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Dynamic Characteristics and Optimal Design of Rubber Vibration Isolation Mounts for Construction Machinery Cabs: A Review

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Abstract

Construction machinery operators are frequently exposed to low-frequency and multi-directional vibration generated by uneven terrain, tire–soil interaction, vibrating drums, powertrain excitation, and working attachments. These vibration sources are transmitted to the cab through the vehicle frame and cab mounting system, affecting ride comfort, operational accuracy, and long-term occupational health. Rubber isolation mounts remain widely used in construction machinery cabs because of their simple structure, low cost, compact layout, and robustness under harsh working environments. However, their vibration isolation performance is strongly governed by dynamic stiffness, damping, preload, excitation frequency, vibration amplitude, temperature, aging, and installation layout. Therefore, rubber mounts should not be treated as ideal linear spring–damper elements in the design of cab isolation systems. This review summarizes the dynamic characteristics, modeling methods, experimental identification, and optimal design strategies of rubber vibration isolation mounts for construction machinery cabs. Particular attention is paid to vibratory rollers and earth-moving machinery, where cab low-frequency shaking and whole-body vibration are critical issues. Previous studies show that optimized rubber mounts can improve ride comfort, but their low damping and high dynamic stiffness often limit performance in the low-frequency range. Recent developments therefore combine rubber mounts with hydraulic damping, pneumatic elements, semi-active control, and multi-objective optimization. Finally, the review identifies research gaps related to nonlinear rubber characterization, multi-directional cab vibration, terrain-dependent excitation, experimental validation, and integrated optimization. The review provides a technical basis for the future design of rubber isolation mounts for construction machinery cab.

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Keywords: rubber mount, cab isolation, construction machinery, ride comfort, whole-body vibration, dynamic stiffness, optimal design

1. Introduction

Vehicle vibration is caused by several excitation sources, including road unevenness, tire-road interaction, powertrain onstruction machinery such as vibratory rollers, wheel loaders, compactors, excavators, and earth-moving vehicles often operates under severe working conditions. Unlike road vehicles, these machines are subjected not only to road roughness but also to deformable soil, impact excitation, vibration from working devices, and low-speed operation on irregular terrain. In vibratory rollers, the rotating eccentric mass of the drum generates periodic excitation, while the nonlinear drum–soil interaction further amplifies vibration transmitted to the vehicle frame and cab. For wheel loaders and similar machines, bucket loading, braking, pitching motion, and uneven ground also produce significant low-frequency vibration. As a result, the cab becomes a key transmission path through which vibration reaches the operator.

The vibration isolation system of the cab is therefore one of the most important subsystems for improving operator ride comfort. Rubber mounts are still the most commonly used cab isolation elements because they are compact, inexpensive, reliable, and easy to manufacture. In practice, a cab is usually supported by four or more rubber mounts arranged between the cab floor and the vehicle frame. The basic design task is to select suitable stiffness, damping, mounting position, and installation angle so that the vibration transmitted from the chassis to the cab is reduced without causing excessive cab motion or resonance.

Construction machinery such as vibratory rollers, wheel loaders, compactors, excavators, and earth-moving vehicles often operates under severe working conditions. Unlike road vehicles, these machines are subjected not only to road roughness but also to deformable soil, impact excitation, vibration from working devices, and low-speed operation on irregular terrain. In vibratory rollers, the rotating eccentric mass of the drum generates periodic excitation, while the nonlinear drum–soil interaction further amplifies vibration transmitted to the vehicle frame and cab. For wheel loaders and similar machines, bucket loading, braking, pitching motion, and uneven ground also produce significant low-frequency vibration. As a result, the cab becomes a key transmission path through which vibration reaches the operator.

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For construction machinery, the low-frequency range is particularly important. Kordestani *et al.* [2] investigated the ride vibration environment of soil compactors and showed that operators can be exposed to significant vibration during machine operation. Sun and Zhang [4] further analyzed earth-moving machinery cabs supported by hydraulic mounts and highlighted the importance of low-frequency pitch and roll vibration. In this context, rubber mounts are effective for high-frequency vibration and noise isolation, but their performance is often limited when the cab is excited in the low-frequency range.

