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Numerical Analysis of Spring Stiffness in Vehicle Design Development Stage

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Abstract
This paper reported the numerical analysis technique to investigate the influence of spring stiffness in automotive suspension towards improving the vehicle ride and performance. There are three type of spring's stiffness categories which have been used to conduct the numerical analysis; soft, medium and hard. Using the full vehicle model and front suspension mathematical model, the study on rolling analysis for these three type of spring stiffness parameter towards the effect of the suspension total roll rate, tramp rate, roll centre height, roll centre lateral as the vehicle subjected to go through the longitudinal and cornering test. The results from the numerical simulation was then applied to the real vehicle model for field test. The outcome from the present work highlight the important of spring stiffness investigation during the vehicle design stage to improve the vehicle ride and performance.

Keywords: Spring stiffness, vehicle ride, suspension, numerical analysis

Introduction

The automotive suspension system is crucial to vehicle ride and performance due to its function and mechanism. The suspension system could absorb the effect from the different situation such as uneven road, bumping, cornering, fast accelerations and braking. Furthermore, it is also required to provide the safety factor demands to undergo understeer, oversteer, bounce and gripping while take cornering in additional to prevent vehicle from damage and wearing[1]. There are many different types of suspension system used in automobile, the commonly use in passenger car are the independent (solid axle) and dependent suspension system (McPherson and Double Wish bone) [2]. The main components of a suspension system are springs, shock absorbers and control arm. In a practical suspension system, the control arm is connected to the body through various links that permit an approximately vertical motion of the wheel relative to the body, controlled by the springs and dampers. The characteristic of suspension system is based on the two major components, damper and spring. Combination of these two component add to the comfort parameter in vehicle handling system.

The main purpose of spring in a suspension system was to provide cushioning and to absorb and control the energy level subjected to shock and vibration[3]. Low stiff spring does not counteract the car's tendency to roll enough during cornering event which result in shifting the centre of gravity outwards and quickly overwhelming the outer tyre ability to keep grip on the road [4]. A spring that's too stiff will slows down the transfer of load from the inner to the outer tyre. As a result, the outer tyre isn't being loaded enough to achieve its potential force before the cornering event is completed.

In most modern passenger vehicles, most manufacturer prefer the use of coil spring due to its flexibility with other component in the suspension system [5]. There are two types of coil spring in automobile industries; the straight-rate and progressive-rate springs. The straight-rate spring compresses equally all across the coil when subjected to a load in which provides the same spring rate whether fully compressed or fully rebounded. The progressive-rate spring becomes the most selected spring using in suspension system because of the characteristic term. It also has different type of design compared with the straight-rate spring.

The different between these springs is the gap between the coils at the end of the spring. Mostly, progressive rate springs are made by varying the spacing between the springs' active coils and during compression the close coils bottom out and deaden meanwhile this reduces the amount of active coils and spring rate increases as a result. The progressive-rate spring is designed with low initial spring rate but the spring rate rapidly increases as the spring coil is compressed. This provide relatively soft when encountering light bumps, but becomes stiffer the harder the jolt [4].

The spring rate also controls the transfer of weight of the car. During braking and acceleration the weight of the car shifts forward and backward [6]. Softer front springs aid in shifting the weight to the front, thereby reducing understeer. In contrast the softer rears springs allow the weight to be transferred which resulting in reducing oversteer problems. Alternatively, to induce the understeer or oversteer scenario, the best solution is to stiffen the corresponding spring rates [7].

Methodology

A significant challenge for the automotive engineer is to identify the best spring to suit its suspension design. This in return will produces vehicle with the optimum ride and performance as it undergoes through the acceleration, braking and cornering situation. The present methodology helps the engineer to analyse the spring stiffness in order to determine the appropriate spring stiffness during the vehicle development design stage. The work flow consists of setting up the spring database, conducting the numerical analysis and finally on-site field testing. The Altair Hyper Works® and MotionView® Student Edition Release 13 software solver is used to develop the two type of mathematical representative vehicle model, full vehicle model and front suspension model. These two model will be used to illustrate the motion of stiffness spring according subjected to cornering test and forward acceleration conditions[8].

