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Design, Optimization, and Integration of the Suspension Mount and Damper to Enhance the Ride and Handling

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Abstract

The paper deals with the study of the damper tuning and the integration of dampers with mount/bush and spring. The ideal approach to tune the characteristics of the vehicle is to modify bushings and mountings, used in the chassis system. In the automotive component's design, mounts and bushings instituted especially in suspension systems are determinant components while dealing with the noise, vibration, and harshness in automobiles. This study represents the utmost benefits derived from suspension dampers when the focus is more on damping force, top mount gain, and top mount phase. The paper emphasizes the transition frequency and its significance. The case study referred to in the paper is presented for the Macpherson. Furthermore, the results of the study are verified by conducting experimental trials. The comparative results showcased a 90% correlation and proved beneficial.

Introduction

MacPherson Suspension System:

The suspension system is the mechanical foundation that bridges the vehicle and the road, contributing to safety, stability, comfort, and driving dynamics. Its intricate interplay of components and engineering considerations are vital factors that define the driving experience across a wide spectrum of vehicles. Suspension comprises springs, shock absorbers, and linkages connecting the vehicle to its wheels and allows the relative motion between the two. The suspension system plays a vital role in contributing to vehicle handling and thereby providing comfort to the occupants, isolating them from bumps, vibrations, and noise. Among the various suspension systems, the MacPherson suspension system is a prominent choice for many vehicles due to its wide range of applications. The MacPherson suspension system is simple, cost-effective, and has a compact design. It also offers good handling and driving dynamics in various ranges of driving conditions.

Top mount in Macpherson Suspension System:

In a MacPherson suspension system, the "top mount" refers to the component that attaches the upper end of the MacPherson strut to the vehicle body or chassis. This component plays a crucial role in maintaining the structural integrity of the suspension while also allowing for controlled movement of the strut during suspension travel. The top mount is a critical component that influences both the performance and comfort of the vehicle's suspension. Its design and material composition can impact the overall ride quality, handling characteristics, and longevity of the suspension system.

The parameters responsible for affecting the ride comfort and harshness are studied considering the optimal top mount characteristics. The characteristics are used as the case study in optimizing the top mount. The objective of the damper top mount optimization is to improve ride comfort and harshness simultaneously.

The top mount of a damper (also known as a shock absorber or strut) is a critical component in a vehicle's suspension system. It affects various aspects of the suspension's performance, including Noise, Vibration, and Harshness (NVH) characteristics and transient frequency response.

Top Mount Damper Gain and Phase Analysis:

The top mount damper gain and phase analysis is a fundamental examination of how the damper's damping force varies with the input from the road surface. This insight is essential for optimizing the suspension's response to different road conditions, ensuring a balanced blend of comfort and control. The consideration of NVH characteristics emphasizes the importance of minimizing noise and vibration levels that occupants might experience while driving. By studying and addressing the sources of noise and vibration within the suspension system, the study likely aims to create a smoother, quieter, and more enjoyable ride for passengers.

The investigation of transient frequency plays a vital role in understanding the suspension's ability to cope with sudden changes in road conditions, such as potholes or quick maneuvers. By analyzing the suspension's response to these rapid inputs, researchers can assess the system's effectiveness in maintaining stability and control.

Here's how these elements are related:

