Performance Of A Regenerative Tuned Mass Damper For An Electric Vehicle Under Varying Road Condition

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***Abstract*—In-wheel motor (IWM) systems in electric cars increase unsprung mass, which can have a detrimental effect on ride comfort and vehicle stability even though they enhance powertrain efficiency. The effectiveness of a Regenerative Tuned Mass Damper (RTMD) incorporated into an electric car suspension system under various road conditions is examined in this study through a numerical simulation approach. In order to assess vibration attenuation and energy regeneration performance under urban and rural road profiles, a quarter-car model with an electromagnetic energy harvesting circuit was created in MATLAB/Simulink. The Root Mean Square (RMS) acceleration of the sprung mass, along with the generated voltage, current, and electrical power output, were used to evaluate the RTMD performance. The findings demonstrate that under both road conditions, the suggested RTMD efficiently enhances vibration attenuation while concurrently harvesting electrical energy. With maximum vibration attenuations of 8.20% and 19.62%, respectively, the ideal RTMD mass for vibration reduction was 9 kg for the urban road profile and 13 kg for the rural road profile. Road roughness has a bigger impact on energy harvesting capabilities than vibration attenuation performance, as seen by the maximum collected power of 9.35 W under urban road circumstances and 126.72 W under rural road conditions. The absorber mass that maximised vibration attenuation was different from the absorber mass that produced the highest power output, indicating a trade-off between vibration suppression and electrical power generation. All things considered, the suggested RTMD shows great promise as a passive suspension augmentation technique that can both increase ride comfort and collect electrical energy from suspension vibrations in electric cars.**

***Keyword*—Energy harvesting, Regenerative Tuned Mass Damper (TMD), Electric Vehicle, Road Condition, Unsprung Mass**

I. Introduction

IN order to reduce greenhouse gas emissions and increase energy efficiency, the worldwide automobile industry is rapidly shifting to electric cars (EVs) as a sustainable mode of transportation. The in-wheel motor (IWM) configuration is one of the new EV architectures that has garnered a lot of interest since it does away with traditional drivetrain components and allows for more design flexibility. However, the unsprung mass is much increased when the electric motor is integrated directly into the wheel assembly. Because bigger wheel masses are more prone to vibration when exposed to irregularities in the road surface, this increase has a detrimental impact on ride comfort, vehicle stability, and tire-road contact performance. As a result, reducing the negative consequences of more unsprung mass continues to be a crucial obstacle in the creation of high-performance electric cars.

Many studies have looked into active and semi-active control strategies to manage suspension-induced vibrations. PID-based controls can efficiently enhance suspension performance by lowering rising and settling times, according to earlier studies [1]. More sophisticated methods, such as adaptive harmonic control and Model Predictive Control (MPC), have shown better vibration attenuation by dynamically adjusting system parameters [2]. To improve the precision of vibration suppression, updated dual-loop PID control schemes have also been suggested [3]. While these methods enhance ride quality, they mostly concentrate on reducing vibration and typically release vibration energy as heat, ignoring the potential to transform mechanical vibration energy into useable electrical power.

Electric vehicles with in-wheel motors present an even greater issue. Advanced control algorithms for vibration abatement have been developed since prior research has shown that increased wheel mass increases wheel-hop resonance and reduces ride comfort [4]. Additional control techniques are needed to offset the decline in suspension performance brought on by greater unsprung mass, despite the fact that IWM technology increases powertrain efficiency, according to other studies [5]. These results suggest that IWM systems' increased vibration levels offer a possible source of recoverable energy that can be used with regenerative suspension technology.

A number of mechanical and control-based strategies have been put forth to lessen vibrations in cars with IWM. For instance, specialised vibration absorbers with spring-damper systems have been designed to separate oscillations caused by motors [6]. Additionally, hybrid suspension techniques that combine groundhook and skyhook control have shown encouraging vibration isolation results [7]. However, the majority of active and semi-active systems need constant external power input, which could lower an electric vehicle's overall energy efficiency and driving range. Due to this restriction, regenerative suspension systems that can simultaneously dissipate vibration energy and transform it into electrical power have been developed.

Tuned Mass Dampers (TMDs) are a well-known vibration mitigation technology that effectively suppresses resonance in particular frequency bands. Nevertheless, the majority of current research concentrates on passive TMD designs without taking energy harvesting functionality into account [8]. Additionally, prior optimisation research has typically ignored the potential advantages of regenerative energy generation in favour of balancing ride comfort and handling stability [9]. More significantly, the performance of regenerative TMD systems under various road conditions has received less consideration. The efficiency of a regenerative suspension system should be assessed under various excitation characteristics since electric vehicles operate on a wide variety of road roughness levels, from reasonably smooth urban roads to extremely uneven rural roads. Road condition variability is crucial for system design and optimisation since road-induced vibrations have a direct impact on energy harvesting capacity and damping performance.

Thus, there is a research gap regarding how a regenerative tuned mass damper balances vibration reduction and energy recovery goals while operating under various road excitation circumstances. Specifically, there are still few research looking at how road roughness and TMD mass change affect regenerative suspension performance for in-wheel motor electric vehicles.