(a)

(b)

Figure 1: UTeM's formula style racing cars model (a) *Jengking Bisa* (b) *FTKRC*

The outcome from the numerical analysis have been tested on the UTeM's formula style racing car model, *Jengking Bisa*as shown Figure 1(a). The spring is expected to increase the ride and performance through the effects of bounce from the previous *FTKRC* model shown Figure 1(b) above.

Spring Database

The market available spring has been used to set up the database of the progressive-rate spring [4]. The common properties of spring modulus of elasticity in tension and shear are shown on Table 1 [9]. For true isotropic materials, the elastic modulus in tension (E) and shear (G) are related through Poisson's ratio by the expression: so that, for common spring materials, any of the parameters may be approximated using the other two [10].For most steels alloys, the modulus varies as a function of chemical composition, cold works and degree of aging. The present models are specified to work at room temperature after having made appropriate compensation for the application temperature.

Table 1: Properties of Spring Materials [9]

Material	Music wire ASTM A 228
Nominal analysis	c--.70 – 1.00% Mn--.20 – 60%
Minimum tensile strength	230-3999
Modulus of elasticity E (MPa)	207
Design stress % minimum tensile	45
Modulus in torsion G (MPa)	79.3
Maximum temperature (ºC)	121
Rockwell hardness	C41-60
Method of manufacture Special properties	• Cold drawn • High and uniform tensile • High quality springs • Wire forms

The identification on the type spring stiffness is based on the spring rate. The spring rate is calculated as below using the equation the number of active coils needed to maintain the desired deflection or spring stiffness [10].

$$k = \frac{F}{Y} = \frac{Gd^4}{8D^3N} \quad (1)$$

where
k: spring rate
d: diameter of the spring wire
G: shear modulus of elasticity of the spring material
D: mean diameter of the spring coils
N: number of active coil

A number of different points of view are taken into account and determine the best option by means of computer software. The spring database provides the stiffness parameter meter input to conduct numerical analysis to simulate the vehicle dynamics ride and performance test.

Numerical Procedure

The Altair HyperWorks® and MotionView® software is used to investigate the effect of the stiffness parameter from the spring database. The representative of the two mathematical model, full vehicle model (FVM) and front suspension model (FSM) as shown in Figure 2 and 3 were developed based on the geometrical and specification of UTeM's *Jengking Bisa* racing car model.

The software '*Assembly wizard*' is used to develop the front suspension topologies by assembling suspension components

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into a representative front suspension vehicle model as well as the full vehicle model.

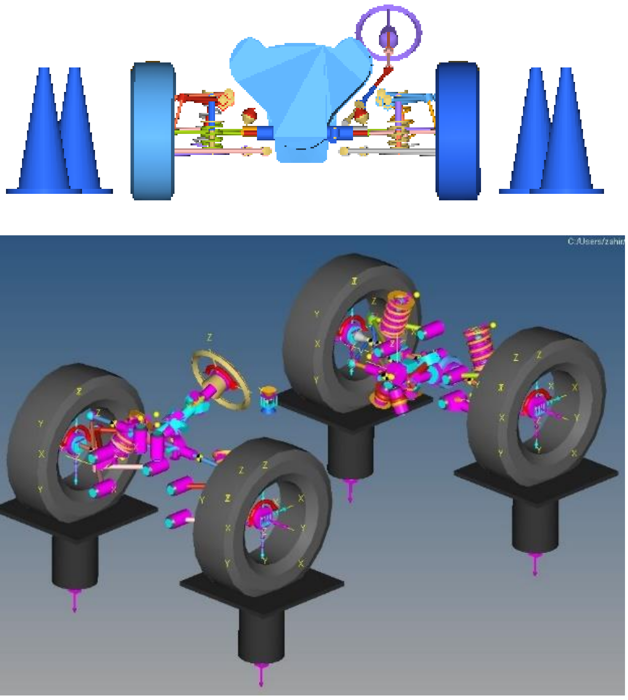
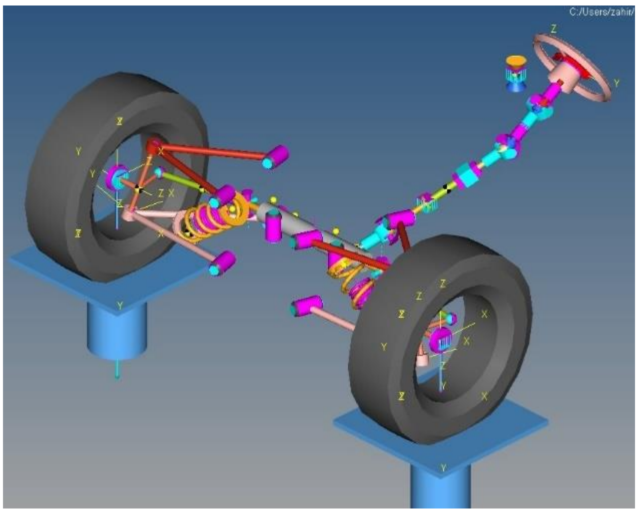


