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Research Article

Optimization of the Vibrational Comfort of Passenger Vehicles through Improvement of Suspension and Engine Rubber Mounting Setups

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The aim of this work is to develop a measurement methodology to perform a vibration analysis of a vehicle. It proposes new setups in the suspension systems, including springs, shock absorbers, and rubber mountings of the engine system, to improve the passengers' comfort levels. The influence of each of these modifications in the vibration levels at specific points is analyzed. The importance of human interaction analysis is clear as, in the past, it was frequently left aside. This is because only the vehicle dynamic behavior is generally emphasized in the vehicles designed. Therefore, this work stresses that concerns about human vibration levels result in vehicles with good performance also in comfort levels, focusing on the users' well-being. A combination of different sets of rubber mountings, springs, and shock absorbers are tested. The changes proposed in this paper are analyzed in sequence and, based on the results, the best combination is proposed.

1. Introduction

When developing a vehicle, the use of the so-called vehicle comfort analysis (or VCA) is generally employed. This involves the quantification of the comfort level perceived by the user, correlating the amplitudes and frequencies in a variety of surfaces to the subjective and objective evaluations of their influence in the human body.

Changes in parts of the vehicle suspension system, such as the set of springs and shock absorbers and the rubber mountings of the engine system, are made to ensure good comfort levels to the users, both static as well as dynamic.

Many papers were published based on this type of analysis made on the vehicle, only focusing on their influence on certain parts of the system [1–6]. Some papers use similar test track conditions to this paper [7, 8], and others use distinct methodologies [9–11].

There are also papers performing the same type of measurement, however, focusing on vibrations at higher frequency spectrum, aiming to study the discomfort caused by noise, vibration, and harshness [12, 13].

The vehicle comfort analysis (VCA) methodology can be used both at the concept stage, as well as at some face-lifts afterward.

In this paper, the use of the VCA methodology is proposed in order to analyze the comfort levels of the vehicle according to predetermined vibration levels [14]. Therefore, it is possible to compare with competitor's vehicles in the market, to study specific parts improvements, to analyze proposals that result in cost reduction, and to point solutions to identified problems, among other uses.

The proposed analysis does not focus on the car vibrations itself, but in the influence of the declared vibrations by the users. So, it is important to know that the human body has some natural frequencies that when in resonance with frequencies present in the vehicle, might cause symptoms that goes from a small discomfort and might get to dizziness and nausea [15, 16].

Then, during the development of a vehicle, the coupling of these frequencies should be balanced in the best way possible, avoiding, for example, that the engine and the suspension work at the same frequency levels getting into resonance, which would make the driver feel a great deal of vertical vibration on his/her feet.

The study of the engine rigid body and natural frequencies is quite important since they are relevant for the vibration comfort in a vehicle. This engine-induced effect is called engine shake. As the name itself suggests, this is connected to the engine movement, which has vibration frequency at the same frequency spectrum as some excitations coming from the suspension. Consequently, some specific frequencies are common between the engine (at its operational regime) and the vehicle suspension (under the track influence). Both excite the car body directly influencing the comfort inside the vehicle.

This happens in the following way:

(i) The unsprung mass is excited by the track in a specific frequency. The response is the natural frequency of the suspension added to the track frequency.

(ii) The car body is excited by that unsprung mass, adding to the aforementioned frequencies, the vibration frequencies of the car body itself.

(iii) The engine is excited by the car body, making it have the three previous frequencies plus the vibration frequencies of the engine itself.

(iv) Finally, the car body is excited by the engine at its vibration frequencies. These matches the vibration coming from the track across the suspension, causing an increase in the vibration amplitude.

The resonances in the frequency range of interest are obtained by accelerometers installed at the vehicle, allowing analyzing if the levels of engine shaking are acceptable or beyond the limit.

The mentioned behavior can be easily seen below, in the region marked in yellow, which shows the difference between the movement of the dead pedal and the seat rail, that is, the engine shake effects.

Such difference happens because the dead pedal is closer to the engine, making it subjected to a bigger influence of the engine vibration, whereas the seat rail is subjected to a smaller influence.

Looking at Figure 1 is noted that the seat rail has amplitudes in the engine modes close to 0.015 g and at the suspension modes close to 0.022 g, being practically equal, whereas in the dead pedal the vibrations are 0.045 g for the engine and 0.020 g for the suspension, what makes the visualization easier.

It is important to remember that much of the improvement in the engine shake levels comes from the subjective conclusions of test drivers. This is because the mentioned resonance is expressively perceived by the human body, and, for being highly perceivable, causes great discomfort. So, high levels of engine shake should always be avoided.