The novelty of this work compared to previous studies is the integrated evaluation of vibration attenuation and regenerative energy harvesting by an electromagnetic Regenerative Tuned Mass Damper (RTMD) for electric vehicles with in-wheel motors under different road conditions. Most existing works have focused on either improving ride comfort through active or passive suspension control or improving optimum energy harvesting with no consideration of the influence of road roughness on both objectives simultaneously. Moreover, most studies have optimised suspension parameters for only one excitation condition which is not suitable for real driving conditions. In contrast, this study numerically investigates the combined effects of RTMD mass variation and different road roughness classes on both vehicle dynamic performance and electrical energy generation using a coupled mechanical-electromagnetic quarter-car model developed in MATLAB/Simulink. This integrated framework enables a better understanding of the trade-off between the ride comfort and the regenerative performance, thus providing practical design guidelines for the optimisation of the regenerative suspension systems in future in-wheel motor electric vehicles under various road conditions.

This study examines the functionality of an Electromagnetic Regenerative Tuned Mass Damper (RTMD) incorporated into the suspension system of an electric car with in-wheel motors in order to close this gap. By using a small back-iron electromagnetic mechanism that is connected in parallel to the main suspension system, the suggested RTMD uses electromagnetic induction to transform vibration energy into electrical energy. A quarter-car model created in MATLAB/Simulink under various road conditions representing urban and rural road roughness classes is used to assess the system's performance. The evaluation takes into account two main performance criteria: energy harvesting capacity, which is measured by the generated voltage, current, and electrical power output, and ride comfort and vehicle stability, which are represented by the Root Mean Square (RMS) acceleration of the sprung mass.

The integrated study of regenerative TMD mass properties and electromagnetic energy harvesting ability under various road excitation circumstances is what makes this work novel. This work assesses the trade-off between ride comfort and collected energy across various road roughness levels, in contrast to earlier research that only concentrate on vibration mitigation or energy regeneration. It is anticipated that the results will offer important information for the development of sophisticated regenerative suspension systems that will improve future electric vehicles' energy economy and vehicle dynamics.

II. Methodology

The research methodology was designed with a structured approach to assess the performance of the Electromagnetic Regenerative Tuned Mass Damper (TMD) in electric vehicles equipped with in-wheel motors (IWM). The study focused on developing a mathematical model that integrates mechanical and electrical systems, supported by numerical simulations to analyse vibration damping capabilities and evaluate the potential for energy harvesting.

A. System Configuration and Quarter Car Model

Vehicle dynamics are modelled in this study using a quarter-car model with three degrees of freedom (3-DOF) that has been especially modified to represent the characteristics of electric vehicles with in-wheel motors. Unlike conventional suspension models, this configuration integrates the electric motor component as part of the unsprung mass Mw which significantly increases the inertia at the wheels and has the potential to worsen the vehicle's vibration response when traversing road excitations. In order to overcome this challenge, a regenerative tuned mass damper (TMD) was added as a third mass Mm dynamically connected to the wheel assembly. These models incorporate the interaction between the sprung mass Mb representing the vehicle body load—the unsprung mass bearing the load of the engine and wheel, and the TMD mass designed to oscillate in the opposite direction to absorb excess kinetic energy.

The distribution of mechanical forces in the main suspension system is determined by the suspension stiffness Kb and suspension damping Cb parameters. Meanwhile, the interaction between the wheels and the road surface is modelled through wheel stiffness Kw and wheel damping Cw. In addition to functioning as a wheel vibration absorber, the RTMD unit acts as an energy harvester whose performance is directly influenced by the electromechanical coupling coefficient Kt. The regenerative characteristics of this system are also determined by electrical parameters, including the coil resistance Rc, load resistance Rr and coil inductance L. This comprehensive 3-DOF approach enables a more precise analysis of resonance phenomena in unsprung mass while optimizing the conversion of kinetic energy into electrical energy through electromagnetic induction mechanisms. It also allows for the identification of resonance phenomena in unsprung mass, which often pose a major challenge to the driving stability of in-wheel electric vehicles.

B. Dynamic Modelling

The dynamic modeling in this study focuses on the dynamic load interaction between the vehicle body, the in-wheel drive system, and the tuned mass damper (TMD) unit. This system is modeled as a multi-mass mechanical system interconnected via spring and damper elements. The primary focus of this dynamic modeling is to represent the transfer of kinetic energy from road excitation to the unsprung mass Mw, which is then simultaneously damped by the main suspension and the RTMD unit. This model assumes purely vertical motion to analyze the vibration isolation characteristics of the body Mb and tire contact stability on the road surface see figure 1.

