

Modeling and validation of an off-road vehicle suspension through Drop Test

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Abstract - The present work presents an analytical modeling of the vertical dynamics suspension of an off-road vehicle and the methodology of experimental validation of the same. For this, a rapid and low complexity test was developed with the acquisition of data made through a compression load cell. With this methodology, it was possible to optimize the time and reduce the validation costs of the project, since it is not necessary to move the vehicle to a test track.

Keywords – suspension, drop test, compression load cell, validation

List of Symbols

Q	-	Amount of movement
Q_f	-	Amount of movement in drop moment
Q_i	-	Amount of movement in initial moment
ψ_a	-	Angle between lower suspension link and the damper
l_a	-	Distance between pivot chassis point and lower damper one
l_b	-	Distance between pivot chassis point and lower pivot knuckle one
IR_F	-	Front installation ratio
ω_F	-	Front natural frequency
K_{RF}	-	Front ride rate
W_{SF}	-	Front unsprung weight
K_{WF}	-	Front wheel rate
G	-	Gravitational acceleration
H	-	Height that car will be suspended
E_c	-	Kinematic energy
M	-	Mass of the wheel considered
E_p	-	Potential energy
IR_R	-	Rear installation ratio
ω_R	-	Rear natural frequency
K_{RR}	-	Rear ride rate
W_{SR}	-	Rear unsprung weight
K_{WR}	-	Rear wheel rate
K_T	-	Tire rate
V	-	Velocity of drop

I. Introduction

The suspension is the system responsible for the stability of the vehicle, absorbing, through its components, "irregularities of the terrain". For competition cars, it is desired that it behaves in a curve characterized by oversteer tendency, because it allows it to make more closed turns [4].

For the suspension design, there are many variables, so it is necessary to pre-select some of them as natural frequency and springs and tires rates.

If the natural frequency is known, the required installation ratio can be calculated. It is a geometric concept that relates the angle change caused by a force-producing device (such as a spring and damper) to the change of the center of the wheel, that is, it functions as a lever mechanism for the distribution of forces. Thus, it is possible to position the shock absorbers so that they reach the desired natural frequency.

For the analytical modeling of the vertical dynamics of the suspension, it is necessary to first calculate the front and rear ride rates, that is, it is a vertical force per unit displacement of the tires ground contact reference point relative to the chassis [4]. They are given by equations (1) and (2):

$$K_{RF} = 2\omega_F^2 W_{SF} \quad (1)$$

$$K_{RR} = 2\omega_R^2 W_{SR} \quad (2)$$

Given the tire rates, the wheel rates or wheel center rate is vertical force acting on the tire per unit vertical displacement at the location along the spindle corresponding to the wheel centerline, measured relative to the chassis [4] are obtained through equations (3) and (4):

$$K_{WF} = \frac{K_{RF} K_T}{K_T - K_{RF}} \quad (3)$$

$$K_{WR} = \frac{K_{RR} K_T}{K_T - K_{RR}} \quad (4)$$

Thus, the installation ratio will be given by equations (5) e (6):

$$IR_F = \sqrt{\frac{K_{WF}}{K_{SF}}} \quad (5)$$

$$IR_R = \sqrt{\frac{K_{WR}}{K_{SR}}} \quad (6)$$

Signal processing is the name given to procedures used in data measured to reveal the information contained in the measurements. The three steps of the methodology of extracting the information of a signal are acquisition, processing and interpretation. These procedures are essentially constituted by transformations that are based in mathematics and are implemented with the use of digital techniques. The laws of physics or other models expressed in mathematical

language comprise a first stage in which the process is characterized by a quantitative form.

Analog and continuous signals are represented by a single uninterrupted response whereas discrete ones are characterized by a data sequence. Therefore, the purpose of signal processing is to extract the information from a signal, especially when it is not feasible by direct observation. [6]

For signals where it is difficult to obtain a representative mathematical function, the passage to the frequency domain makes details of periodicity clearer. Thus, the Fourier transform decomposes a periodic function into a discrete frequency spectrum making the information system information under study, such as coefficient of damping and natural frequency, easier. This is important, since often in the laboratory the function that composes the signal. [3]

When the signal sampling rate is not high enough, problems arise in signal interpretation in both time and frequency domain. For the Nyquist condition to be reached, the sampling frequency must always be twice as large as the maximum signal frequency. If it is not reached, there may be distortions in the interpretation and discretization of the signal in the time domain, or even the appearance of aliasing frequencies, which show false data in signal analysis since high frequency components are not distinguishable from lower frequencies. [6]

The force data is acquired in the test with the use of a load cell of compression. The model used is a commercial load cell acquired from the manufacturer HBM, which has four extensometers in the Wheatstone bridge configuration. This configuration ensures data accuracy and reliability. The force to be measured deforms the strain gauge being the deformation measured as a change in the electric signal.