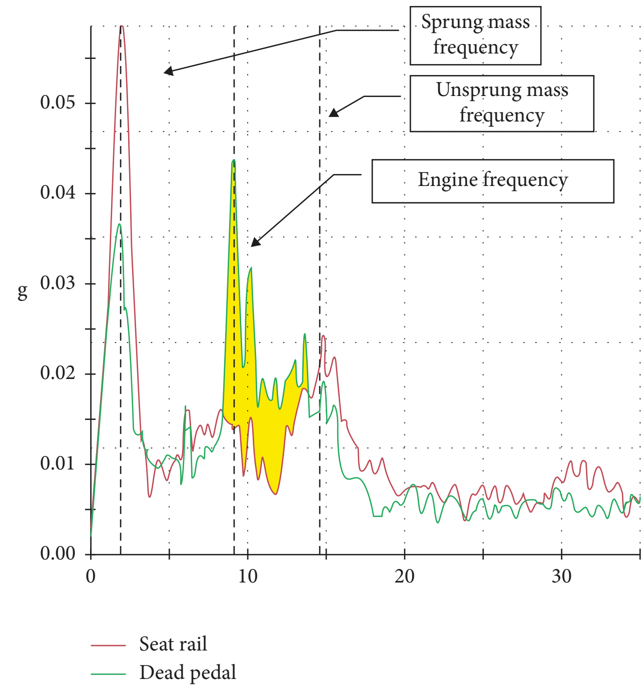

Figure 1: Engine Shake illustration.

2. Materials and Methods

To perform vibration measurements and to observe if the frequencies and amplitudes are within the expected values, a standard procedure should be adopted. This involves the instrumentation to be used, the track conditions for each test, details on how the signal analysis should be developed, and how to remove the instrumentation from the vehicle without causing any damage to the equipment since it is highly sensitive to impacts. To comply with the rules established by the methodology, all the details should be treated carefully, as they are responsible for the reliability and acceptance that this analysis has within the car manufacturers. This is also important at the end of the acquisition, to allow comparison with previously obtained data.

In this paper, the acquisitions were made in mixed track conditions [8]. They can be regarded as standards during the use of a vehicle in Brazil, aiming to bring the results as close as possible to what is perceived by the final user on their daily activities. In most cases, except to solve specific problems, to get results as close as possible to the real use of the car, measurements are made in three conditions: smooth soil (new asphalt), irregular soil (repaired asphalt), and rough soil (harsh asphalt) [7].

The objective evaluations are validated by the measurement of the vibration levels energy in specific points of the vehicle, that, when instrumented, show how the car behaves in different situations. The subjective evaluation is made by engineers trained to sense the discomfort of the vehicle, what in some cases, common users do not notice.

In the tests performed in this paper, the comfort level of the vehicle is evaluated by comparing the signals collected from a prototype with different suspension settings, and from a reference vehicle from the same manufacturer and in the same market position.

Triaxial accelerometers are used to measure the levels of vibration in each of the desired points in the vehicle. These points should be instrumented to depend on the focus of the analysis and they can be the following: the hubs of each wheel; the four fixation points of the shock absorber in the chassis; the three engine rubber mountings; the seat; the backrest; the seat rail; the dead pedal; and the steering wheel.

There are cases in which other points are instrumented for specific studies. However, in these cases, the signals gathered are only used for comparison in those specific studies, as they are not comparable with standard signals regularly used.

For the present study, the monitored points are presented in Table 1.

For all the points, triaxial accelerometers are used, fixed according to the standard orientation in the vehicle, that is, X axis (longitudinal) positive to the front of the car; Y-axis (transversal) positive to the left; and Z axis (vertical), positive upwards, following the right-hand rule.

A GPS is used to get the speed signals. The speed of the vehicle is gathered and recorded across all the data acquisition tracks, to have a way to validate the signal. It should be obtained at a constant speed previously determined for each track. It is important to check tire pressure, accelerometers' axis position along the car, and to eliminate the offset of the used sensors.

At the end of the instrumentation, the operation of the sensors should be checked, to ensure the quality of the signal. The software and hardware used to digitalize and gather the data, in the case of this paper, are Catman® [17] and MGCplus® [18], respectively. The predicted acquisition rate used was 1200 Hz, which is 10 times higher than the desired frequency of 120 Hz, to prevent loss of signal quality.

At this work, three types of tracks are used, and at least five runs performed along each one of them, to ensure that at least three valid runs are obtained.

Table 2 presents the data description for the standard tracks used.

In order to maintain a standard, it is important to have, alongside the data collected, photographs of each point instrumented, notes with information about the vehicle, such as weight and tire pressure, besides detailed information about the parts used in each setup.

The mentioned signal analysis follows a series of steps, to improve the signal quality, removing unnecessary information. The collected signals shall be imported, and the following steps performed:

(i) Signal filter using a 120 Hz low-pass filter, eliminating high frequencies, unwanted for this kind of study

(ii) As the acquisition frequency used (1200 Hz) is high and more than necessary for the desired study, a resampling of the signals to a lower frequency, 512 Hz, and the elimination of signal distortions shall be performed, making the signal cleaner and more consistent

(iii) The resampled signals are treated by a frequency analysis method that uses a Fourier transform algorithm to get a frequency spectrum content

Table 1: Monitored points.