A series of studies has been conducted on cab vibration isolation systems of vibratory rollers. Quynh *et al.* [7] analyzed low-frequency cab shaking and proposed an optimal design approach for the cab isolation system of a vibratory roller. Le *et al.* [8] evaluated the ride comfort of vibratory rollers under different soil grounds, showing that terrain conditions have a strong influence on cab vibration. Later, Le and Nguyen [9] combined a nonlinear dynamic model with a multi-objective genetic algorithm to optimize cab isolation parameters. Nguyen *et al.* [10] compared three different cab isolation mounts for an off-road vibratory roller using a nonlinear dynamic model. Nguyen and Le [11] reviewed the development of cab isolation systems for off-road vibratory rollers and pointed out the limitations of traditional rubber mounts in the low-frequency range.

Although substantial progress has been made, the dynamic characteristics and optimal design of rubber vibration isolation mounts for construction machinery cabs remain open research topics. Most existing studies focus on vehicle-level vibration response or lumped-parameter optimization, while fewer works deeply consider the nonlinear dynamic behavior of rubber mounts, the coupling among vertical, pitch, and roll motions, and the relationship between mount design and actual working terrain. This paper reviews the main research directions and discusses future development trends for rubber cab isolation mounts in construction machinery.

2. Dynamic characteristics of rubber isolation mounts for construction machinery cabs

Rubber isolation mounts are usually modeled as elastic and damping elements placed between the cab and chassis. In the simplest form, the vertical force of a rubber mount can be written as a combination of stiffness and damping terms. However, this simplification is only suitable for preliminary analysis. In real applications, rubber mounts exhibit viscoelastic, nonlinear, and frequency-dependent characteristics. Their dynamic stiffness is usually higher than static stiffness and varies with frequency. The damping capacity also changes with excitation amplitude and temperature. Therefore, both static and dynamic properties must be considered during design.

The basic functions of a rubber cab mount include supporting the cab weight, isolating vibration transmitted from the chassis, limiting excessive cab displacement, and reducing structure-borne noise. For construction machinery, these functions must be achieved under severe operating conditions. The cab center of gravity is often located above the mounting plane, which makes pitch and roll vibration more likely to occur. In addition, the frame excitation is not purely vertical; it contains longitudinal, lateral, and rotational components. Hence, the mounting system should be designed as a coupled multi-degree-of-freedom system rather than a set of independent vertical springs.

The key dynamic parameters of rubber mounts include static stiffness, dynamic stiffness, loss factor, damping coefficient, preload, natural frequency, and transmissibility. Static stiffness determines the cab static deflection and installation height. Dynamic stiffness affects the vibration transmission path. Damping reduces resonance amplitude but may increase force transmission at higher frequencies. A mount with very low stiffness can improve vibration isolation at high frequencies, but it may cause excessive cab displacement and low-frequency shaking. Conversely, a mount with high stiffness improves cab stability but transmits more vibration to the operator.

Previous studies on vibratory rollers have shown that traditional rubber mounts can reduce some vibration components but are not always effective in suppressing cab low-frequency shaking. Nguyen and Le [11] summarized the development of cab isolation systems for off-road vibratory rollers and reported that traditional rubber mounts are widely used but limited by high stiffness and low damping. The same review also showed that improved rubber mounts, hydraulic mounts, pneumatic mounts, and semi-active hydraulic mounts have been studied to overcome these limitations.

The dynamic behavior of rubber mounts is also influenced by mounting layout. Xu *et al.* [3] showed that mount locations and stiffness distribution affect the natural frequency and modal coupling of a cab isolation system. This is important for construction machinery because the cab is a spatial structure supported by several mounts. If the stiffness distribution is not properly designed, the cab may experience coupled vertical–pitch–roll vibration. In practice, this coupling can lead to a subjective feeling of shaking even when the vertical acceleration is not very high.

Hydraulic damping rubber mounts have been proposed to improve low-frequency isolation performance. Sun and Zhang [4] developed a six-degree-of-freedom cab model supported by hydraulic mounts with nonlinear damping and analyzed the low-frequency characteristics of earth-moving machinery cabs. Liao *et al.* [19] further investigated a hydraulically damped rubber mount with an inertial track, showing that fluid–structure interaction inside the mount can be used to improve damping performance in the low-frequency range. These studies indicate that pure rubber mounts may be insufficient when the cab vibration is dominated by low-frequency pitch and roll motion.

For a review article focused on rubber mounts, it is important to distinguish between three levels of analysis: material level, mount level, and vehicle level. At the material level, the viscoelastic behavior of rubber determines stiffness and damping. At the mount level, geometry, preload, and installation direction determine the force–displacement relationship. At the vehicle level, mount parameters interact with cab mass, center of gravity, chassis vibration, terrain excitation, and seat suspension. A reliable design should connect all three levels.

