

Table 4 NI 9234 acceleration module specifications

No. of channels	4 analog input channels
ADC resolution	24 bits
Frequency	13.1072 MHz
Accuracy	± 50 ppm maximum

3.2 Data interpretation

Figure 9 shows, in the 1st setting, both the sprung and unsprung accelerations register as the lowest compared to other configurations, indicative of superior ride comfort and vehicle stability.

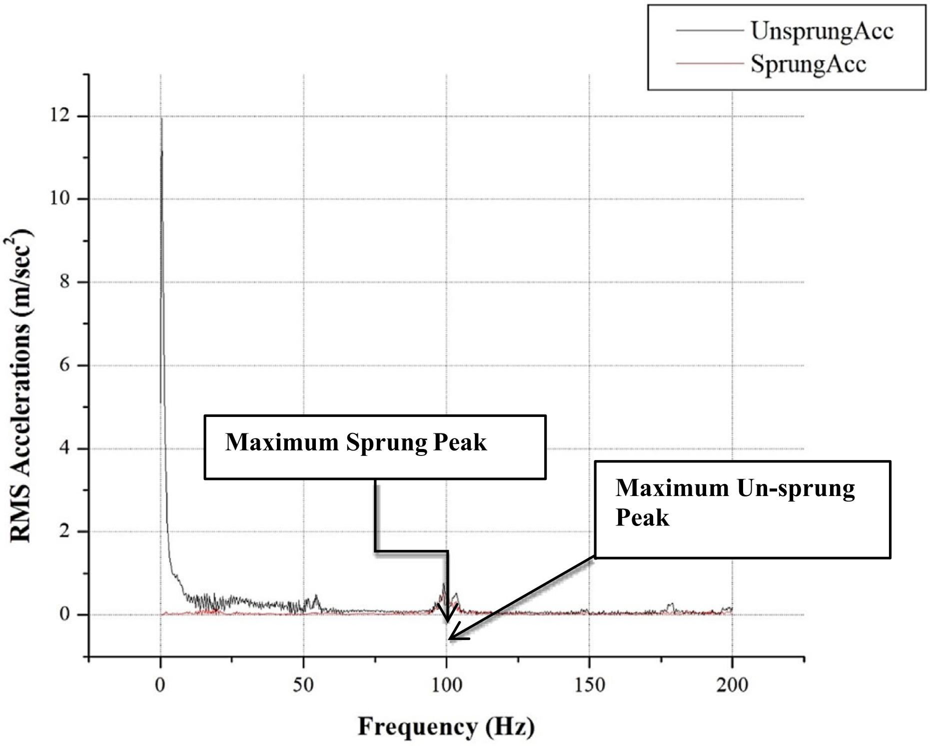
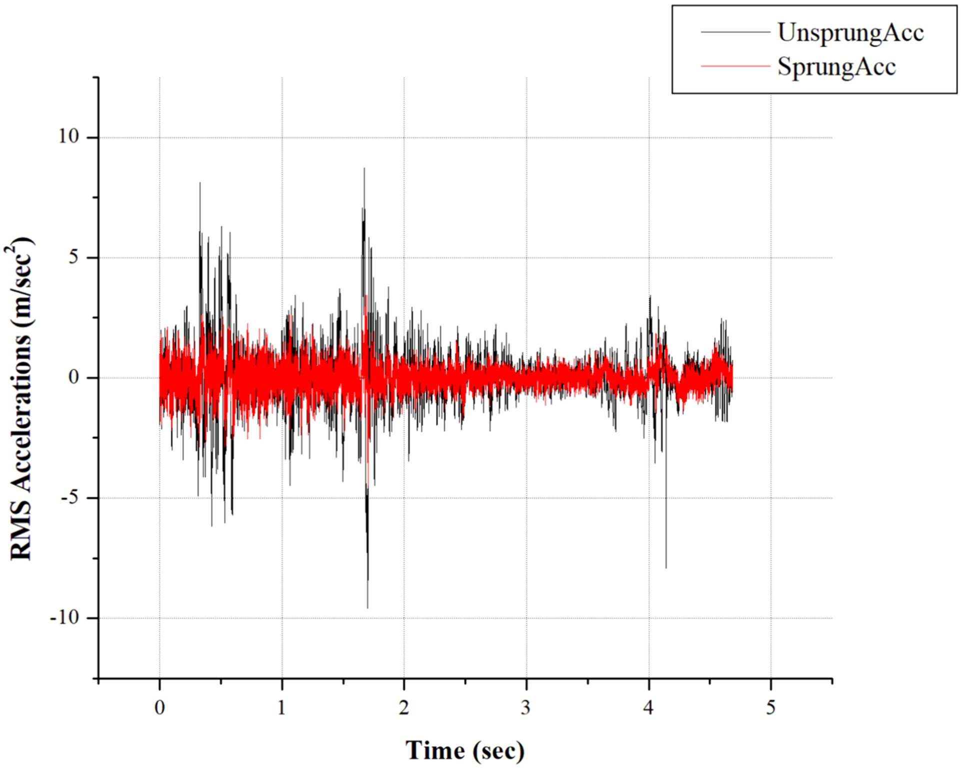