1. **NVH (Noise, Vibration, and Harshness):**

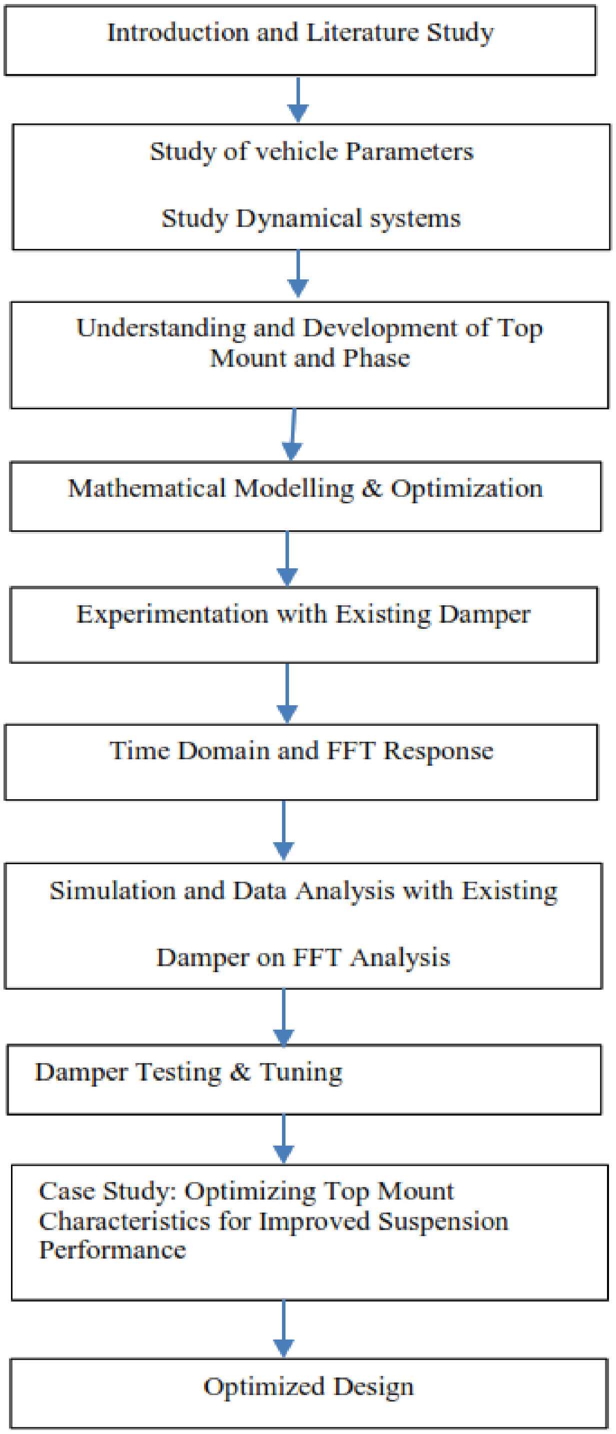
   - The top mount can influence the transmission of noise and vibrations from the road into the vehicle's cabin. It serves as a point of connection between the suspension system and the vehicle's structure.
   - A well-designed top mount can help isolate vibrations and reduce the transfer of road noise, leading to a smoother and quieter ride for passengers.
   - When the top mount is engineered to effectively dampen vibrations, it can contribute to lower NVH levels by preventing the transmission of these vibrations to the vehicle's body.

2. **Transient Frequency Response:**

   - Transient frequency refers to the frequency of rapid changes in road conditions, such as hitting a pothole or encountering a sudden bump.
   - The top mount, along with the damper, affects how the suspension system responds to transient frequencies. It influences how quickly the suspension can absorb and dissipate the energy from these sudden inputs.
   - A well-tuned top mount and damper combination can help the suspension react appropriately to transient frequency inputs, ensuring that the vehicle remains stable and controlled during unexpected road disturbances.

The relationship between the top mount, NVH, and transient frequency lies in the top mount's ability to effectively manage forces, vibrations, and movements within the suspension system. A top mount that is designed to dampen vibrations and isolate noise can contribute to improved NVH characteristics by minimizing the transfer of unwanted disturbances to the cabin. Additionally, a top mount that is optimized for transient frequency response can enhance the suspension system's ability to provide a comfortable and controlled ride, even when encountering sudden changes in road conditions.

Methodology



Damper & Top Mount Gain:

Damper top mounts are used in vehicles to provide ideal noise vibration–harshness performance. It also offers ride comfort, improved suspension, and handling. The ride comfort and harshness are the responses gained due to the frequency variation of the vehicle body. By the consideration of the vertical acceleration up to 20 Hz, the ride comfort can be evaluated. The harshness measurement is evaluated by considering the body's vertical acceleration in the frequency range of 20 -100 Hz. Another type of vehicle harshness is impact harshness (IH) which has a direct impact on the ride comfort.