Figure 2: Full vehicle model

The study on three type spring stiffness parameter (soft, medium and hard spring stiffness) have been carried out to evaluate the effect of the spring suspension as the vehicle undergoes through the two type of vehicle dynamics test. The first test was to simulate the cornering effect followed by longitudinal test (forward acceleration). The double lane change test only being simulated using the FVM mathematical model while the FSM model was used to conduct both tests.

A number of standards output have been integrated into the racing car numerical models that provides a variety of typical suspension input that relate to the rolling analysis subjected to spring effect. These includes the total roll rate, tramp rate, roll centre height and roll centre lateral.



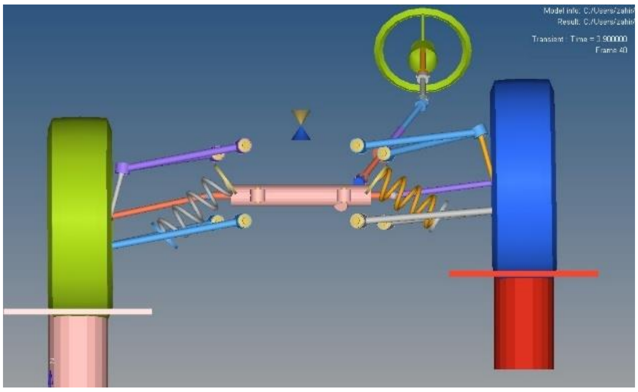


Figure 3: Front Suspension Model

Field Testing

The predictive results from the numerical analysis have been further investigate by installing the three types of spring stiffness attach to the racing vehicle. The test has been conducted at *MIMC Go-Kart International* circuit which is 1.6 km long shown in Figure 4 below. The vehicle is powered by 135 cc engine driven by the same professional racing driver. The best time laps for different type of spring were collected to support the numerical simulation.

Figure 4: *MIMCGo-Kart International* circuit [11]

Results and Discussion

Spring Database

The calculated spring rate stiffness are presented in Table 2.The stiffness parameters are classified as either soft, medium or hard spring which further used in numerical analysis to simulate the effect of the spring stiffness.