Point	Objective
Dead pedal	Engine shake
Seat rail	Engine shake
Engine rubber mounting	Engine shake
Transmission rubber mounting	Engine shake
Front wheel rub	Unsprung mass frequency
Rear wheel rub	Unsprung mass frequency
Front shock absorber	Sprung mass frequency
Rear shock absorber	Sprung mass frequency

Table 2: Standard tracks description.

Soil	Asphalt condition	Velocity	Gear
Irregular	Repaired	60 km/h	3rd
Rough	Harsh	40 km/h	3rd
Smooth	New	80 km/h	4th

(iv) Finally, the average value between the three signals at each track is calculated, creating a signal that better represents the behavior of the vehicle, eliminating punctual errors that exist in some runs, like big defects in the track or needed trajectory corrections

The range of frequencies used is defined according to the type of study performed. The proposed methodology is capable of analyzing, among other factors:

(i) Unsprung mass frequency uses the signal of the Z axis at the wheel hubs, comparing front and back of the car in order to analyze the difference between the suspensions. It has acceptable values between 12 Hz–15 Hz for the hatchback segment [19].

(ii) Sprung mass frequency uses two of the four signals from the attachment points of the shock absorbers in the Z axis, and, if needed, the software calculates the frequency of vibration of the car body. For the hatchback segment, values between 1 Hz and 3 Hz are acceptable [19].

(iii) Engine frequency: using the signals from the three accelerometers at the engine, the frequencies in which the engine rotates or translates in each of its three directions are analyzed.

(iv) Frequency of engine shake uses the accelerometers at the dead pedal and at the seat rail, resulting in all the vehicle movement, directly felt by the user. It is graphically seen when the signals from the dead pedal and the seat rail are analyzed together in the Z axis.

In the development of a new project, the vehicle is compared to other stages of the same project. This means comparing the same vehicle with different setups of engine and suspension, to obtain the best set to be manufactured.

Moreover, comparisons with different vehicles at the same market position as the competitors can be made, allowing to verify the adequacy of the comfort level of the vehicle for its intended market.

In order to show what the analysis brought in knowledge and improvement to the project, the relevant information and valid improvement suggestions are summarized. They can be directly related to car parts, as in the case of this paper, or just geometry or structural adjustments in the vehicle.

The analyzed case investigated in this work consists of the design of a small hatchback vehicle denominated simply as Vehicle A, and a reference vehicle denominated as Reference. The names of the vehicles were suppressed for nondisclosure reason.

Vehicle A is an entry-level car, with a 1 liter displacement engine. It underwent Ride adjustments. This is the initial condition considered in this work. When it was evaluated by the product quality sector, it does not fulfill the levels of vibrational comfort suitable for the market the manufacturer wished to insert it.

The proposition made initially modified the suspension of the vehicle (springs and shock absorbers) and right after also altered the vertical stiffness of the engine rubber mounting, which is responsible for absorbing a great deal of the engine movements.

For this paper, four acquisition runs were made, three on the prototype of the Vehicle A and one on the Reference, all using the track with the repaired asphalt, for being the track most fit for this evaluation, with more track irregularities.

The acquisitions were named in the following manner:

(i) Reference consists of a model already in production that has medium complaints index related to its comfort level.

(ii) 1st Ride rubber NP: acquisition made on the prototype, with the suspension setup defined by the 1st ride, using a rubber mounting with specifications already known by the factory, called here as a normal production part, shortened as NP.

(iii) 2nd Ride rubber NP: using the same prototype, but with the second suspension setup for the vehicle, proposed by this paper, refined by various subjective tests, and still the same engine rubber mounting of the previous acquisition.

(iv) 2nd Ride proposed rubber: with the suspension of the second ride and a new engine rubber mounting, yet never used by the factory, with an improvement proposition.

As it can be seen in Table 3, the two-vehicle suspension solutions differ from each other in the spring preload and in the damping of the shock absorbers. The engine suspensions differ by the stiffness in the vertical axis, that is, the Z axis, of the rubber mounting applied on the engine.

3. Results

As already mentioned, this paper aims to show the effects of the suspension setups of a vehicle, modified during the Ride phase, relative to the users' comfort. Besides, this paper also shows how the methodology of vehicle comfort analysis (VCA) is important to guarantee good levels of vibration, making the vehicle more pleasant for its users.

The front and rear suspensions were modified during the development phase through changes in the parameters of the springs and shock absorbers, to achieve the desired level.

The results of the modifications can be seen in Figures 2 and 3, showing the signals gathered in the front and rear wheel hub, respectively. It is noticeable that the second suspension setup has vibrational behavior with a slightly bigger amplitude, which is minimized using the proposed engine rubber mounting.

An explanation for that is the fact that the second suspension setup was chosen to be stiffer, which decreases the ability to filter vibrations, so to achieve, besides the desired comfort level, a minimum level of handling is needed.

The mentioned choice was made because the engine rubber mounting was still to be altered, to minimize the suspension modification. It should be noted that the VCA helps to understand up to which points comfort can be compromised to improve handling, without reaching concerning comfort levels, as this work's focus is the response the user perceives, not the response of the suspension itself.