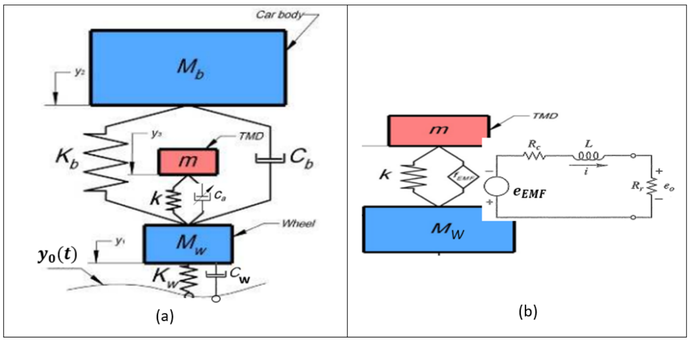

Figure 1. (a) Dynamic Quarter car dynamic model equipped TMD, (b) TMD Model with a regenerative circuit

Figure 1(a) shows a quarter-car dynamic model of a suspension system equipped with a regenerative TMD, then in Figure 1(b) we see the electrical circuit of the regenerative TMD where C_a is converted into f_{EMF} . This is because in the equation of motion for the TMD design with the addition of regeneration, an electromagnetic force arises, so that the value of the TMD damping coefficient C_a is the electrical damping coefficient d_e adding of mechanical damping d_m. Assuming d_m is constant, the value of the f_{EMF} can be determined using Kirchhoff's voltage law. Furthermore, based on the dynamic model that has been created, it can be converted to a Free Body Diagram (FBD) based on an analysis of the direction of the forces acting on each component. The FBD of the dynamic model of a quarter-scale vehicle equipped with a TMD, viewed in the vertical plane, can be seen in the following figure 2.

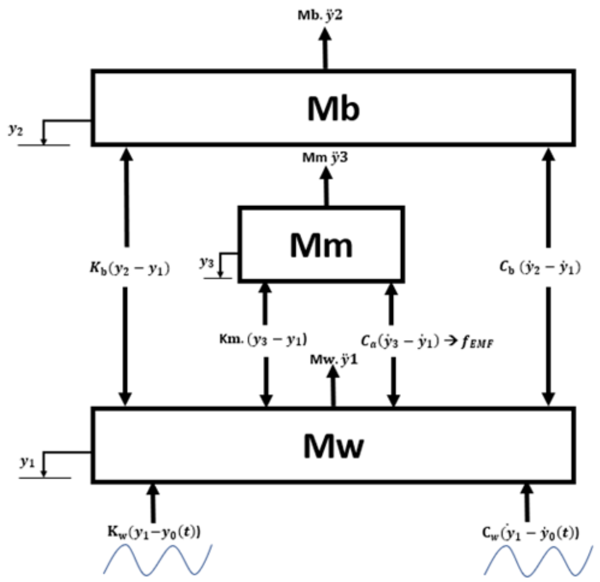

Figure 2. Free Body Diagram of Quarter car dynamic model equipped TMD

C. Mathematical Modelling

The mathematical equations underlying this system are derived using Newton's Second Law to produce a set of linear differential equations that fully represent the vehicle's dynamic behavior. This model incorporates all internal forces acting on the system, including spring forces (K_b,K_w) and viscous damping forces (C_b, C_w) as representations of the suspension's mechanical components. To complement these mechanical aspects, the model also includes an electromagnetic damping force F_e defined as a function of the electromechanical coupling coefficient K_t and the relative velocity between the TMD mass and the wheel.

The analysis was conducted by examining each mass individually to ensure that the force distribution conforms to the action-reaction principle. Therefore, based on Kirchhoff's Voltage Law for electrical circuits and the results of the FBD analysis in Figure 2, The dynamic equations that have been formulated are then expressed in terms of state variables so that they can be further analyzed through simulation block diagram modeling. This transformation is performed to describe the system's response in the time domain in a more structured manner. The following are the definitions of the state variables used in the analysis of vertical vibrations.

$$\dot{v}_1 = \frac{1}{M_w}\Big[K_w y_0(t) + C_w y_0(t) - (C_b + C_w)\dot{y}_1 + C_b\dot{y}_2 - (K_m + K_b + K_w)y_1 + K_b y_2 + K_m y_3 + k_t i\Big] \tag{1}$$

$$\dot{v}_2 = \frac{1}{M_b}\left(-C_b\dot{y}_2 + C_b\dot{y}_1 - K_b y_2 + K_b y_1\right) \tag{2}$$

$$\dot{v}_3 = \frac{1}{M_m}\left(k_t i - K_m y_3 + K_m y_1\right) \tag{3}$$

where $\dot{v}_1$ is velocity of wheel, $\dot{v}_2$ velocity of body, and $\dot{v}_3$ velocity of TMD with used to model simulation in MATLAB or Simulink.

D. Structure Design of Electromagnetic Regenerative TMD

The design structure of the Regenerative Tuned Mass Damper (RTMD) in this study focuses on a physical configuration that is integrated in parallel with the vehicle's suspension system. This arrangement allows the Regenerative TMD to directly respond to vibrations in the unsprung mass, thereby functioning simultaneously as a vibration damper and an energy harvester. Overall, the Regenerative TMD consists of two main components: the mechanical subsystem (mass, springs, and motion restraints) and the electromagnetic subsystem (permanent magnets, coils, and back-iron structure), which are interconnected to convert mechanical energy into electrical energy.

In the electromagnetic section, the design utilizes permanent magnets and coils optimized through a back-iron structure. The back-iron plays a crucial role in directing the magnetic flux to be more focused and efficient, ensuring that the magnetic field lines intersect the coils perpendicularly. This condition increases the magnetic flux change in the coil and directly impacts the increase in the electromechanical constant K_twhich affects the magnitude of the induced voltage. Additionally, the back-iron design offers flexibility in adjusting the oscillating mass, as its dimensions can be modified without significantly altering the magnet configuration.