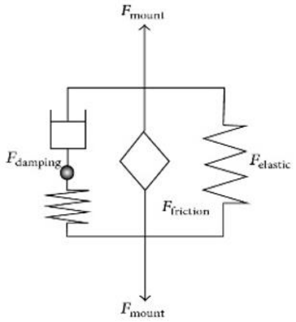


Figure1: Damper top mount model [16]

Damper Testing and Tuning :

Damper testing is carried out to measure the characteristics of the damper system. Damper tuning plays a significant role in enhancing the ride comfort of a passenger vehicle. Dampers help absorb shocks and vibrations from the road surface, preventing disturbances from directly reaching the occupants. By testing and tuning dampers, we have achieved a balance between absorbing road imperfections and providing a smooth ride. Well-tuned dampers contribute to improved handling and stability of the vehicle. Dampers control the rate at which a vehicle's suspension system compresses and rebounds, ensuring that the tires maintain better contact with the road during cornering, braking, and acceleration.

Proper tuning minimizes body roll, enhances cornering grip, and helps the driver maintain better control over the vehicle. Damper testing and tuning are also essential for optimizing the dynamic behavior of a vehicle. Different driving conditions, such as city driving, highway cruising, and spirited driving, require varying levels of damping. Adjusting dampers to match these conditions improves the vehicle's response and performance. Dampers contribute to vehicle safety by preventing excessive oscillations and bounces that could lead to loss of control or accidents. In emergencies, well-tuned dampers help the vehicle maintain stability, ensuring that the driver can react effectively to unexpected events. Damper tuning can impact the levels of noise, vibration, and harshness experienced inside the vehicle cabin. Excessive vibrations and noise can lead to discomfort and fatigue for passengers. Proper damper tuning helps minimize these unwanted effects.

The procedure for finalizing top mount/bush stiffness:

Damper tuning refers to the process of adjusting the characteristics and settings of automotive shock absorbers (dampers) to achieve desired performance outcomes.

Tuning procedure of Rear Damper Top Mount of a passenger vehicle:

1. Estimate linear approximation of damper behavior.
2. Evaluate damping force and velocity graph results regarding the rebound, and compression. With the help of linear approximation, get the approximate values of DF.
3. Tuning of stiffness is done by varying pre-strain

Damper Test:

Analyzing the gain and phase of a damper's response involves advanced testing equipment, such as damper dynamometers, to measure how the damper responds to different input frequencies and forces. This data is then used to fine-tune the damper's properties and settings, ultimately improving the overall performance and comfort of the vehicle's suspension system.

A damper dynamometer, also known as a shock absorber dynamometer or suspension damper tester, is a specialized testing device used to evaluate the performance and characteristics of automotive shock absorbers or dampers.

Analysis & Optimization

Damper equation excluding top mount -

1. Place a damper in the damper dynamometer

2. Vary the displacement of the free end of the damper while observing the force

3. Assume,

Input, u=z_c

Output, y =F_{zc}

According to the LTI module, $y = c\frac{du}{dt}$

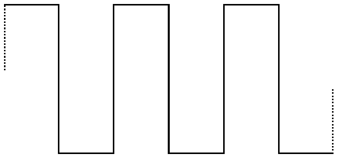
Hence,
(1)

$$\boxed{F_{zc} = c\frac{du}{dt}}$$

Result:

Damper displacement VS Time Response curve

Damper Force VS Time Response curve



Conclusion:

The sudden change in force response showcases a harsh ride response. These results are undesirable and unacceptable.

Damper equation including top mount -

To prevent the harsh ride response, dampers are attached to the vehicle bodies using compliant mounts. The resulting system is comprised of the top mount in series with the damper system.