Fig. 8 Variation in RMS acceleration (Frequency domain)

Fig. 9 Variation in acceleration (Time domain)



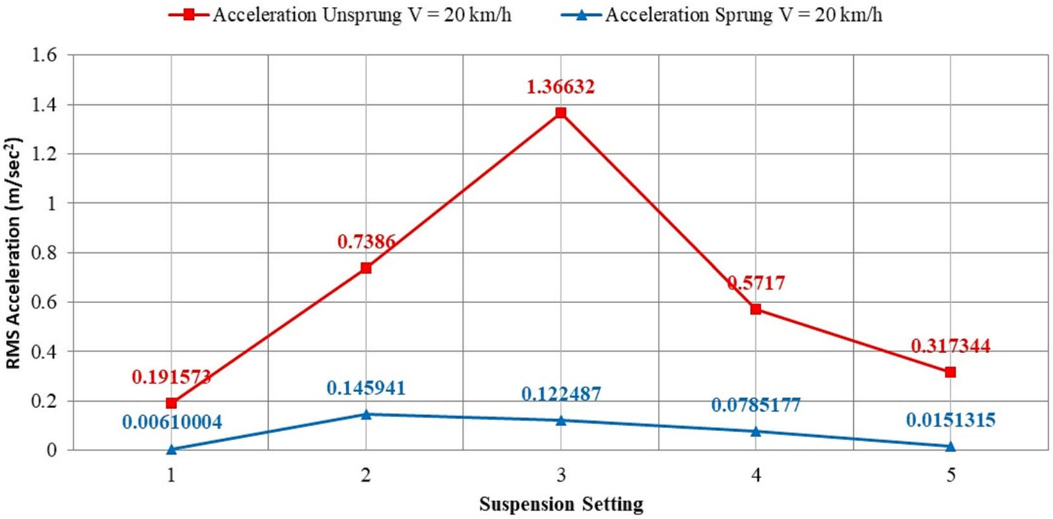


Fig. 10 Variation in RMS accelerations with setting

Figure 10 shows, in the 1st setting, both the sprung and un-sprung accelerations register as the lowest among all settings, indicative of superior ride comfort and vehicle stability (Fig. 11).

Figure 12 shows, at the 4th setting, both the sprung and un-sprung accelerations register the lowest values compared to other settings, indicative of enhanced ride comfort and vehicle stability.

3.3 Shock Absorption rate

Percentage Shock Absorbed serves as a pivotal metric for assessing the efficacy of a sports floor or automotive shock absorber in mitigating impact forces.