Meanwhile, from a mechanical standpoint, the TMD mass is designed to have controlled vertical freedom of motion governed by a specific spring constant. The spring stiffness is selected such that the natural frequency of the RTMD matches the resonance frequency of the unsprung mass, thereby achieving optimal tuning. This condition allows for maximum transfer of vibration energy from the main system to the TMD mass, thereby significantly reducing vibration amplitude. Additionally, motion limiters are applied to maintain operational stability and prevent excessive displacement, ensuring the system remains safe and reliable under various road conditions. The design can see in figure 3.

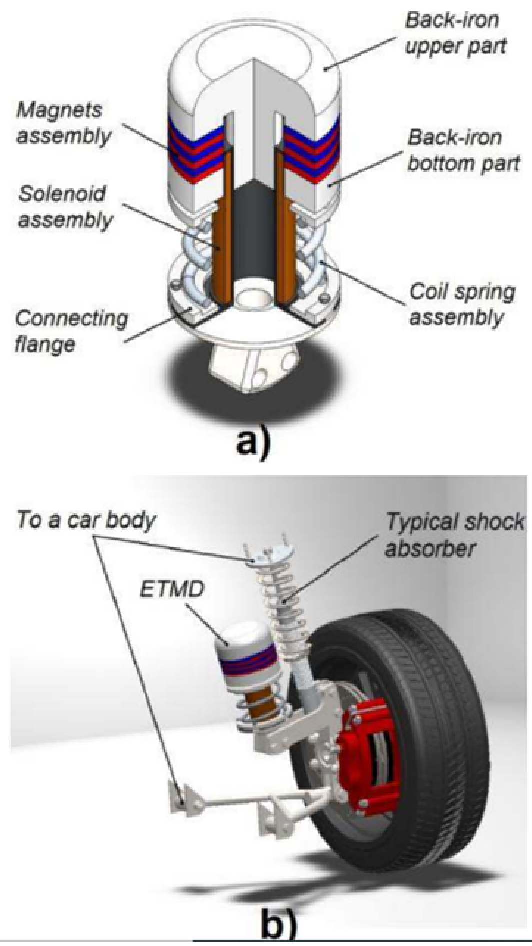

Figure 3. (a). Electromagnetic TMD based back iron design, (b) ETMD implementation in a car suspension [10]

E. Simulation

After mathematically formulating the state-space model, the next crucial step is to implement these equations into MATLAB Simulink software using dynamic system block diagrams. This transformation aims to translate complex mathematical relationships into a visual simulation capable of processing road disturbance inputs in real time. The block diagram architecture designed to represent the operating mechanisms of the suspension and Regenerative TMD is as follows figure 4.

Model integration is performed by assembling block components such as an integrator to calculate velocity and position from acceleration, as well as gain blocks to input specific parameter values such as body mass M_b and unsprung mass M_w. In addition to mechanical aspects, this block diagram also models electromagnetic interactions via the coupling coefficient K_t that links suspension oscillations with the regenerative electrical circuit. Through this approach, the simulation system can accurately represent the additional damping force f_{EMF} as well as the resulting electric current and voltage, thereby enabling a comprehensive analysis of vehicle performance across various TMD mass variations.

F. Perform Evaluate Criteria

Two main criteria characteristics that represent mechanical and electrical elements are used in this study to evaluate the design efficacy of the Regenerative Tuned Mass Damper (RTMD). The first criterion is ride comfort and vehicle body stability, which are assessed using the vehicle body's Root Mean Square (RMS) value (sprung mass). A lower value of the RMS parameter, which serves as a gauge of damping quality, suggests that the system is better able to reduce vibrations brought on by road disturbances. The second criterion is energy harvesting capability, which is determined by the amount of power, voltage output, and

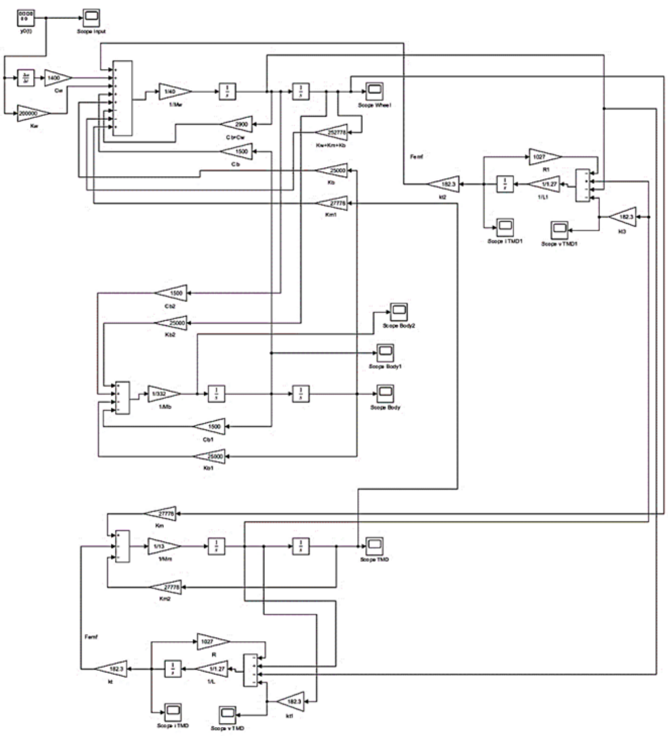

Figure 4. Electromagnetic TMD based back iron design

regeneration electrical current produced by the TMD's electromagnetic mechanism.