Assume, Input, u =z_{kc}

Output, y=F_{zkc}

According to the linear time-invariant module,

$$\frac{c}{k} + \frac{dy}{dt} + y = c\frac{du}{dt} \qquad (2)$$

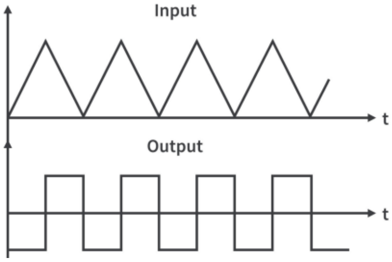
Putting u =z_{kc} and y=F_{zkc}

$$\frac{c}{k} + \frac{dFz_{kc}}{dt} + y = c\frac{dz_{kc}}{dt} \qquad (3)$$

Results: After the compliance of the top mount:

Damper displacement VS Time Response curve to

Damper Force VS Time Response curve:



Top Mount Tuning:

1. If the top mount is too compliant, it shows the spring-like behavior of the system, resulting in little damping. This type of damping has low energy absorption capability.
2. When the top mount is enough compliant, it provides a smooth ride, resulting in less loss of damping.
3. If the top mount is too stiff, it shows damper-like behavior, resulting in a harsh ride and providing a harsh response to sharp inputs.

Dynamical Systems:

Linear Time-Invariant System:

LTI systems are both linear and time-invariant. Linear systems include the output which changes linearly concerning the input. As the input changes linearly, the output also changes linearly in the LTI systems.[14]

So if the input x1(x)$x1(t)$ produces the output y1(y)$y1(t)$ and the input x2(x)$x2(t)$ produce the output y2(y)$y2(t)$, then linear combinations of those inputs will produce linear combinations of those outputs.

The input (x1(x)+x2(x))($x1(t)$+$x2(t)$) will produce output (x1(x)+x2(x))($y1(t)$+$y2(t)$).

Further, the input (x1·x1(x)+x2·x2(x))($a1$·$x1(t)$+$a2$·$x2(t)$) will produce output (x1·x1(x)+x2·x2(x))($a1$·$y1(t)$+$a2$·$y2(t)$) for constants x1$a1$ and x2$a2$.

In other words, for a system xT over time tx, composed of signals x1(x)$x1(t)$ and x2(x)$x2(t)$ with outputs x1(x)$y1(t)$ and x2(x)$y2(t)$, x[x1x1(x)+x2x2(x)]=y1y[y1(y)]+y2y[y2(y)]=x1y1(x)+y2x 2(y),$T[a1x1(t)+a2x2(t)]=a1T[x1(t)]+a2T[x2(t)]=a1y1(t)+a2y2(t)$, (4)

where x1a1 and y2a2 are constants.

Example:

In a passenger vehicle, the rolling motion of a wheel over a step is considered a geometric concern. The dynamical analysis comes into the picture to find out the body response to given road inputs. With the help of the linear-time invariant systems(LTI), the analysis is carried out.

The representation of the LTI system (considering a single input and output module) is as follows:

$$a_1 \frac{d^n y}{dt^n} + a_1 \frac{d^{n-1} y}{dt^n} + \cdots + a_n \frac{d^n y}{dt^n} + a_{n+1} y = b_1 \frac{d^m u}{dt^m} + b_2 \frac{d^{m-1} u}{dt^m} + \cdots + b_m \frac{du}{dt} + b_{m+1} u \quad (5)$$

a_i and b_i =coefficients of the linear time-invariant system

Approach: MATLAB mathematical solution

Transfer Function:

LTI systems can also be defined by their transfer function. The transfer function can be described as the Laplace transform from the impulse response. The transformation leads to the change in the time domain to the frequency domain. The transformation includes the change in the differential equations into the algebraic equations and turns convolution into multiplication. The out, the frequency domain is the product of the transfer function with the transformed input. The change is illustrated in the following figure:

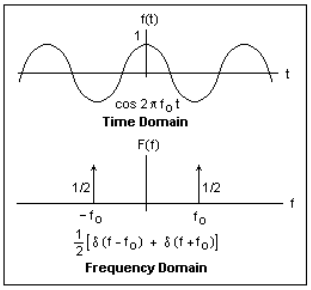


Figure 2:Transformation of time to frequency domain

The transfer function defines the complete system considering a single input and providing a single output. It is considered one of the most important systems for solving complications of the system.