Looking at the analysis of the fixation point of the frontal shock absorber, Figure 4, the second suspension setup does not mean to improve comfort, but the proposed rubber mounting has this objective, eliminating a great deal of the discomfort caused by the stiffer suspension.

It is important to understand that during the Ride of the vehicle, which is the phase of adjustments in the vehicle and engine suspensions, not only comfort-oriented modifications are made. The stability and handling of a vehicle should also be of paramount importance because that is what makes the vehicle safe and fit to be driven by common drivers. A car excessively focused on comfort might become dangerous in emergency conditions.

Thus, having a proposed suspension focused on handling, a third proposal is tested, with an engine rubber mounting capable of maintaining the handling level but assuring the expected comfort improvement.

When the fixation point of the rear shock absorber is analyzed (Figure 5), it is seen that opposing the aforementioned analysis of the front suspension, there is a big improvement in the vibration at the second suspension setup, even with the NP rubber mountings. This demonstrates that even the suspension is stiffer, a more desirable vibration is achieved.

It is also seen that because of the distance between the engine and the rear axle, the proposed rubber mounting has a very small effect when analyzing the rear suspension, opposing the big effects on the front suspension analysis.

Figure 6 shows the efficiency of the proposed rubber mounting in the raw signals of the engine rubber mounting, mainly in the interest frequencies between 8 Hz and 15 Hz, coincident with the engine shake.

The above modification also has a significant effect on the transmission side, as the rubber mountings are closely related.

Figure 7 shows the less efficient engine suspension of the reference vehicle, as it is an older model with a less improved rubber mounting solution.

Table 3: Description of each acquisition.

Acquisition	1st Ride rubber NP	2nd Ride rubber NP	2nd Ride proposed rubber
Engine rubber mounting (stiffness–Z axis)	110 N/mm	110 N/mm	90 N/mm
Transmission rubber mounting (stiffness–Z axis)	195 N/mm	195 N/mm	195 N/mm
Third point rubber mounting (stiffness–Z axis)	170 N/mm	170 N/mm	170 N/mm
Front spring (flexibility and preload)	0.535 mm/daN Preload: 2720N	0.535 mm/daN Preload: 2900N	0.535 mm/daN Preload: 2900N
Rear spring (flexibility and preload)	0.29–0.18 mm/daN Preload: 3515N	0.29–0.18 mm/daN Preload: 3340N	0.29–0.18 mm/daN Preload: 3340N
Front shock absorbers (code and damping)	~1849.3 N s/m Code: 208	~1821.5 N s/m Code: 407	~1821.5 N s/m Code: 407
Rear shock absorbers (code and damping)	~1429.5 N s/m Code: 93	~1452.4 N s/m Code: 415	~1452.4 N s/m Code: 415

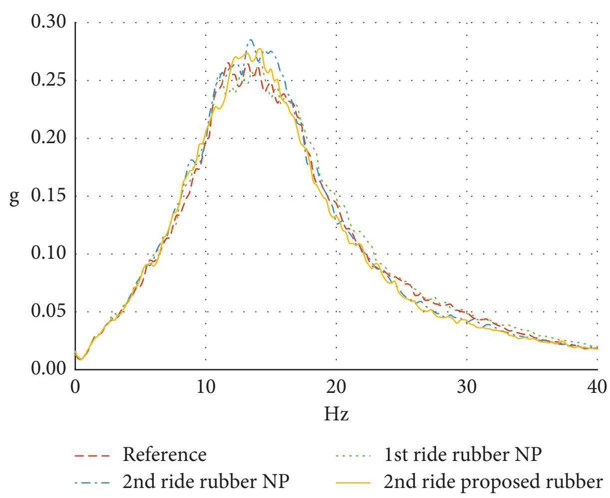

Figure 2: Vibration of the front wheel hub—Z axis.

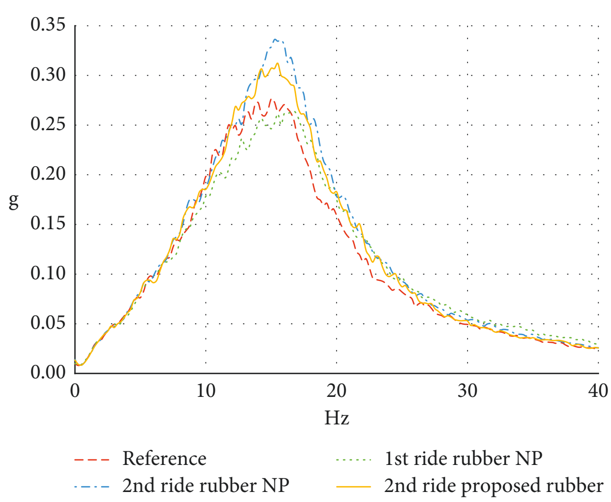

Figure 3: Vibration of the rear wheel hub—Z axis.