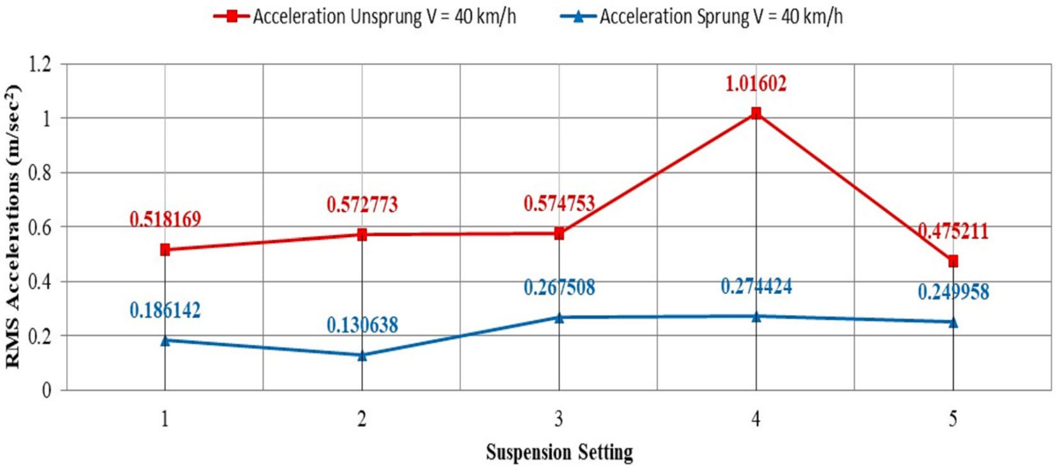


Fig. 11 Variation in RMS accelerations with setting

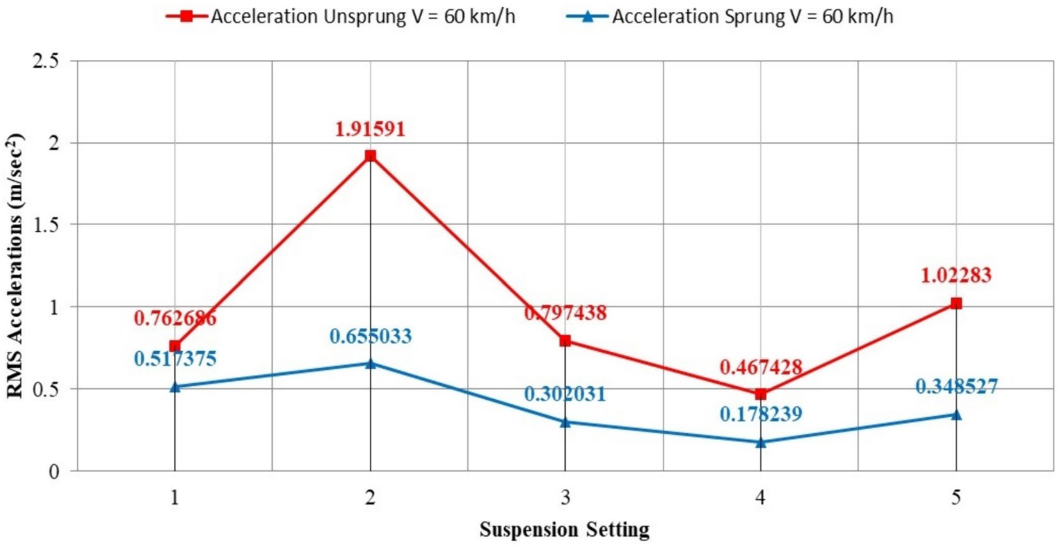


Fig. 12 Variation in RMS accelerations with setting

The mathematical formula for calculating Percentage Shock Absorption is,

$$\text{Percentage Shock Absorption} = \frac{(\text{Accelerations caused due to Unsprung Mass})}{(\text{Accelerations caused due to Sprung Mass})} \times 100$$

$$= \frac{Zu}{Zs} \times 100$$

The data collected by Real Time Road Test is as follows:

The Fig. 13 illustrates the percentage of shocks absorbed at different suspension settings and speeds.

3.4 Discussion

The data presented provides a comprehensive analysis of the vibration characteristics and shock absorption behavior of a vehicle's passive suspension system across various operating conditions and settings.