In order to estimate the tire / ground reaction force, some physical principles are used [5]. The first one is energy conservation. In the case of a body of mass m with a certain height h relative to the ground, its maximum potential energy is.

$$E_p = mgh \quad (7)$$

Immediately before the object reaches the ground, its potential energy becomes null while the kinetic is maximum. With equation 8 is possible estimate velocity.

$$E_c = \frac{1}{2} mv^2 \quad (8)$$

The next concept to be used is the amount of movement. This physical quantity is the product between mass and speed.

$$Q = mv \quad (9)$$

The change in the amount of movement of a body is equal to the impulse of the resulting force in a given time interval.

$$I = Q_f - Q_i \quad (10)$$

In this way, with the knowledge of the variation of the impulse and with an estimate of time, the force to be measured can be determined.

$$I = F(\Delta t) \quad (11)$$

The ease of measurement with a compression load cell helps speed up processing and output, reducing the time taken to get results, and ultimately reducing costs. [2]

II. Methodology

For competition cars the natural frequency should not exceed 2 Hz due to comfort conditions. And, it is also advised that the frequency of the rear does not exceed 30% of the front [1]. Thus, the natural frequency of the front was set at 1.67 Hz and the rear at 1.92 Hz.

With the frequency values set together with the stiffness of the springs and tires, it was possible to calculate the ride rates and wheel rates and, consequently, the required installation ratio for both the front and the rear. The values obtained were, respectively, 0.37 and 0.46.

In addition, knowing that the installation ratio can also be given by equation (12), by manipulating it, one finds the angle at which the damper must be installed. In Figure 1 it is possible to verify the parameters of the equation..

$$IR = \frac{l_a \sin \psi_a}{l_b} \quad (12)$$

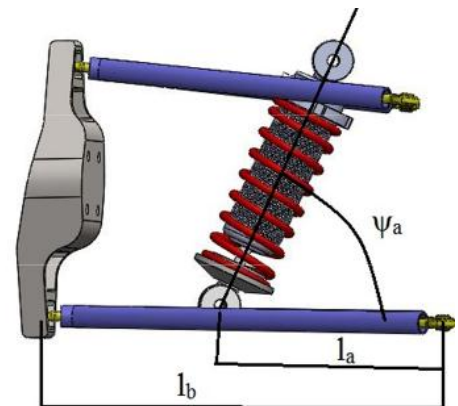


Figure 1: Parameters used to calculate the installation ratio

The contact area of the load cell needed to be enlarged since it would be very difficult to align the tire with its sensitive part. In this way, a hole in the device was used to screw a 10 mm steel plate with a suitable size so that the whole area of the tire would trigger the mechanism in the fall of the vehicle, ensuring a better consistency of the data. The figure 2 is a representative illustration of the load cell used.

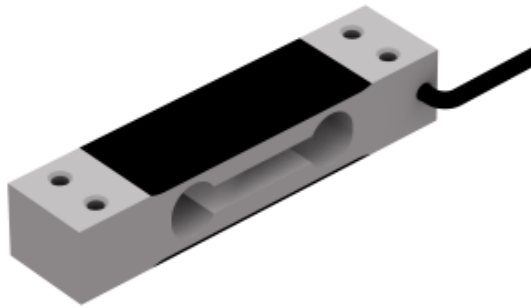


Figure 2: Illustration load cell compression used to perform the test

The manufacturer did not provide the calibration curve, so it was necessary to obtain it. Previously known mass rings (5, 10 and 15 kg) were used to create a graph and with the straight line of this equation obtained, it was possible to convert the electric signal change into the desired study variables (mass and later force).

In order to guarantee the reliability of the data, it is necessary to ensure that the cell remains immobile throughout the experiments. Thus, double-sided tape was used to fix it to the floor, since the tests were performed in non-team dependencies. Drilling the floor and screwing the device would be a simpler and more efficient measure, but the adopted configuration did not compromise the measurements.