In the sense of perceived comfort, the cabin is the focus of bigger concern in Ride. Therefore, Figure 8 shows that the last solution represents the best conditions in user comfort in practically all frequency spectrum, being the dead pedal close to the driver the region most affected by this solution. This region is the main focus of this work since it deals with a passenger vehicle.

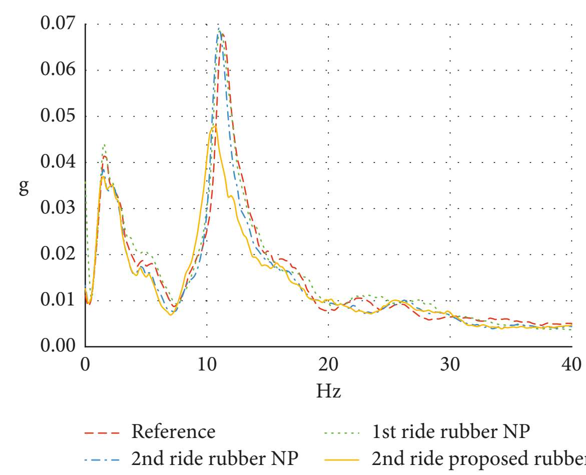

Figure 4: Vibration in the fixation point of the front shock absorber—Z axis.

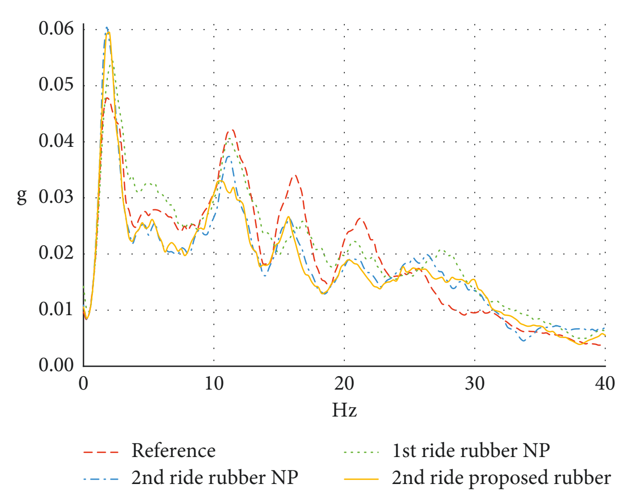

Figure 5: Vibration in the fixation point of the rear shock absorber—Z axis.

The vibration in the seat rail (Figure 9) also shows that the second suspension setup (which presents better handling), combined with the proposed engine rubber mounting, perfectly fulfills the required comfort levels, making the vehicle to present its users a more pleasant sensation during driving.

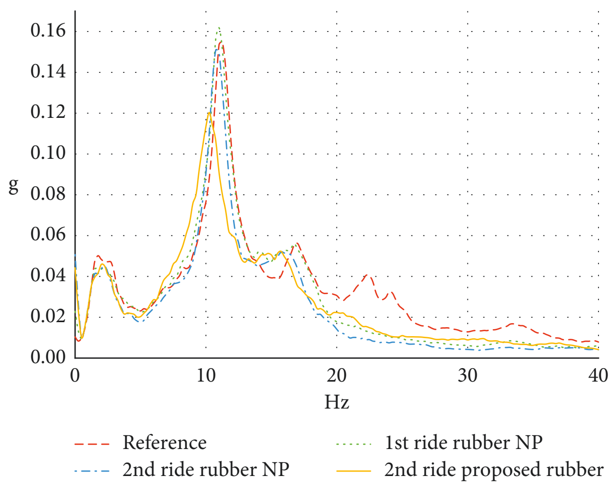

Figure 6: Vibration in the engine rubber mounting—Z axis.

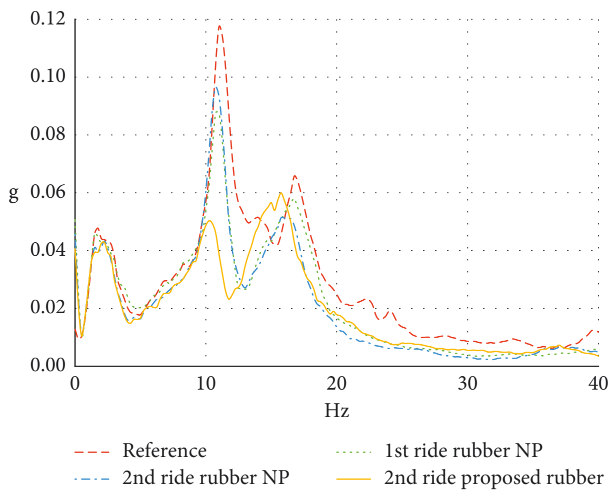

Figure 7: Vibration in the transmission rubber mounting—Z axis.