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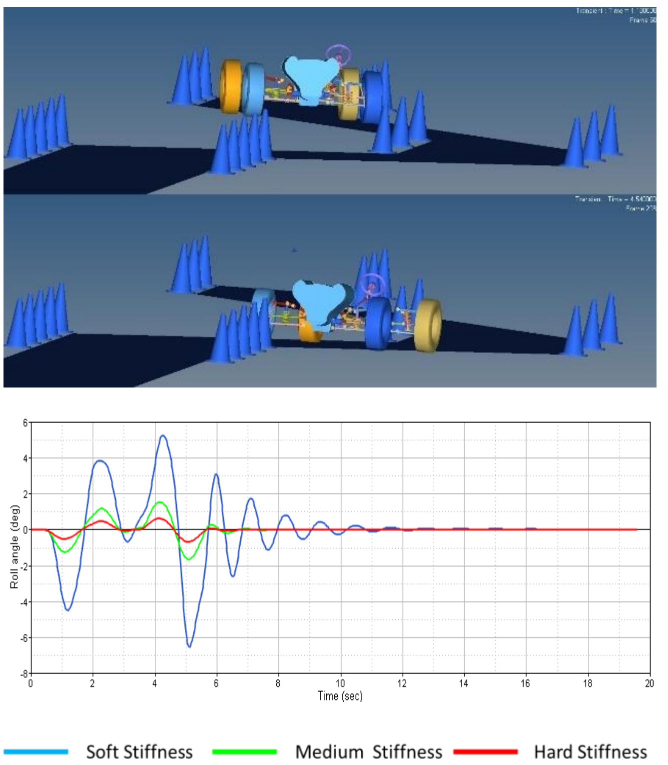
Table 2: Spring stiffness

Compression Spring Constant (*k*)	
Soft	
Spring constant (*k*)	64.75
Medium	
Spring constant (k)	154.68
Hard	
Spring constant (k)	924.97

Numerical Analysis

Full Vehicle Model

The double lane change simulation analysis are presented by Figure 5.There are three lines representing the roll angle over period of time. Blue line represents the graph in which the car uses the soft stiffness spring whereas the green and red line represent medium and hard stiffness spring respectively.



Time (s)	1.2	2.2	3.2	4.2	5.2	6.0
Soft (°) Roll Angle	-4.4	3.9	-0.7	4.2	-6.6	3.0
Medium (°) Roll Angle	-1.2	1.2	0.0	1.6	-1.6	0.2
Hard (°) Roll Angle	-0.6	0.6	0.0	0.7	-0.7	0.0

Figure 5: Double lane test roll angle

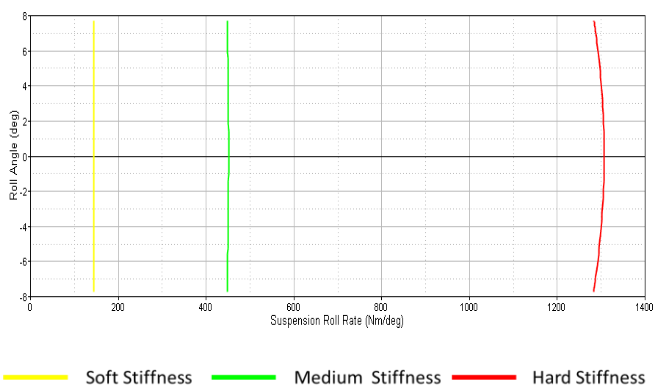
Each point of peak shows the value of roll angle for different type of spring stiffness during cornering. It shows that the car with soft stiffness spring experience more rolling and higher value of rolling angle. As the car start to turn left at the position of 1.2 seconds, the rolling angle reached -4.4degree for soft stiffness, -1.2 degree for the medium stiffness and -0.6 degree for the hard stiffness until it reached 1.7 seconds as the car turns back the steering angle to 0 degree. The polar of movement remain the same throughout the analysis.

Both medium and hard stiffness spring shows the same pattern with slight different on the degree of roll angle. They also reach stable value and remain straight throughout the simulation period compared to the soft stiffness spring. The roll angle for the soft stiffness was also high which shows that the car is subjected to bounce condition during the lane changing position. This result in decreasing control over the car handling situation as the centrifugal force applied to the car's centre of gravity push the car to the outside of a cornering angle in which will increase the tendency of the car to roll. Higher stiffness on the other hand reduces the body roll of a vehicle during cornering or any road irregularities.