The car was hoisted in about 1 meter, with the use of a crane present in the laboratory of the Civil Engineering Department, which is capable of operating objects up to 3 tons. This height was chosen because it is very close to the maximum elevation of the obstacles present in the test track of the team as well as the ramps faced in the competitions BAJA SAE. At each outlet, the wheel of the car was always carefully aligned with the cell, as well as ensuring that the underside of the tire was at the correct distance from the ground.

Being all the steps verified, a student let go the rope and instantly the car fell on the load cell. In order to speed up the repeatability and avoid changing the place-measuring device, the bridge operator would rotate the car in the air, so when it was desired to obtain the data for another wheel, the new alignment was performed with the vehicle suspended.



Figure 3: Car suspended 1 meter high from the ground, just before the fall

III. Results and Discussions

Aiming for greater reliability of the acquired data, the test was repeated multiple times on each of the wheels of the vehicle. The graphs are illustrations of the behavior of the curves and the values presented are results of the arithmetic mean of the several repetitions.

Firstly, the front of the vehicle will be analyzed. Three measurements were made for the right side and 3 for the left side. Figure 4 contains the original force x time plot as well as the interpolated by a spline.

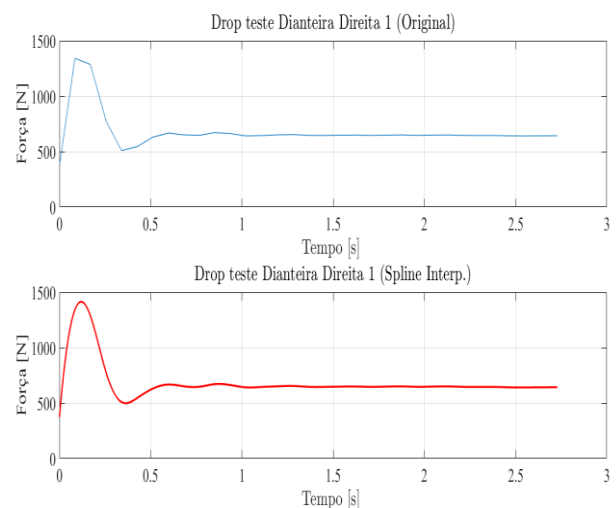


Figure 4: Curves of force x time in the first fall of the right front wheel

Figure 5 contains the same curve but now in the frequency domain. The peak value in the power axis (y) corresponds to the natural frequency value of the system being studied. An

approximation of the frequency collected in the wheel contact with the ground is made as corresponding to the natural frequency of the suspension system itself.

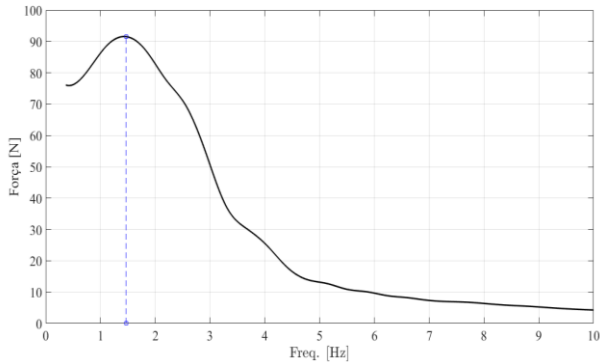


Figure 5: Interpolated curve present in figure 4, in the frequency domain

The same methodology was used for the rear region of the vehicle. The car was hoisted and released 12 times, with the right wheel aligned with the load cell 6 times and the left wheel on the other 6. The curves of figure 6 are an illustration of the force values collected in the 6th measure on the left side.

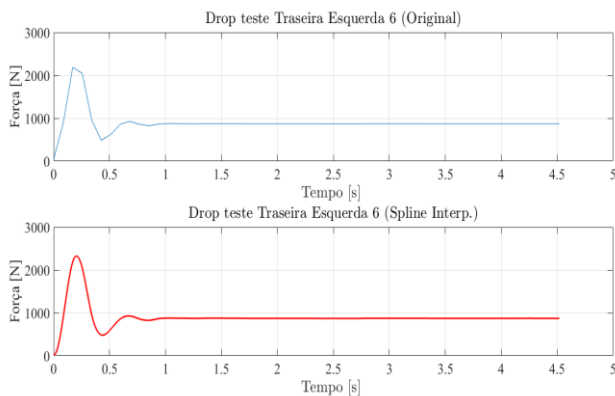


Figure 6: Curves of force x time in the sixth fall of the left rear wheel

Figure 7 contains the same graph in the frequency domain. Again, the frequency value corresponding to the power peak indicates the natural frequency of the study system, which has been approximated as the natural frequency of the rear suspension system.