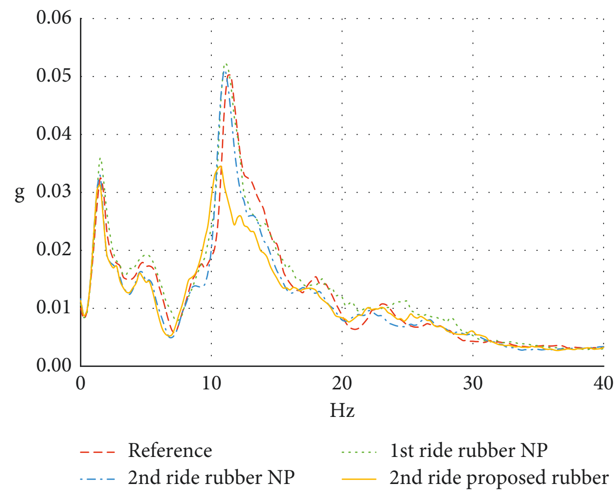

Figure 8: Vibration in the dead pedal—Z axis.

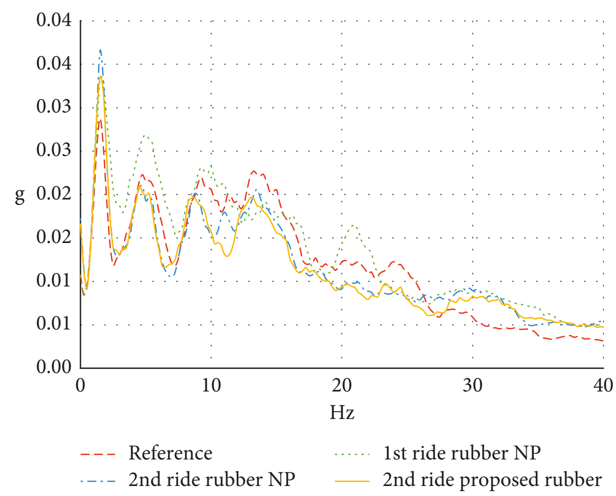

Figure 9: Vibration in the seat rail—Z axis.

When evaluating the last proposal behavior regarding the second most relevant axis (X axis), Figure 10, it is noticeable that a large reduction of vibration amplitude occurs in all frequencies between 0 and 40 Hz.

And so, the vehicle is not more comfortable only in the Z axis (vertical response), but also in the X-axis, which represents the responses to acceleration and braking, in which the vehicle moves to the front and back, as in speed bumps and short braking during traffic jams, for example.

Figure 11, which uses the effects of the engine shake as a reference (highlighted in yellow), demonstrates that through a Ride analysis and with the help of VCA, it is possible to obtain better comfort levels to the users.

Such effect has great influence on the vehicle quality since it is sensed by whatever vehicle user, even those with a little sensibility to vibration. This is because the driving quality is affected, mainly during long journeys.

Analyzing the effects of each of the acquisitions performed in this work, some observations can be highlighted. It is initially perceived that, for the Reference vehicle, which has a medium rate of complaints about vibration from the consumers, there is a band of engine shake that reaches acceleration levels of 0.05 g or 0.49 m/s^2 (Figure 11).

The first solution of the prototype, an increase in the yellow area compared to the Reference vehicle (Figure 11), indicates a worse sensation of engine shake. As a result, it is important to elaborate on new proposals.

When the springs and the shock absorbers are altered, aiming for handling improvement, it is perceived that the behavior related to the dead pedal and the seat rail is altered, increasing the total RMS values in the curves, as shown in Figure 11. The stiffer suspension shows a bigger vibration in the wheel hubs compared with other positions in the vehicle, degrading by a significant level the comfort perceived by the user, even if that is not identified in terms of the peak amplitude.

Although the second suspension solution does not cause a decrease in comfort levels, it shows no improvement in comparison with the Reference vehicle in terms of comfort, and the only improvement was in handling (Figure 11).

In the last proposal, the use of an engine rubber mounting with a different stiffness level, represented in the

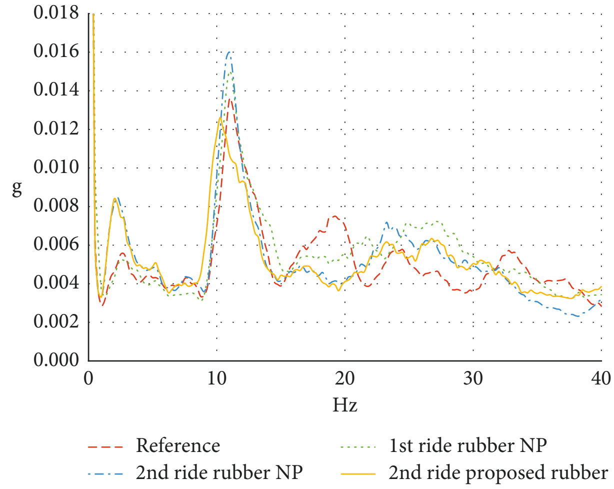

Figure 10: Vibration in the seat rail—X axis.