Using the parameter specifications given in Table I, a simulation was run in MATLAB Simulink to test these parameters. Based on the road roughness classification ISO road classes used in the Agostinacchio study [11], the simulation was executed using an approximate sinusoidal profile of road condition waveform input $y_0(t)$ as shown in figure 5. Two types of road conditions were taken into consideration: poor rural road conditions and ordinary urban road conditions. In accordance with the maximum documented road surface imperfections for each road class, the amplitudes were adjusted to 0.050 m and 0.100 m. The obtained excitation frequencies were 2.22 Hz and 3.70 Hz, respectively, at a vehicle speed of 40 km/h. Although these excitations were selected to approximate the severity levels commonly associated with ISO 8608 road classes C–D and D–E, respectively, they do not represent the full stochastic characteristics of actual ISO 8608 road profiles.

To test these parameters, a simulation was conducted in MATLAB Simulink using the parameter specifications listed in Table I. The simulation was run by applying a road condition waveform input $y_0(t)$ with an amplitude of 0.02 m or 20 mm at a frequency of 1 Hz. The TMD mass Mm was varied in nine situations (5, 7, 9, 11, 13, 15, 17, 19, and 21 kg) to conduct the evaluation. Through these variations, the system was analyzed to assess the effect of mass changes on the RMS value of vehicle body vibrations, as well as their impact on stability and the magnitude of the current and voltage produced by the regenerative system. The selection of the optimal mass is ultimately determined based on the equilibrium point where the system is capable of generating maximum regenerative energy while maintaining vibration damping quality at an acceptable level.

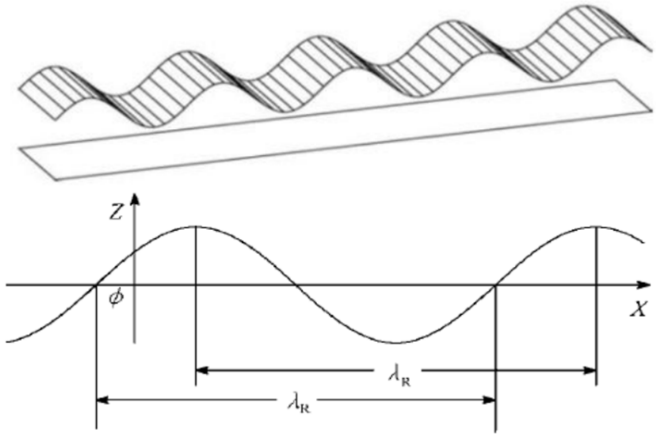

Figure 5. Sinusoidal road profile adopted from Priyambada and Sutantra representing urban road excitation condition [12]

Through these modifications, the system was examined to see how mass changes affected stability, the amount of current and voltage generated by the regenerative system, and the RMS value of car body vibrations. The equilibrium point at which the system may produce the most regenerative energy while preserving an acceptable degree of vibration damping quality is finally used to choose the ideal mass.

The following table provides a summary of the factors that are part of the Regenerative TMD system's operating design, including mass, spring constants, and electromagnetic characteristics:

TABLE I
Parameter Regenerative TMD

Parameter	Symbol	Value	Unit	Source
Quarter car parameters				
Sprung mass	M_b	417.25	Kg	[13]
Unsprung mass	M_w	41.5	Kg	[14]
Suspension damping	C_b	3647.6	N.s/m	[15]
Suspension stiffness	K_b	53500	N/m	[15]
Tire damping	C_w	3430	N.s/m	[16]
Tire stiffness	K_w	221973.43	N/m	[17]
TMD parameters				
Electromechanical coupling coefficient	K_t	182.3	T.m	[14]
TMD Spring stiffness	K_m	39000	N/m	[14]
Resistance of the coil	R_c	513.5	Ohm	[14]
Resistance of the load	R_r	513.5	Ohm	[14]
Inductance of the coil	L	1.27	H	[14]

Unsprung mass is derived from prior studies by the author [14].The wheel mass value is taken from Kopylov's study [14]. Priyambada and Sutantra's work [15] provides the suspension spring stiffness and damping coefficients, whilst Yudhyadi's study [16] and Philips' experimental tire damping data at Kruczek research [17] provide the tire stiffness and damping values.

III. Result and Discussion

The proposed regenerative tuned mass damper (RTMD) performance was studied under two representative road conditions related to urban and rural environments. The urban road profile was represented with an estimated sinusoidal excitation amplitude of 0.05 m and excitation frequency of 2.22 Hz, whereas the rural road profile was represented with an estimated amplitude of 0.10 m and frequency of 3.70 Hz. The vehicle speed was kept constant at 40 km/h in all the simulations to exclude the effect of road roughness on vibration attenuation and energy harvesting performance.