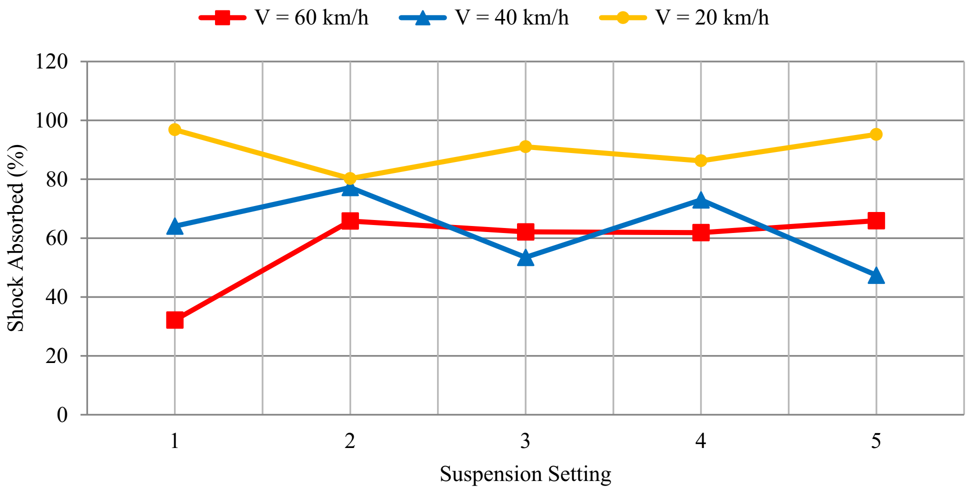


Fig. 13 Percentage shock absorbed by suspension

3.4.1 Vibration analysis

The data in Tables 5 and 6 provides valuable insights into the vibration frequencies and amplitudes affecting the passive suspension system components. The "Frequency Un-sprung (FFT-(RMS))" column indicates the vibration frequencies experienced by the un-sprung components, which are not directly integrated into the suspension mechanism. This data is derived from a combination of Fast Fourier Transform (FFT) and Root Mean Square (RMS) analyses, offering a detailed understanding of the vibration frequencies. The subsequent "Amplitude Un-sprung" column delineates the corresponding vibration amplitudes manifesting on the un-sprung components. The remaining columns in the table are expected to follow a similar schema, potentially furnishing vibration details pertaining to the sprung components (those interfacing with the suspension) at various locations. This comparative analysis of vibration frequencies and amplitudes across different sections of the suspension network enables operators to discern the trajectory of vibration propagation and optimize suspension efficacy. Figure 9 further elucidates the graphical representation of the vibrational data, with the horizontal axis (X-axis) denoting frequency in Hertz (Hz) and the vertical axis (Y-axis) portraying RMS acceleration in meters per second squared (m/sec^2). The discrepancy between the sprung acceleration (representative of vehicle body movement) and the un-sprung acceleration (representative of wheel movement) underscores the effectiveness of the passive suspension system in attenuating the transmission of road-induced vibrations to the vehicle. The discernible peaks in the acceleration profiles signify resonant frequencies, where the system experiences heightened vibrational activity. The analysis of vibration data using Fast Fourier Transform (FFT) functions provided a powerful tool for examining the frequency content of signals. The "FFT VI" and "FFT Power Spectrum and PSD VI" offer versatile options for visualizing the frequency-domain representation of the signals, enabling engineers to identify and analyze the critical vibration frequencies affecting the passive suspension system.

Table 5 Sample output data from sensors

Frequency–Un-sprung/ Sprung (FFT—(RMS))	Amplitude–Un-sprung (FFT—(RMS))	Amplitude—Sprung (FFT—(RMS))
0	6.59041	0.00122931
0.213333	13.7967	0.00162765
0.426667	13.3049	0.00256805
0.64	8.64708	0.00280119
0.853333	6.15879	0.00703365
1.066667	5.38646	0.0172954
1.28	4.86846	0.0315865
1.493333	3.97348	0.0521817
1.706667	3.03396	0.0644858
1.92	2.46276	0.0637325
2.133333	2.17892	0.0558555
2.346667	1.89518	0.0322876
2.56	1.56935	0.0165617

3.4.2 Shock absorption analysis

The data presented in Table 7 and the accompanying discussion, provide insights into the dynamic behavior of the spring-mass system under different suspension configurations and velocities. The table delineates the maximum acceleration points for both the sprung (vehicle body) and un-sprung (wheel) masses across five configurations (1, 2, 3, 4, and 5) and three distinct velocities (20, 40, and 60 km/h).