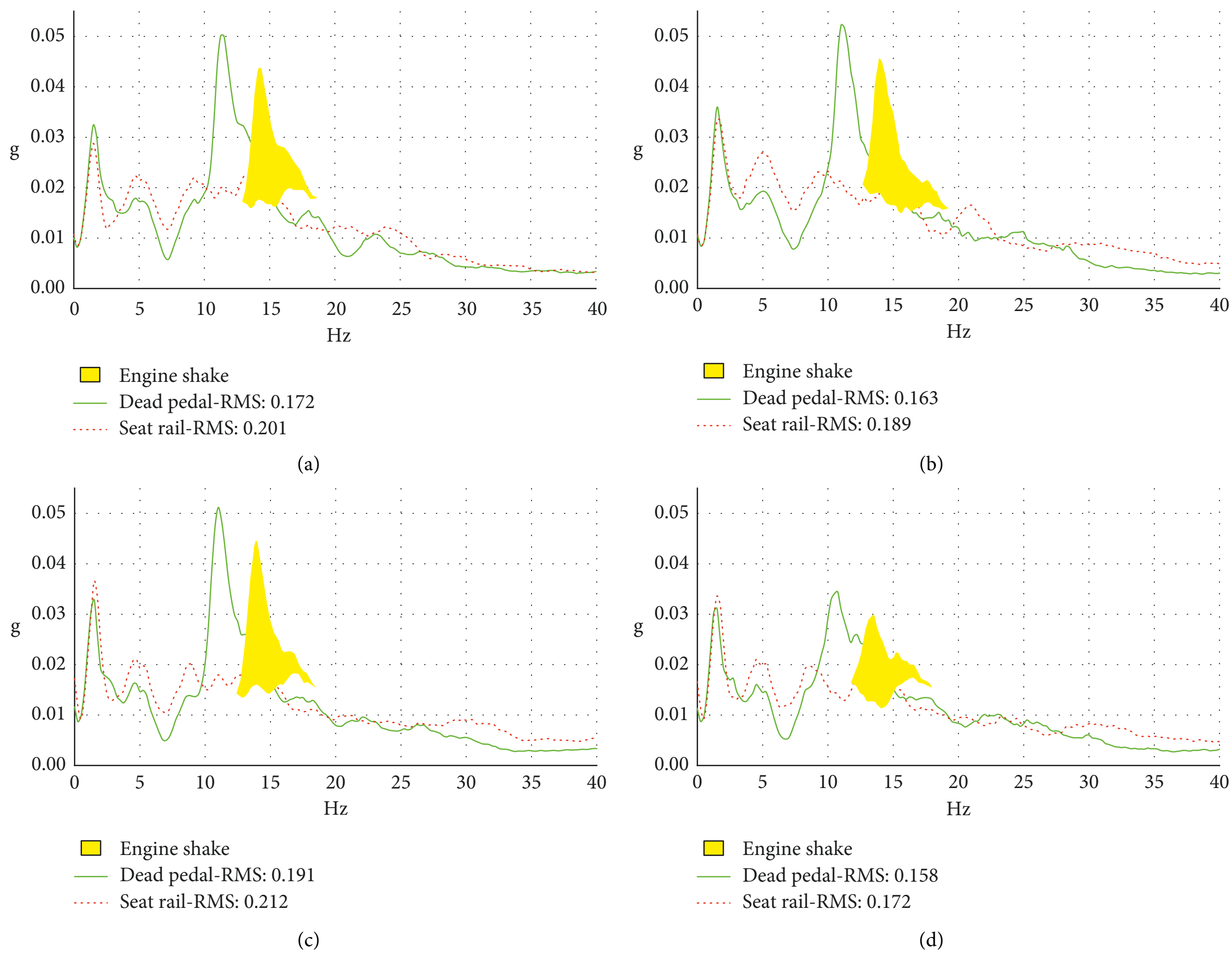

Figure 11: Engine shake effect RMS values.

Figure 11, shows that the vibration amplitude felt in the dead pedal was 0.04g, or 0.39m/s^2, evidencing a significant decrease in the range of the engine shake effect.In the last proposal, adopting a new level of stiffness for the engine rubber mounting, it is clear in Figure 11, the smaller vibration amplitude felt in the dead pedal, reaching 0.04 g or

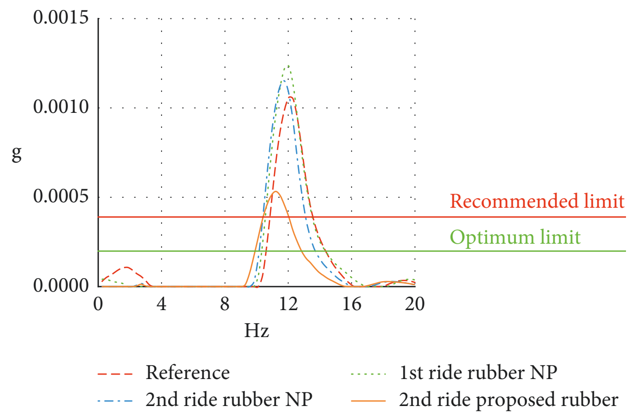

Figure 12: Evidence of improvement of the solutions.

Table 4: Description of the peak values of vibration amplitudes and critical frequencies.