For instance, the transfer function of 2 systems placed in series provides the output of the first system considering the input of the second system. It is a simple product of two transfer functions. Similarly, the transfer function for 2 systems placed in parallel is represented as the sum of the transfer of those 2 systems.

Frequency Response:

The alternate method of defining the LTI system is the frequency response. When a sine wave input is applied to the LTI system, the system shows stability initially. After the initial response, the output will be the sine wave with the same frequency, different amplitude, and different phase from the input signal.

The ratio of the sine wave frequency of the output to the sine wave frequency of the input is the gain of the system. The difference between the phases of two signals is defined as the phase shift. Combining both two signals, the system provides the frequency response of the overall system. The measurement of the frequency can be determined by the use of the frequency analyzer. The frequency analyzer offers sinusoid test signals and system response.

Principle of Superposition:

The most important part of the LTI is the principle of superposition. The principle of superposition states that the final response of the LTI system to the weighted sum of inputs is the same weighted sum of responses of those individual inputs[15].

Assume,

Input u= u1+u2

Output y=y1+y2

Where,

y1= response of the system when the input is u1

y2=response of the system when the input is u2

According to the principle of superposition,

$$u = u_1 + u_{2+} \dots\dots\dots\dots. + u_n \quad (6)$$

With corresponding output,

$$y = y_1 + y_2 + \cdots + y_n \qquad (7)$$

The principle of superposition offers the creation of a simple input as per the response of the system, providing an output on the verse of various responses given. The representation can be showcased in sine waves as per Fourier analysis.

Fourier Expansion:

Fourier series represents the periodic functions. The form of a series of inherently periodic with period 2π each completing n cycles of oscillations in the range of time interval. Thus, while the coefficients in a Fourier expansion are determined from an interval of length 2π, the expansion itself (if the function involved is periodic) applies for an indefinite range of *x*. The periodicity also means that the interval used for determining the coefficients need not be [0,2π] but may be any other interval of that length. [13]

Fourier analysis for a damper and a top mount system:

System Response to First Harmonic of Input:

When a sine wave is an input, perpetually an output is also a sine wave with a different amplitude and a phase shift. The response to the first input harmonic system of the damper:

System displacement Zkc (m) VS Time:

System Force Fzkc (N) VS Time:

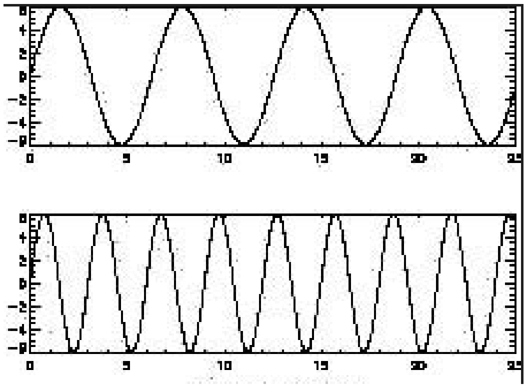


Figure 3: Transforming the sine wave into the cosine wave with a phase shift of π

System Response to the 2nd and 3rd harmonic Systems:

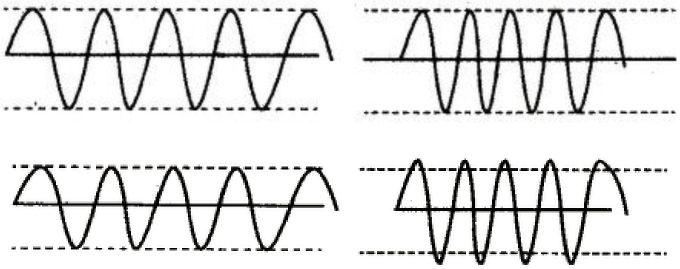


Figure 4:Sine waves transform to cosine waves

The graphs represent the optimization of the top mount concerning varying amplitude and phase shifts. The changes in graphs are frequency-dependent. For a given frequency in input, there is a change in amplitude (gain) and variation in the phase of the output. The system can be optimized with varying frequencies and fixed amplitude to inspect the behavior of the system on a sinusoidal input.