At a speed of 20 km/h, the findings suggest that in settings 1, 2, and 4, the maximum acceleration point for the sprung

Table 6 Data of the maximum frequency peak of the sprung and sprung mass acceleration

Setting	Speed (km/hr)	Maximum peak of acceleration of un-sprung mass (m/s^2)	Maximum peak of acceleration of sprung mass
1	20	0.191573	0.00610004
	40	0.518169	0.186142
	60	0.762686	0.517375
2	20	0.7386	0.145941
	40	0.572773	0.130638
	60	1.91591	0.655033
3	20	1.36632	0.122487
	40	0.574753	0.267508
	60	0.797438	0.302031
4	20	0.5717	0.0785177
	40	1.01602	0.274424
	60	0.467428	0.178239
5	20	0.317344	0.0151315
	40	0.475211	0.249958
	60	1.02283	0.348527

Table 7 Percentage shock absorbed at each setting

Setting	$V=20$ km/h	$V=40$ km/h	$V=60$ km/h
1	96.81581434	64.07697103	32.1640885
2	80.24086109	77.19201149	65.81086794
3	91.0352626	53.45687626	62.12482977
4	86.26592619	72.99029547	61.86813798
5	95.23183044	47.40062835	65.92522707

mass exceeds that of the un-sprung mass. However, at higher velocities (40 and 60 km/h), the highest acceleration point for the un-sprung mass surpasses that of the sprung mass in settings 1 and 3. Setting 2 at a velocity of 40 km/h demonstrates a higher maximum acceleration point for the sprung mass compared to the un-sprung mass, while at a velocity of 60 km/h, setting 2 exhibits a higher maximum acceleration point for the un-sprung mass.

These findings underscore the complex interplay between the passive suspension system's configuration, vehicle speed, and the dynamic behavior of the sprung and un-sprung masses. The passive suspension system's ability to effectively attenuate vibrations and maintain a comfortable ride for the vehicle's occupants is contingent on striking the right balance between these factors. The analysis of shock absorption behavior at different speeds provides further insights. At a speed of 40 km/h, the passive suspension system demonstrates optimal shock absorption efficiency at setting 2, achieving nearly 100% absorption. However, a notable decline is observed at setting 3, highlighting the significance of precise calibration of suspension parameters to maintain desired performance levels. Nevertheless, the system exhibits a commendable level of stability across settings 4 and 5, indicating the potential for maintaining satisfactory shock absorption under varying conditions.

At a speed of 20 km/h, the shock absorption behavior exhibits distinct trends. Initially, absorption commences near 100%, showcasing a high level of damping effectiveness. However, there is a discernible decrease to approximately 80% upon transitioning to setting 2, indicating a slight reduction in damping efficiency. Interestingly, absorption levels rise once more to nearly 100% at setting 3, suggesting a reversion to optimal damping performance. Subsequently, a steady decline is observed through settings 4 and 5, underscoring a diminishing shock absorption capacity as suspension settings progress.

At a speed of 60 km/h, the shock absorption behavior follows a different pattern. At suspension setting 1, the absorption stands at approximately 40%. As the setting progresses to 2, it notably improves, reaching around 80%. However, at setting 3, there is a decline, settling at approximately 60%. Remarkably, the absorption remains relatively stable across settings 4 and 5.

These findings highlight the nuanced fluctuations in shock absorption across various suspension settings and vehicle speeds, providing valuable insights for optimizing vehicle dynamics and ride comfort. The passive suspension system's ability to effectively attenuate shock and vibrations is crucial for ensuring both safety and a comfortable driving experience.