The main design aspects of rubber cab isolation mounts are summarized in Table 1. These aspects are synthesized from representative studies on nonlinear passive isolators, rubber and hydraulic mounts, cab vibration isolation, and optimization of construction machinery cab suspension systems [1, 3–5, 7–12, 15, 16, 18–20].

Table 1: Main design aspects of rubber cab isolation mounts

Design Aspect	Main Variables	Influence on cab Vibration	Representative References
Material property	Rubber hardness, loss factor, temperature sensitivity, aging	Determines dynamic stiffness, damping capacity, and long-term isolation stability	[1, 5, 18, 19]
Mount geometry	Mount height, diameter, bonded area, void structure, rubber–metal connection	Affects stiffness, damping, load capacity, and nonlinear force–displacement behavior	[3, 4, 11, 19]
Mount layout	Number of mounts, mounting position, installation angle, stiffness distribution	Controls cab natural frequencies and vertical–pitch–roll coupling	[3, 7, 9, 10, 12]
Operating condition	Terrain type, machine speed, load state, drum excitation, frame vibration	Changes excitation amplitude, dominant frequency, and transmitted vibration level	[2, 8, 10, 11, 16]
Optimization target	Weighted seat acceleration, cab pitch/roll angle, transmissibility, relative displacement	Defines the trade-off between ride comfort, cab stability, and mount working space	[7, 9 12, 15, 16, 20]

As shown in Table 1, the performance of rubber cab mounts is governed not only by material stiffness and damping but also by mount geometry, layout, operating condition, and optimization target. Therefore, the design of cab isolation mounts for construction machinery should be treated as a coupled dynamic problem rather than a simple selection of linear stiffness and damping coefficients.

3. Modeling and optimal design approaches

Modeling is the foundation for the design and optimization of cab rubber isolation systems. The most common approach is to build a lumped-parameter dynamic model of the cab, chassis, seat, and mounting system. Depending on the research objective, the model may include vertical, longitudinal, pitch, roll, and seat vibration degrees of freedom. For vibratory rollers, the drum–soil interaction and excitation force from the vibrating drum must also be considered.

Quynh *et al.* [7] focused on low-frequency cab sloshing of a vibratory roller and used dynamic testing and simulation analysis to identify the main causes of cab shaking. Their work is important because it linked the practical phenomenon of cab shaking with the design of the cab isolation system. Instead of only evaluating ride comfort after design, the study attempted to locate the reason for low-frequency vibration and then improve the isolation structure.

Le *et al.* [8] evaluated the ride comfort of a vibratory roller under different soil grounds. This direction is particularly relevant for construction machinery because the excitation source is terrain-dependent. A mount design that performs well on one type of ground may not be optimal under another condition. Therefore, terrain properties should be considered when defining optimization cases for cab isolation systems.

Nguyen *et al.* [10] developed a nonlinear dynamic model of an off-road vibratory roller equipped with three different cab isolation mounts. Their study compared traditional rubber mounts, hydraulic mounts, and pneumatic mounts under different operating conditions. The results showed that hydraulic mounts have a clear advantage in reducing cab vibration compared with traditional rubber mounts. This finding does not mean that rubber mounts are obsolete, but it indicates that the dynamic limitation of rubber mounts should be recognized when designing cab systems for low-frequency vibration environments (see Fig.1).