Front Suspension Model

Figure 6shows the effect between the suspension roll rates with roll angle at three different types of spring rate; soft, medium and hard using front FSM vehicle model. The data for soft rate spring shows the wheel start to jounce when the angle of roll is 7.6904 degree. At this point, the suspension roll rate is 144.561 Nm/degree. Once the angle roll at 0 degree, the condition of wheel will return to neutral (static) and suspension roll rate is 144.207 Nm/degree. The wheel will rebound when the angle of roll reach -7.6904 degree. At this point, the suspension roll rate is 144.561 Nm/degree. For the medium rate spring the wheel start bounce when the angle of roll is 7.6904 degree. At this point, the suspension roll rate is 447.943 Nm/degree. Once the angle roll at 0 degree, the condition of wheel will neutral (static) and suspension roll rate is 450.903 Nm/degree. The wheel will rebound again when the angle of roll reach -7.6904 degree. At this point, the suspension roll rate is 447.943 Nm/degree. Furthermore, the hard rate spring shows the condition of wheel start bounce when the angle of roll is 7.6904 degree. At this point, the suspension roll rate is 1283.71 Nm/degree. Once the angle roll at 0 degree, the condition of wheel will neutral (static) and suspension roll rate is 1306.43 Nm/degree. The wheel will rebound when the angle of roll reach -7.6904 degree. At this point, the suspension roll rate is 1283.71 Nm/degree.

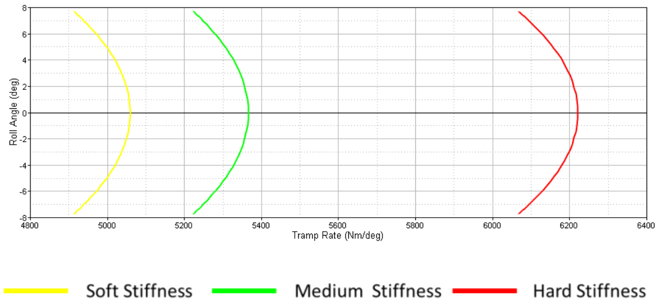
This result shows that movement of suspension and the value of suspension roll rate increase proportionally with the spring stiffness. During cornering, the graph reveal that medium stiffness helps the suspension to counter roll the car body that in return stable stabilize the vehicle movement during longitudinal acceleration.



Type stiffness	Suspension roll rate (Nm/deg)	Roll angle (degree)	Position
Soft	144.561	7.6904	Bounce
	144.207	0	Neutral
	144.561	-7.6904	Rebound
Medium	447.943	7.6904	Bounce
	450.903	0	Neutral
	447.943	-7.6904	Rebound
Hard	1283.71	7.6904	Bounce
	1306.43	0	Neutral
	1283.71	-7.6904	Rebound

Figure 6: Suspension roll rate

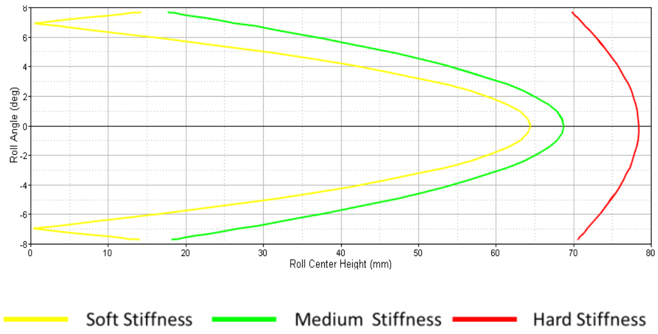
Tramp is the form of wheel hop in which a pair of wheels hops in opposite phase. A form of wheel hop which is usually found in rear axle cars occurs when sudden torque loads on the suspension cause the driven wheels to shake violently by slightly rotating the wheels and then springing back.
Figure 7shows the tramp rate over roll angle. It shows that the medium stiffness spring is helping the vehicle suspension to reduce the tramp rate which gives comfort to the vehicle compare to the soft spring that tend to sway during cornering. The hard spring in contrast contribute to driving discomfort due to jerking occurrence. Furthermore, as the vehicle speed at higher speed, it will also contribute to affect the vehicle acceleration. It is necessary then to use middle stiffness in order to counter this problem.