A. Result

1) Vibration Attenuation Performance: The root mean square (RMS) acceleration recorded at the vehicle body was used to assess the suspension system's vibration response. With an input excitation of 0.03685 g and an output RMS acceleration of 0.03512 g under urban traffic conditions, the baseline suspension without RTMD resulted in a 4.69% vibration attenuation. For all examined absorber masses, the RTMD's application lowered the vibration level. At an RTMD mass of 9 kg, the lowest RMS acceleration of 0.03383 g was achieved, leading to the maximum vibration attenuation of 8.20%, which is an additional 3.50% decrease over the baseline suspension. The vibration attenuation detail displayed in Table II.

TABLE II
Result of TMD Vibration Attenuation

TMD Mass (kg)	Urban Road		Rural Road	
	RMS	Vibration Att. (%)	RMS	Vibration Att. (%)
Without TMD	0.03512	4.69%	0.06081	17.26%
3	0.03435	6.78%	0.05954	19.00%
5	0.03413	7.38%	0.05934	19.27%
7	0.03394	7.90%	0.05912	19.57%
9	0.03383	8.20%	0.05910	19.58%
11	0.03387	8.09%	0.05924	19.40%
13	0.03391	7.98%	0.05908	19.62%
15	0.03394	7.90%	0.05918	19.48%
17	0.03399	7.76%	0.05942	19.16%
19	0.03404	7.63%	0.05973	18.74%
21	0.03411	7.44%	0.06005	18.30%

In rural road conditions, a similar pattern was noted. The RMS acceleration was lowered by the baseline suspension from 0.07350 g to 0.06081 g, indicating a 17.26% damping effectiveness. After the RTMD was added, the vibration response was further decreased, and for a mass of 13 kg, the minimum RMS acceleration was 0.05908 g. In comparison to the baseline system, this design produced the maximum vibration attenuation of 19.62%, which is an improvement of 2.36%.

The findings suggest that vibration suppression is not consistently improved by increasing the RTMD mass. The ideal absorber mass was determined to be 9 kg in urban road conditions and 13 kg in rural road conditions. The damping effectiveness progressively declined above these limits. Den Hartog's classical tuned mass damper theory, which claims that there is an ideal absorber mass ratio for maximising vibration attenuation, is compatible with this behaviour. The dynamic interaction between the main and secondary systems is changed and the efficiency of vibration energy transmission is decreased when the absorber mass is increased above its ideal value.

Road excitation characteristics have a significant impact on absorber tuning requirements, as evidenced by the shift in optimal RTMD mass from 9 kg to 13 kg. Greater vibration energy was introduced into the suspension system by the rural road profile, which produced bigger displacement amplitudes and higher excitation frequencies than the urban road profile. In these circumstances, effective dynamic contact with the primary suspension needed a larger absorber mass. This finding emphasises the potential benefits of adaptive tuning techniques and implies that a single set RTMD configuration could not offer optimal performance in all operating scenarios.

The observed tendency is in line with the results of Kopylov et al. [14], who showed that tuning parameters and excitation characteristics have a significant impact on an electromagnetic regenerative tuned mass damper's efficacy. Their research shown that as the absorber departs from its ideal operating condition, RTMD performance declines, highlighting the need of appropriate mass selection in vibration control applications.

2) Energy Harvesting Performance: For both road conditions, the captured electrical power rose steadily as the RTMD mass grew. The produced power rose from 7.16 W at an absorber mass of 3 kg to 9.35 W at 21 kg under the urban road profile. The generated voltage increased from 85.78 V to 98.05 V and the current from 0.083 A to 0.095 A in tandem with this increase. Under the country road profile, a noticeably greater rise was noted. The power that was gathered rose by almost 108%, from 60.95 W at 3 kg to 126.72 W at 21 kg. The generated current went from 0.244 A to 0.351 A, and the generated voltage went from 250.32 V to 361.13 V. Table III displays the vibration attenuation percentage in detail.

TABLE III
Result of TMD Regenerative Energy

TMD Mass (kg)	Urban Road			Rural Road		
	Cur. (A)	Volt. (V)	Power (W)	Cur. (A)	Volt. (V)	Power (W)
3	0.08344	85.7789	7.16	0.2435	250.3226	60.95
5	0.08513	87.5352	7.45	0.2532	260.6774	66.00
7	0.08682	89.2702	7.75	0.2638	271.6422	71.66
9	0.08831	90.7972	8.02	0.2743	282.4578	77.48
11	0.08945	91.9355	8.22	0.2847	293.2140	83.48
13	0.09062	93.1252	8.44	0.2976	306.3907	91.18
15	0.09180	94.3459	8.66	0.3101	319.2379	99.00
17	0.09298	95.5637	8.89	0.3228	332.2488	107.25
19	0.09418	96.8009	9.12	0.3361	345.9498	116.27
21	0.09539	98.0530	9.35	0.3509	361.1299	126.72

Faraday's law of electromagnetic induction provides an explanation for the increase in electrical output. Greater relative displacement and velocity between the moving magnetic assembly and the coil are produced by a bigger absorber mass, which raises the rate of magnetic flux variation and, as a result, increases the electromotive force. Higher voltage, current, and electrical power are therefore generated.