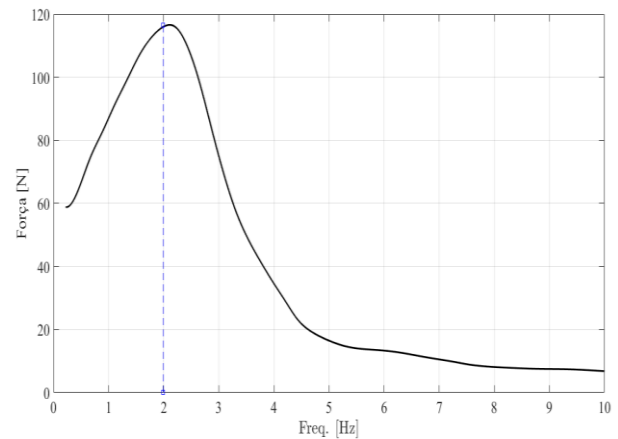


Figure 7: Interpolated curve present in figure 6, in the frequency domain

Table 1 contains the natural frequency values estimated in the design phase for both the front and rear suspension, the mean natural frequency values obtained after successive repetitions of vehicle fall and the subsequent percentage errors.

Region	Project natural frequency (Hz)	Test natural frequency (Hz)	Percentage error (%)
Front	1,67	1,82	10,9
Rear	1,93	2,01	4,14

Table 1: Project and test suspensions natural frequency

It is noted from Table 1 that the reliability of the planned test does not exceed 11%, an acceptable standard within engineering.

Furthermore, previously, to obtain the same data, we used a system composed of accelerometers and a data acquisition platform that cost around \$ 25,000. Already the cost for the experimental apparatus used in the work was around \$ 50.

In addition to the higher cost, the first system had time discretization and aliasing problems. To avoid them, you would need a filter that would work on a very low-frequency range to allow only the desired signal to pass through. As our sample would have a very small amount of data, it would be difficult to obtain the information we needed, rendering this work impossible.

Another advantage of the methodology presented is the no need to move the vehicle to a test track. This allows a faster pace both in the test and in obtaining the results of the project, because with the going to the track, it would be necessary to move a larger group of people specialized in each area in the possible event of a vehicle failure. Already for the laboratory test, only the presence of the pilot and the bridge operator together with the person responsible for data acquisition is sufficient.

IV. Conclusions

Suspension is vital to the operation of any vehicle, especially the off-roads due to the obstacles they are submitted along their paths. There are multitudes of parameters that influence the dynamic and kinematic behavior of the vehicle, so each designer chooses its main variables by determining the values of the others consequently. In the suspension project used by TEC Ilha Baja SAE team from the year of 2018, in the initial phase the values of natural frequency as well as spring and tire rate were determined. The idealized and described test was aimed at the collection and verification of the natural frequency values, since once convergence between design and practical values can be verified, the behavior of the vehicle can be guaranteed as expected.

The use of a compression load cell proved to be a valid alternative. This instrument had previously been used by the team to collect the values of the impact force of the tire / ground contact acting on the vehicle in the 1 meter drop condition, height of the most critical ramp on the test track as well as in the competition. The application of a frequency response function in the graphs of force x time proved to be an adequate methodology since the test thus fulfills two requirements and it is not necessary to move the vehicle to the track. This would require greater contingency of the team present in the test, could culminate in damage or failure of some component besides requiring the purchase of instruments that would be rarely used.

The calibration of the experimental apparatus with the use of washers is simple, and can be performed in the same place of the test instants before the execution of the same. Moreover, immediately after the fall of the vehicle, observing the collected values, it is possible to check if there was any inconsistency and several measurements can be taken, since hoisting the vehicle and realigning the wheel is done in a matter of minutes.

Furthermore, the test fulfilled its objective being satisfactory the verification of the natural frequency of the suspension of the vehicle. That indicates that the guidelines established in the design phase are present, in a fast, efficient and without additional costs way, since the team already possessed all the items used, without displacing a large contingent of members and not causing the failure of any component.

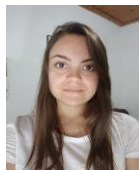
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