3.4.3 Optimization considerations

The data and analysis presented in the search results emphasize the critical importance of striking a balance between performance and stability in the design and optimization of vehicle suspensions. The inherent trade-off between ride comfort and handling characteristics underscores the need for a tailored approach to passive suspension system configuration.

The findings suggest that the optimal suspension settings depend on the specific driving conditions and individual driver preferences. While superior shock absorption might seem desirable, empirical testing highlights that it does not guarantee an inherently comfortable or stable ride. This underscores the nuanced interplay of passive suspension system components, such as spring rigidity, damping characteristics, and geometric design, all working in concert to achieve an optimal balance.

Remarkably, the data demonstrates that it is feasible to achieve both reduced shock absorption and enhanced ride comfort and stability. This suggests that judicious engineering and design choices can facilitate a harmonious equilibrium, even if shock absorption is not the primary focus.

The analysis of maximum acceleration points for the sprung and un-sprung masses further emphasizes the importance of considering the specific configuration and velocity parameters. The findings indicate that the relationship between these acceleration points can vary, highlighting the need for a comprehensive understanding of the system's dynamic behavior under different operating conditions.

4 Conclusions

The data and analysis presented in the search results provide a comprehensive understanding of the vibration characteristics and shock absorption behavior of a vehicle’s passive suspension system. The insights gained from the tabulated data, graphical representations, and LabVIEW-based signal analysis offer valuable guidance for the design and optimization of passive suspension systems.

By understanding the nuances of vibration propagation, the dynamic interactions within the passive suspension system, and the trade-offs between ride comfort and handling characteristics, manufacturers can enhance the overall performance, safety, and user experience of their vehicles. The ability to strike the right balance between these factors is crucial for developing passive suspension systems that cater to a wide range of driving conditions and user preferences.

The findings underscore the importance of continuous monitoring, precise calibration, and the exploration of advanced suspension technologies to achieve optimal suspension performance. By leveraging these insights, engineers can design and implement passive suspension systems that deliver a smooth, stable, and responsive driving experience, ultimately enhancing the overall quality and safety of the vehicle.

- Suspension trade-offs: The test results underscore a fundamental aspect of suspension design: the absence of a one-size-fits-all or perfect configuration. A passive suspension system that delivers a smooth ride at lower speeds may compromise stability at higher velocities, illustrating the inherent trade-off between comfort and control.
- Optimal performance: The analysis reveals that setting 2 demonstrates optimal shock absorption efficiency at both 60 km/h and 40 km/h speeds. However, a notable decline is observed at setting 3, underscoring the significance of precise calibration of suspension parameters to maintain desired performance levels.
- Stability across settings: The system exhibits a commendable level of stability across settings 4 and 5, indicating the potential for maintaining satisfactory shock absorption under varying conditions.
- Interplay of suspension components: The findings demonstrate that it is feasible to achieve both reduced shock absorption and enhanced ride comfort and stability. This suggests that judicious engineering and design choices can facilitate a harmonious equilibrium, even if shock absorption is not the primary focus.
- Correct Suspension Configuration: Correctly configuring a motorcycle's suspension is paramount to an enjoyable driving experience. These settings significantly influence ride comfort and on-road handling characteristics.

This study on vehicle’s passive suspension system highlights promising avenues for future research and development. Exploring the effects of different suspension settings on various road conditions (On-road and Off-road) would provide a more comprehensive understanding. Studying the impact of driver preferences and developing personalized suspension configurations could lead to tailored solutions. Maintaining precise calibration, striving for balanced performance, and exploring advanced suspension technologies can contribute to enhanced vehicle dynamics and safety. Investigating advanced suspension designs, such as semi-active or active–passive systems, could potentially yield significant improvements in performance and stability. However, these sophisticated suspension technologies are often highly expensive and may not be the most practical or reliable solution for the unique road conditions commonly found in India. As a result, the researchers had to explore more cost-effective and durable alternate methods to enhance comfort and stability, without compromising on the specific challenges presented by the local driving environment. Overall, the future scope encompasses a multifaceted approach to advancing the state-of-the-art in vehicle suspension systems.

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