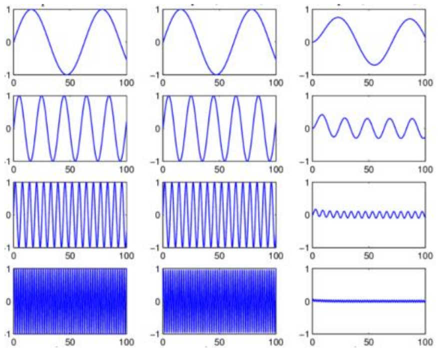


Figure 5:LTI response to sinusoidal input signal with four frequencies

The response represents variation in the gain and phase of the output as the top mount stiffness varies (input is same for all three cases)

Frequency vs. Top mount gain (logarithmic)

The frequency response and top mount gain relation show the transition from damper-like behavior (positive slope) to spring-like behavior (zero slopes). The transition frequency increases with the change in top mount stiffness.

Damper and Top Mount Phase:

Plot the system phase using a logarithmic frequency axis and a linear phase axis with phase in degrees.

The relation between the damper and top mount phase provides a transition from damper-like behavior (90-degree phase) to spring-like behavior (zero phase change).

The transition frequency reached when the phase shifted to 45 degrees.

Mathematical representation of the phase shift

$$f_{shift} = \frac{K}{2\pi C} \quad (8)$$

Case Study

Optimizing Top Mount Characteristics for Improved Suspension Performance

Background: The aim was to enhance performance and ride comfort of a new model. We recognized that optimizing the characteristics of the top mount in the suspension system could play a crucial role in achieving goals.

Challenge: The existing suspension setup provided good handling, but there were concerns about ride comfort on uneven roads. We aimed to strike a balance between handling and a smoother ride without compromising stability.

Approach: We embarked on a comprehensive study that involved testing and optimizing the top mount characteristics. Here's an overview of the approach:

- The study highlights the importance of considering even seemingly minor components like the top mount in the pursuit of a well-rounded driving experience.
- The new top mount configurations were tested in controlled environments, such as a test track and a simulation rig that replicated various road conditions. The manufacturer assessed the suspension's behavior, ride comfort, stability, and handling qualities.
- Examined the tuning of the rear damper top bushes.
- Plot damper force vs. velocity graph

Damping Force		Front	Rear
Velocity (m/s)		DF(kg)	DF(kg)
Rebound	0.05	2630	1240
	0.13	1970	850
	0.26	1760	740
	0.39	1470	620
	0.52	690	470
	1.02	250	260
Compression	0.05	140	100
	0.13	330	220
	0.26	440	300
	0.39	530	350
	0.52	610	400
	1.02	910	560