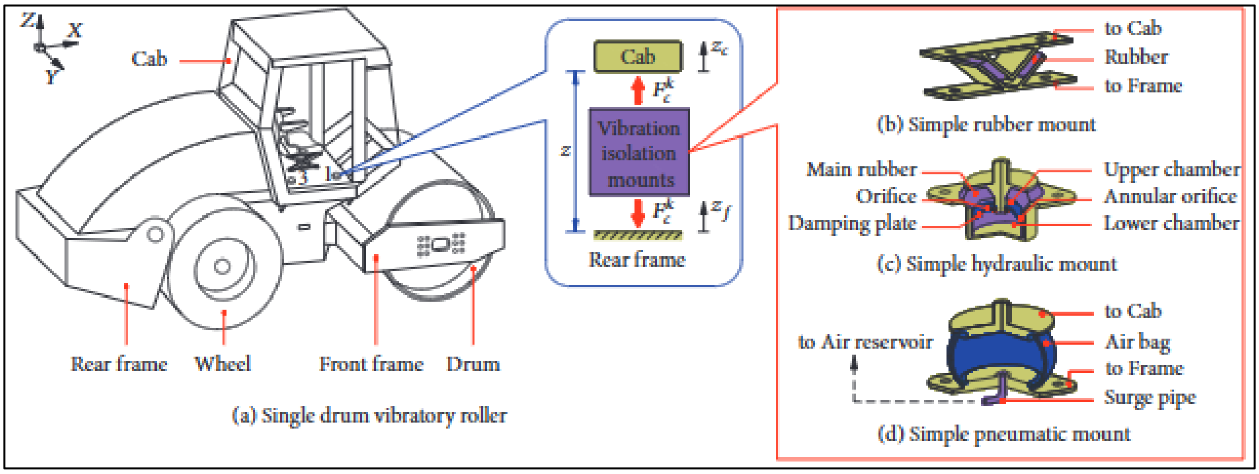

Fig 1: Cab vibration isolation system of a single-drum vibratory roller and representative rubber mounts for low-frequency vibration environments [10].

Optimization methods have been increasingly used to improve cab isolation systems. Le and Nguyen [9] proposed a multi-objective optimization method based on NSGA-II to optimize the design parameters of a cab isolation system for a vibratory roller. The objective functions included the weighted root-mean-square acceleration of the driver's seat and the pitch and roll angles of the cab. This is a suitable optimization framework because ride comfort cannot be represented by a single response index. Reducing vertical acceleration alone may increase pitch or roll vibration, while reducing cab rotation may require higher mount stiffness and increase transmitted vibration. Therefore, multi-objective optimization is more appropriate than single-objective tuning.

Experimental validation is another important aspect. Quynh *et al.* [12] combined experimental modal analysis and optimal design for a single-drum vibratory roller. Modal testing was used to identify natural frequencies and validate the numerical model. This approach is valuable because the actual cab structure may differ from the idealized model due to joint flexibility, frame deformation, manufacturing tolerance, and mount installation conditions (see Fig.2). For rubber mounts, experimental identification is even more important because stiffness and damping values may vary from nominal catalog data.

Semi-active and hybrid isolation systems have also been studied. Jiao *et al.* [13] proposed a horizontal auxiliary damping mount to control cab shaking of vibratory rollers. Quynh *et al.* [15] studied a semi-active cab isolation system for earth-moving machinery and reported improvement in ride comfort compared with passive systems. Nguyen Tien Duy *et al.* [16] evaluated a double-drum vibratory roller with a semi-active hydraulic cab mount system. These studies suggest that the future design of cab isolation systems may combine optimized rubber elements with additional damping or controllable components.


a) First- order natural frequency b) Second-order natural frequency


c) Third-order natural frequency d) Fourth-order natural frequency

Fig 2: Mode shapes corresponding to the first four natural frequencies of the cab supported by rubber isolators [12].

In addition to material properties and mount layout, the design methodology plays a decisive role in improving the vibration isolation performance of construction machinery cabs. Previous studies have employed different approaches, ranging from passive rubber mount optimization and terrain-dependent ride comfort analysis to hydraulic mounts, semi-active isolation systems, experimental modal validation, and data-driven optimization. These research directions are summarized in Table 2 to clarify their main contributions and remaining limitations.

Table 2: Representative research directions in cab vibration isolation design for construction machinery

Research direction	References	Main contribution	Limitation
Passive rubber mount optimization	[3, 7, 9, 11]	Optimizes stiffness, damping and mount layout for simple, low-cost cab isolation.	Limited performance in low-frequency pitch/roll vibration.
Terrain-dependent ride comfort analysis	[2, 8, 10]	Clarifies the effects of soil, speed and excitation conditions on cab vibration.	Results depend strongly on operating conditions.
Hydraulic and rubber–hydraulic mounts	[4, 10, 18. 19]	Improves low-frequency damping and reduces cab shaking.	Higher structural complexity and cost.
Experimental modal validation	[12]	Identifies cab natural frequencies and improves model reliability.	Requires prototype testing and measurement equipment.
Semi-active and auxiliary damping systems	[13, 15, 16]	Enhances vibration control adaptability under variable conditions.	Requires sensors, actuators and control algorithms.

Table 2 shows that passive rubber mounts remain attractive for practical cab isolation because of their simplicity and low cost. However, their low-frequency performance is limited, especially for cab pitch and roll vibration. Therefore, future studies should combine rubber mount characterization, multi-directional cab modeling, experimental validation and robust optimization under realistic working conditions.