This pattern is in line with research by Li and Zuo [18], who found that suspension motion brought on by road excitation has a significant impact on the functioning of electromagnetic regenerative dampers. Similar to this, Li et al. [19] showed that higher suspension displacements and velocities greatly enhance the electromagnetic energy-harvesting shock absorbers' capacity to generate power through analytical modelling and road trials. It's interesting to note that the absorber mass that maximised electrical power generation and the absorber mass that maximised vibration attenuation were different. The greatest collected power was obtained at the largest examined mass of 21 kg, even though the best vibration attenuation happened at 9 kg and 13 kg under urban and rural road conditions, respectively. This result highlights a basic trade-off between energy harvesting efficiency and ride comfort. Zuo and Zhang [20] observed a similar trade-off, showing that it is typically impossible to maximise energy recovery, ride comfort, and road handling all at once due to the intrinsic contradiction between these goals.

B. Discussion

Road roughness significantly affects energy harvesting performance more than vibration attenuation capability, according to a study of the two road conditions. The gathered power increased from 9.35 W to 126.72 W, despite the maximum vibration attenuation rising from 8.20% under the urban road profile to 19.62% under the country road profile. This results in a 13.6-fold increase in captured electrical output but a roughly 2.4-fold increase in dampening efficacy. This discrepancy suggests that energy harvesting performance is significantly more impacted by road roughness than vibration suppression performance.

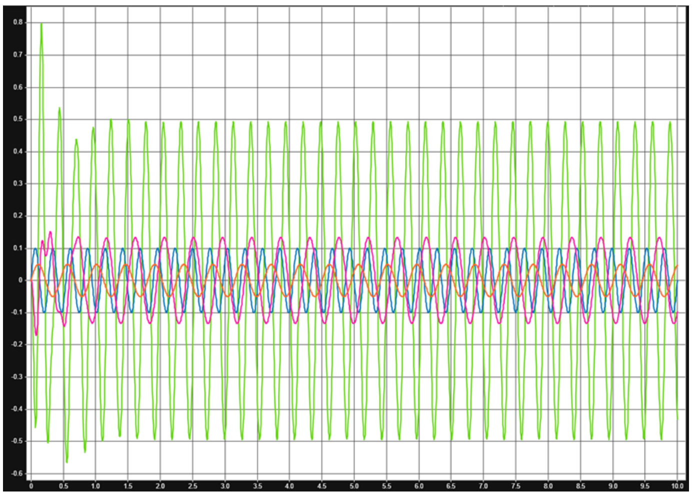

Figure 6. Current generation of TMD under different road conditions

The larger excitation amplitude and higher excitation frequency associated with rural road conditions result in significantly higher current, voltage, and power output, as shown in Figure 6. The rural road profile induces greater suspension travel and relative motion between the electromagnetic components of the RTMD, thereby increasing magnetic flux variation and improving electromechanical energy conversion. This trend is consistent with previous studies on regenerative suspension systems, which reported that increased suspension displacement and velocity enhance the energy harvesting capability of the system [18], [19]. Therefore, the higher power generation observed under rural road conditions can be attributed to the increased vibrational energy available for conversion into electrical energy.

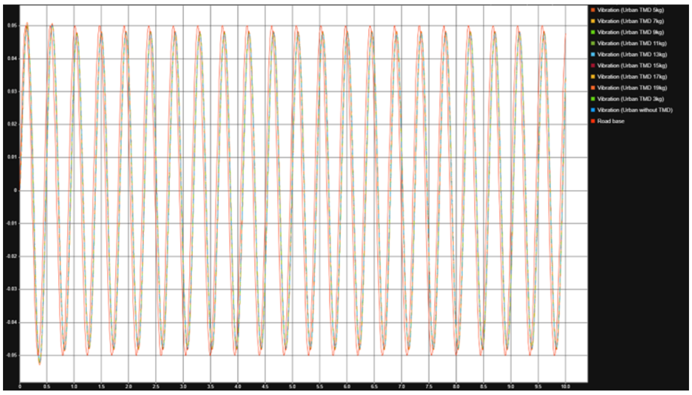

Figure 7. Vibration attenuation result of Urban Road conditions

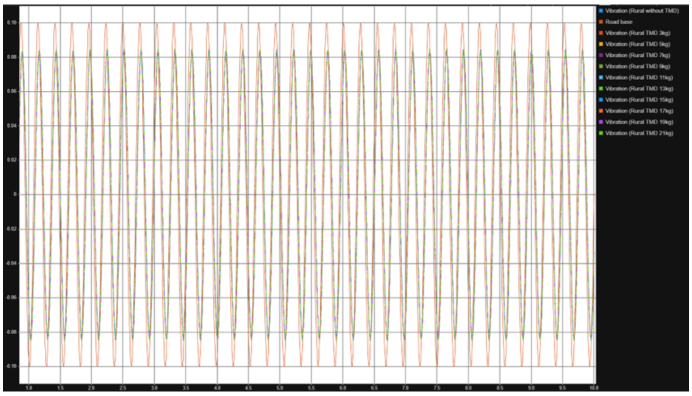

Figure 8. Vibration attenuation result of Rural Road conditions

Result of vibration response under different road conditions as shown in figure 7 and figure 8 show the TMD can reduce the vibration from road condition better than suspension without TMD. The study's overall vibration attenuation and energy harvesting tendencies are in line with earlier research findings. Electromagnetic regenerative tuned mass dampers have been shown by Kopylov et al. [14] to be able to both minimise vibration and recover electrical energy from suspension motion. Similar behaviour was seen in the current investigation, where the RTMD produced useful electrical power while also providing quantifiable vibration reduction.