Type stiffness	Tramp rate (Nm/deg)	Roll angle (degree)	Position
Soft	4914.28	7.6904	Bounce
	5059.22	0	Neutral
	4914.28	-7.6904	Rebound
Medium	5225.64	7.6904	Bounce
	5365.78	0	Neutral
	5225.64	-7.6904	Rebound
Hard	6068.27	7.6904	Bounce
	6220.91	0	Neutral
	6068.27	-7.6904	Rebound

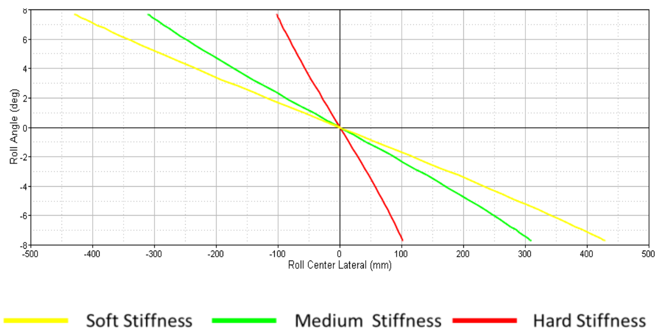
Figure 7: Tramp rate

Figure 8 explained the vehicle behaviour in cornering situations using FSM focussing on the roll centre height. The vehicle imbalance is represented by a negative occurrence at the centre position roll centre high which show that the vehicle to sway during cornering. For the medium stiffness spring, the graph shows that the centre high is in a state of high comfort. The vehicle does not sway during cornering situation. The vehicle roll centre is relatively low compared to the soft spring with only 10 mm movement in longitudinal direction.



Type stiffness	Roll centre height (mm)	Roll angle (degree)	Position
Soft	14.2793	7.6904	Bounce
	64.4073	0	Neutral
	14.2793	-7.6904	Rebound
Medium	17.6762	7.6904	Bounce
	68.6865	0	Neutral
	17.6762	-7.6904	Rebound
Hard	69.8008	7.6904	Bounce
	78.3827	0	Neutral
	69.8008	-7.6904	Rebound

Figure 8: Roll centre height



Type stiffness	Roll centre lateral (mm)	Roll angle (degree)	Position
Soft	-428.993	7.6904	Bounce
	0	0	Neutral
	428.993	-7.6904	Rebound
Medium	-310.129	7.6904	Bounce
	0	0	Neutral
	310.129	-7.6904	Rebound
Hard	-102.384	7.6904	Bounce
	0	0	Neutral
	102.384	-7.6904	Rebound

Figure 9: Roll centre height (lateral)

Roll centre lateral as shown in Figure 9 described the racing car numerical model going through a bump which result in one side of wheel to bounce and the other side of wheel to rebound. The figure shows that the rebound value is higher at lateral roll centre for the middle stiffness spring. This allow the middle stiffness spring to perform better during cornering situation. The hard spring may also create the understeer problem if entering a sharp cornering angle due to it low value in roll centre lateral.

Field Testing

The outcome from the field test revealed as expected that medium stiffness delivered the best single time laps which is 1.56 minutes. The medium stiffness spring allow smooth cornering which is crucial to a racing car as predicted earlier using numerical approach.

Table 6: Time laps subjected to spring stiffness

Stiffness Level	Time laps (minute)
Soft	3.15
Medium	1.59
Hard	2.30

Conclusion

The present work has shown the effect of spring stiffness as the vehicle travel through cornering and straight movement using mathematical vehicle model. The results show that the medium spring stiffness provide comfort and good handling in both numerical and real vehicle model which can be overserved from the result of experimental testing. The results also show that the medium spring stiffness can minimize the roll effect which could further led to oversteer or understeer problem. The outcome from the present work highlight the important of spring stiffness investigation during the vehicle design stage to improve the vehicle dynamics ride and performance.

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