Point or effect	1st Ride rubber NP	2nd Ride rubber NP	2nd Ride proposed rubber
Front wheel rub	0.26 g @ 14.25 Hz	0.28 g @ 13.50 Hz	0.27 g @ 14.00 Hz
Rear wheel rub	0.26 g @ 16.75 Hz	0.33 g @ 15.25 Hz	0.31 g @ 15.50 Hz
Front shock absorber	0.07 g @ 11.5 Hz	0.07 g @ 11.00 Hz	0.04 g @ 10.75 Hz
Rear shock absorber	0.05 g @ 2.25 Hz	0.06 g @ 1.75 Hz	0.06 g @ 2.00 Hz
Engine rubber mounting	0.17 g @ 11.00 Hz	0.15 g @ 10.75 Hz	0.12 g @ 10.25 Hz
Transmission rubber mounting	0.08 @ 10.75 Hz	0.09 @ 10.75 Hz	0.06 g @ 15.75 Hz
Dead pedal	0.05 @ 11.00 Hz	0.05 @ 11.00 Hz	0.03 @ 10.75 Hz
Seat rail	0.03 @ 1.50 Hz	0.04 @ 1.50 Hz	0.03 @ 1.50 Hz
Engine shake	0.0012 g @ 11.75 Hz	0.0011 g @ 11.50 Hz	0.0005 g @ 11.00 Hz

0.39 m/s^2, decreasing significantly the range of the engine shake effect.

The movement decrease is giving by a ~30% of the amplitude of the bigger peak in the dead pedal, from 0.49 m/s^2 to 0.34 m/s^2 (Figure 11) and a decrease of 18–19% in the total RMS, which highlights a significant subjective improvement. This achievement is in a great deal because of the new rubber mounting.

The engine shake can be graphically verified when calculating the difference between the signals coming from the dead pedal, denominated ZZP, and from the seat rail, denominated ZZG, as follows:

$$\text{engine shake} = \frac{(\text{ZZP} - \text{ZZG})}{\text{ZZG}}. \quad (1)$$

The results of the calculation are shown in Figure 12. The upper horizontal red line establishes the maximum acceptable level of the difference, and the lower horizontal green line, the limit of action of this difference, in which some measure must be taken regarding comfort improvement, limits those stated by the Directive EU 44/2002 [14].

The results of the first four acquisitions are shown in Figure 12, to highlight the difference between them.

A similarity in vehicle response is noted. The peak responsible for the engine shake effect happened between 10 and 14 Hz, with a secondary peak, close to 18 Hz.

For each of those is identified the peak frequency where the biggest amplitude occurred, and the value of this amplitude is referenced and calculated through the difference between the response in the dead pedal and the seat rail, as aforementioned.

For the reference vehicle, there is an amplitude above the expected (0.00105 g at 11.5 Hz), so it is clear for its project, that either methodology of comfort index might not have been used, or, they were not successful against the engine shake effect.

This is very common, as this kind of analysis is just recently a concern in entry-level vehicle projects. Vibration comfort concern is present only on higher level products.

The vehicle defined in the first Ride had even worse indexes than the Reference vehicle (0.0012 g at 11.75 Hz), being this the reason for the product quality sector not approving this suspension setup.

In the third proposal (focusing on improving handling), the vehicle comfort quality gets worse, keeping a peak at 11.5 Hz but reaching higher amplitudes (0.00115 g). The reason is that the rubber mounting is not being adapted to the springs and shock absorbers work.

Finally, installing the proposed rubber mounting, the vehicle presents amplitude closer to the acceptable limit (0.00053 g at 11.00 Hz) compared with the other solutions, despite still exceeding it by 13%. Hence, it has a better comfort level for the user.

For an easier visualization of the obtained results and achieved improvements, Table 4 gathers the peak amplitudes of vibration with their respective critical frequencies, for each of the measured points of the vehicle.

4. Conclusions

As discussed in this work, the engine shake effect has a great influence in the vibration quality of the vehicle, as it is perceived by any user of the vehicle, even if the user has a low sensibility to vibration. It may cause relevant discomfort during driving, especially for a long period of time.

For the vehicle studied in this work, to get a better comfort level avoiding exceeding the maximum acceptable level, it would be necessary, for example, an investment in designing a rubber mounting at the gearbox side with the same solution as the one at the engine side (hydraulic).

However, the cost of this improvement would not be interesting for the industry, as the vehicles of this market segment are not built with this objective, rather they are focused in costing less for the clients.

Nevertheless, the results obtained and described in this work show the direct influence of changes in the setups of components of the suspension in the results of comfort perceived by the users. It is clear the achievement of a very significant improvement with the proposed vehicle and engine suspension, allowing it to be applied in the project.

Furthermore, it is clear how the VCA methodology, which focuses on improving the vibrations in the human body, is of great value in the development of up to date vehicles and the tendency is that this factor gets increasingly relevant, as now the clients are more concerned with the comfort of the vehicles they buy, not only with dynamic performance and safety.

Data Availability

Any survey data will be available if necessary for stakeholder consultation or available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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