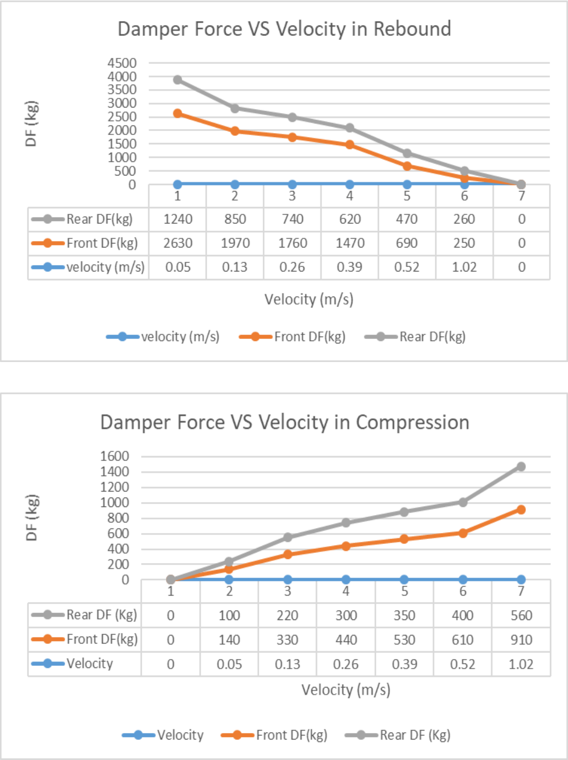
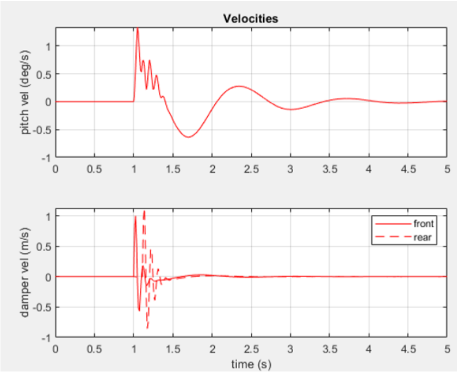
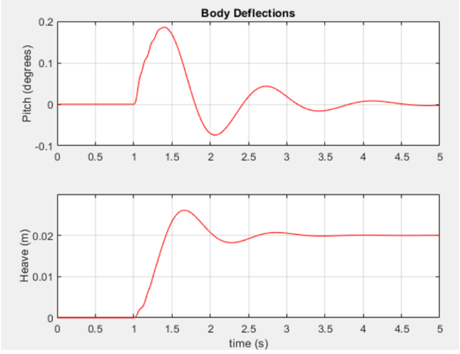


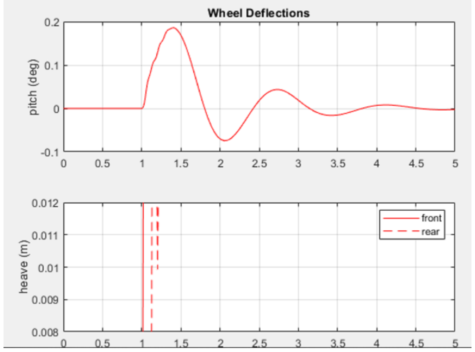
Figure 6: Damper Force VS Velocity linear approximation

- The graph provides damper behavior in rebound and compression. It has been observed that the damper performs different in rebound, different in compression and has a falling rate with increasing velocities.
- By analyzing the graph, the approximate linear rate of C was found:
  C =1200 Ns/m
- Calculated rate of top mount
- Calculated load and deflection

Load Vs Deflection Outputs:







The graphs represent the non-linear load and deflection characteristics of one-half of the top mount.

Top bushes with selected damper were evaluated on the vehicle and a 90% correlation was observed.

The same theory was applied while designing a dual path top mount in order to improve secondary ride without affecting the handling.

Conclusion

This case study demonstrates how optimizing the characteristics of the top mount can significantly influence the overall performance of a vehicle's suspension system. By employing a systematic approach that combines real-world testing, and engineering calculations, we have successfully achieved the objectives of improving ride comfort and handling qualities while maintaining stability and control.

Optimized Design Development:

Pre-strain	Stiffness	F trans(HZ)
10	250000	33.17
15	700000	92.88

The results in the table show that the pre-strain of 10mm and 15mm are providing higher shift frequencies. The band range to smoothen harsh inputs should be in the range of 0 to 20 HZ

Results and Discussion:

After the implication of theory of this study, the secondary ride and impact harshness has been improved by 30%.

Additional benefits observed:

a. 200 Man Hours saved.

b. The time required for development was reduced by 4 weeks.

c. Proto-cost saving – INR 0.5 Cr.

References

1. X. Yang, D. Zhang, S. Medapalli, and M. Malik, “Suspension tuning parameters affecting impact harshness performance evaluation,” SAE Paper, no. 2006-01-0991, 2006.

2. M. Kaldas, K. Calıskan, R.Henze, and F.K¨uc¨ukay, The influence of damper top mount characteristics on vehicle ride comfort and harshness: parametric study,” SAE International Journal of Passenger Cars-Mechanical Systems, vol 5, no. 1, pp.1-21,2012.