In recent years, data-driven and surrogate-assisted optimization methods have also appeared in construction machinery vibration design. Zhuang *et al.* [20] introduced a multi-target regression forest method for cab vibration comfort optimization of construction machinery. Such methods can reduce the computational burden of repeated simulations and provide a mapping between structural parameters and vibration performance. However, for rubber mount design, data-driven methods should be used carefully because they require reliable experimental or high-fidelity simulation data.

4. Research gaps and future directions

The reviewed studies indicate that rubber cab isolation mounts are still technically important, although many improved systems have been proposed. For construction machinery manufacturers, rubber mounts remain attractive because of their low cost, reliability, and ease of installation. However, the design method needs to be improved from empirical selection toward model-based and experiment-supported optimization.

First, the nonlinear dynamic characteristics of rubber mounts should be measured more carefully. Many vehicle-level models still use constant stiffness and damping coefficients. This assumption may be acceptable for initial analysis but is not sufficient for final design. Future studies should identify dynamic stiffness and damping under different preload, amplitude, frequency, and temperature conditions. The obtained data can then be fitted using frequency-dependent or nonlinear models.

Second, the coupling among vertical, pitch, and roll vibration should be treated as a central design problem. Construction machinery cabs often have high centers of gravity, and the mounting plane is usually below the cab mass center. Therefore, improper stiffness distribution may create strong rotational vibration. Optimization should not only minimize vertical seat acceleration but also control cab pitch angle, roll angle, and relative displacement between the cab and frame.

Third, the excitation model should reflect real working conditions. For vibratory rollers, soil stiffness, damping, plastic deformation, drum excitation frequency, and compaction state influence cab vibration. For wheel loaders, load condition, bucket operation, braking, and road roughness are important. A mount design optimized under a single harmonic or random input may not be robust enough for real operation. Therefore, multi-condition and robust optimization should be considered.

Fourth, the relationship between cab mounts and seat suspension should be studied in an integrated way. The operator receives vibration through the seat, but the seat vibration depends on the cab motion. If cab mounts and seat suspension are designed separately, the final system may not achieve the best ride comfort. Future research should optimize the cab isolation system and seat suspension together, using ISO 2631-1 weighted acceleration as one of the main evaluation indices.

Fifth, experimental validation should be strengthened. Model simulation is useful, but rubber mounts and cab structures are sensitive to boundary conditions. Modal tests, shaker tests, road/field measurements, and parameter identification should be used to validate numerical models. In particular, the dynamic properties of rubber mounts should be measured under realistic preload and excitation amplitude.

Finally, the design of rubber cab mounts should consider durability and manufacturability. A mount with excellent vibration isolation performance may not be suitable if it has poor fatigue life, excessive deformation, or high production cost. Therefore, the next generation of optimal design should include ride comfort, cab stability, mount stress, fatigue life, cost, and installation constraints in a unified design framework.

5. Conclusions

This review has summarized the dynamic characteristics and optimal design of rubber vibration isolation mounts for construction machinery cabs. Rubber mounts remain widely used because of their simple structure, low cost, and good durability. However, their performance is strongly influenced by nonlinear viscoelastic behavior, dynamic stiffness, damping, preload, excitation amplitude, frequency, temperature, and mounting layout. Therefore, the traditional linear spring–damper model is not sufficient for high-quality cab isolation design.

The reviewed literature shows that rubber mounts can improve vibration isolation, but their low damping and relatively high stiffness limit their effectiveness in the low-frequency range. This limitation is especially important for vibratory rollers and earth-moving machinery, where cab pitch, roll, and low-frequency shaking are common.

Optimized rubber mounts, hydraulic mounts, pneumatic mounts, and semi-active hydraulic mounts have been studied to overcome these limitations. Among these solutions, optimized rubber mounts are still valuable for practical engineering, while hydraulic and semi-active mounts provide better low-frequency performance at the cost of increased complexity.

For future research, the design of rubber cab isolation mounts should move beyond the conventional linear spring–damper assumption. More experimental data are needed to identify the dynamic stiffness, damping loss factor, amplitude dependence, preload effect and aging behavior of rubber mounts under realistic working conditions. In addition, the optimization process should consider deformable soil excitation, multi-directional cab motion, vertical–pitch–roll coupling, and the interaction between cab mounts and seat suspension. A more reliable design framework should therefore combine rubber mount testing, cab dynamic modeling, ISO 2631-1-based comfort evaluation, multi-objective optimization and field validation. This direction is expected to support the development of practical, durable and cost-effective cab isolation systems for construction machinery.

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