The increase in electrical output with RTMD mass can be explained through the dynamic interaction between the absorber and the electromagnetic transducer. As the RTMD mass increases, its inertia becomes larger, allowing the absorber to maintain a greater oscillatory motion relative to the primary suspension system. This condition increases the relative velocity between the moving magnetic assembly and the stationary coil. According to Faraday's law of electromagnetic induction, the induced voltage is proportional to the rate of magnetic flux variation, which is directly related to the relative velocity. Consequently, the higher relative velocity generated by larger RTMD masses produces higher induced voltages. Since the electrical circuit resistance remains constant throughout the simulations, the increase in induced voltage also results in a corresponding increase in current. As electrical power is proportional to the product of voltage and current, both quantities contribute to the continuous rise in harvested power observed with increasing RTMD mass. This relationship is evident in Table III, where increasing the RTMD mass from 3 kg to 21 kg increased the generated voltage from 85.78 V to 98.05 V and the current from 0.083 A to 0.095 A under urban road conditions, while under rural road conditions the voltage increased from 250.32 V to 361.13 V and the current from 0.244 A to 0.351 A, resulting in substantially higher power output.

According to Li and Zuo [18], road-induced suspension motion has a significant impact on electromagnetic regenerative dampers' efficacy. This observation is supported by the current results, which show that the harvested power under rural road conditions was roughly 13.6 times larger than that obtained under urban road conditions because of the increased excitation amplitude and frequency. Regenerative suspension systems inevitably include a trade-off between ride comfort, road handling, and energy harvesting goals, according to Zuo and Zhang [20]. By identifying several absorber masses that optimise vibration attenuation and electrical power generation, the current study validates this behaviour. In particular, while electrical power output increased with absorber mass, the best vibration attenuation was attained at middle RTMD masses.

Suda and Shiiba [21] originally used a hybrid suspension system with active control and energy regeneration to illustrate the more general idea of concurrently managing vibration and recovering energy from suspension motion. By combining an electromagnetic harvesting mechanism with a passive tuned mass absorber architecture, the current RTMD expands on this idea and offers a more straightforward option with less control complexity.

The identification of various optimal RTMD masses under various road conditions is a significant contribution of the current work. Road excitation characteristics have a considerable impact on absorber tuning requirements, as seen by the optimal absorber mass of 9 kg for the urban road profile and 13 kg for the rural road profile. This result implies that adaptive tuning techniques that can sustain optimal performance under a range of operating situations may be advantageous for future RTMD systems.

Overall, the findings show that the suggested RTMD may recover meaningful electrical energy from vehicle suspension motion while also enhancing ride comfort. In rural road conditions, the system produced up to 126.72 W with a maximum vibration attenuation of 19.62%. The findings also show that vibration attenuation performance is less important in determining energy harvesting output than road roughness. Therefore, RTMD deployment may yield significantly greater benefits in terms of energy recovery while still maintaining acceptable vibration levels for vehicles that operate on rough rural roads on a regular basis.

Future research should concentrate on adaptive RTMD tuning techniques that may dynamically modify absorber characteristics based on vehicle speed and road conditions. To find the best tradeoffs between vibration suppression and electrical power generation, multi-objective optimisation techniques like those put out by Zuo and Zhang [20] should be applied to RTMD systems.

IV. Conclution

In this study, the performance of a regenerative tuned mass damper (RTMD) integrated in an electric vehicle suspension system has been investigated under various road conditions. The objective of the research was to evaluate the capacity of the RTMD to attenuate the vibration of the vehicle and to harvest electrical energy from the suspension movement simultaneously.

The results showed that the proposed RTMD effectively enhanced vibration attenuation under both urban and rural road conditions. The optimal RTMD mass for vibration reduction was found to be 9 kg for the urban road profile and 13 kg for the rural road profile, achieving maximum vibration attenuations of 8.20% and 19.62%, respectively. These findings indicate that the road excitation characteristics significantly influence the tuning requirements of the absorber. In terms of energy harvesting performance, the electrical power output increased with both RTMD mass and road excitation severity, reaching maximum values of 9.35 W under urban road conditions and 126.72 W under rural road conditions. The approximately 13.6 times increase in harvested power between the two road profiles suggests that energy harvesting capability is considerably more sensitive to road roughness than vibration attenuation performance, highlighting the strong dependence of regenerative energy recovery on the magnitude of suspension excitation.

The study also found a trade-off between vibration suppression and electrical power generation. The absorber mass that maximised vibration attenuation was different from the mass that yielded the highest electrical power output, suggesting that RTMD design should take into account both ride comfort and energy recovery objectives. Overall, the proposed RTMD is a promising candidate for electric vehicle passive suspension enhancement technology, which can improve the ride comfort and recover useful electrical energy from suspension vibrations simultaneously.

Additional research should investigate adaptive or semi-active RTMD configurations that can modify the absorber parameters based on changing road conditions and vehicle speeds. Moreover, experimental validation and multi-objective optimisation methodologies are proposed to further improve the trade-off between vibration attenuation and energy harvesting performance.

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