3. B. Heißing and M. Ersoy, Chassis Handbook, Vieweg & TeubnerVerlag, Springer Fachmedien Wiesbaden GmbH, 1st edition, 2011.

4. S. Dehbari, J. Marzbanrad, “Kinematics and Dynamic Analysis of new MacPherson Strut Suspension System”, Mechanics and mechanical engineering, July 2018.

5. Mina M. S. Kaldas, Kemal Çalışkan, Roman Henze, Ferit Küçükay, "Optimization of Damper Top Mount Characteristics to Improve Vehicle Ride Comfort and Harshness", Shock and Vibration, vol. 2014, Article ID 248129, 15 pages, 2014.
6. Rahul Sharma, "Role of Dampers in NVH CAE procedures, Faculty of Engineering, Blekinge Institute of Technology, 371 79 Karlskrona, Sweden, Nov 2021.
7. M. Aydın and Y. Ünlüsoy, "Optimization of suspension parameters to improve impact harshness of road vehicles," The International Journal of Advanced Manufacturing Technology, vol. 60, no. 5, pp. 743–754, 2012.
8. M. J. Thoresson, P. E. Uys, P. S. Els, and J. A. Snyman, "Efficient optimization of a vehicle suspension system, using a gradient-based approximation method, Part 2: optimization results," Mathematical and Computer Modelling, vol. 50, no. 9-10, pp. 1437–1447, 2009.
9. X. Wu, M. Farhad, and R. Sheets, "Designing suspensions to achieve desirable impact harshness and impact shake performance," SAE Paper, no. 2007-01-0585, 2007.
10. A. F. Naudé and J. A. Snyman, "Optimisation of road vehicle passive suspension systems. Part 2. Qualification and case study," Applied Mathematical Modelling, vol. 27, no. 4, pp. 263–274, 2003.
11. X. Yang and S. Medepalli, "Sensitivities of suspension bushings on vehicle impact harshness performances," Tech. Rep. 2005-01-0827, SAE Paper, 2005.
12. M. Gobbi, G. Mastinu & C. Doniselli (1999) Optimising a Car Chassis, Vehicle System Dynamics, 32:2-3, 149-170, DOI: 10.1076/vesd.32.2.149.2085
13. James Kirkwood, "Mathematical Physics with Partial Differential Equations," Academic Press, 2018.
14. Ming Zhang, Xiaoming Chen, "The Importance of Continuity for Linear Time-Invariant Systems [Lecture Notes]", IEEE Signal Processing Magazine, vol.37, no.2, pp.77-100, 2020.
15. M. Zhang and A. Zhang, "The Superposition Principle of Linear Time-Invariant Systems [Lecture Notes]," in IEEE Signal Processing Magazine, vol. 36, no. 6, pp. 153-156, Nov. 2019.
16. Alex Chumbley, João Areias, Christopher Williams. "Linear Time Invariant Systems", Brilliant.org. Retrieved 16:05, August 23, 2023, from https://brilliant.org/wiki/linear-time-invariant-systems/
17. Sinha, A., H. Vijay, A. & Sinha, U. On the superposition principle in interference experiments. Sci Rep 5, 10304 (2015). https://doi.org/10.1038/srep10304
18. Acoustics Testing Laboratory of the NASA Glenn Research Center (Distributor), Auditory Demonstrations II: Challenges in Speech Communication and Music Listening, Available from the NASA Glenn Research Center Acoustical Testing Laboratory 04 from http://acousticaltest.grc.nasa.gov, Dec 2003.
19. SAE International, "How Does SAE World Congress Enable

    Industry Networking and Relationship-Building?" SAE Video 10943, uploaded Nov. 11, 2011.
20. Mulder, Max & Van Paassen, Marinus M. & Flach, John & Jagacinski, R.J.. (2005). Fundamentals of Manual Control Theory. https://www.researchgate.net/publication/278677973_Fundamentals_of_Manual_Control_Theory

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