7 DOF Analysis of Full Car Model With Vibrations Using Ansys

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Abstract- *Traditional vehicle suspension systems, which are passive in nature consists of elastic elements, damping elements and a set of mechanical elements responsible to the suspension kinematics. Active and semi-active suspension systems are the solutions to achieve the desired dynamic behavior of the vehicle system. Sincethe active system is bulky and requires high energy for working a semi-active suspension system is considered in the present work to analyze vehicle traversing over various road profiles for ride comfort.*
In the present work, a small passenger car model with 7 DOF is considered. A semi-active suspension system with skyhook linear control strategy avoids resonant road excitation frequencies by shifting the natural frequencies of the model by varying damping coefficients based on the vehicle response for different road conditions like harmonic, transient and random. Hence, modal analysis is carried out for the above model to identify the un-damped natural frequencies and mode shapes for different values of damping.

I. INTRODUCTION

The suspension systems in the vehicles are primarily to support the vehicle, provide effective isolation of passengers from road disturbances, provide adequate directional control during handling maneuvers and provide sufficient traction for driving, braking,and vehicle stability. Road vehicles experience vibration while moving, mainly due to road surface irregularities unbalanced engine forces, aerodynamic forces etc. Road induced vibrations can be isolated by well-designed suspensions systems. Automotive suspensions have been designed to satisfy conflicting requirements of better ride comfort, road handling and suspensions working space. Better ride comfort requires a soft suspension, whereas a stiffer suspension is required for better control of both body and wheel as well as to provide adequate working space between the chassis and the car body. Due to these conflicting demands, the suspension designer has to balance the requirements of the ride comfort, road handling and suspension working space in different measures depending on the type of vehicle like a passenger car, truck, off-road vehicle etc.Regarding the suspension systems, it is of great importance to have specific evaluation tools to measure its performance. More specifically, when dealing with suspension systems, the two main aspects of interest are:

- Comfort characteristics.
- The road-holding (or handling) characteristics.

The quarter car is a 2 DOF system to study the characteristics of the vehicle suspension system like ride comfort and road holding by considering the vertical vibration of sprung mass and un-sprung mass[5-7]. Unsprung mass is linked to the ground with a tire modeled by stiffness and to the sprung mass with a suspension made up of a linear shock absorber and a linear spring[9,11 and 12]. Half car model having 4 DOF is used to study the pitching/rolling characteristics of the vehicle suspension system along with the bounce of sprung and un-sprung mass[2,3,8 and 10]. The accuracy of evaluation can also be improved compared to the quarter car model. Full car model having7 DOF is made up with sprung mass in vertical translation and its rotation about two horizontal axes and the four un-sprung masses bounce [1, 4]. A full car model gives accurate results when investigated for vibration response. Also, we can analyze the pitch, roll, and bounce of the sprung mass simultaneously with the help of a full-car model. To compare different control strategies a quarter car model reduces the complexity of the problem.
With the advancement in the technology in the vehicle suspension system, the thrust for improvement in ride quality is gaining significance. One such alternative is semi-active suspension which will improve the ride qualities of the suspension system with less energy consumption and compactness in design.

Therefore, it is required to analyze the vehicle suspension system for the ride qualities of the semi-active suspension system and its improvement by comparing it with a passive suspension system. In the present work, the Sky-hook control strategy is adopted in semi-active suspension and analyzed.

II. NOMENCLATURE

M1	-	Mass of the car body / sprung mass (kg)
M2	-	mass of the wheel /un-sprung mass (kg)
I_x	-	pitch moment of inertia of the car (kg-m^2)
I_y	-	roll moment of inertia of the car (kg-m^2)
x_1	-	bounce of sprung mass(m)
x_2	-	car wheel displacement for un-sprung mass1(m)
x_3	-	car wheel displacement for un-sprung mass2 (m)
x_4	-	car wheel displacement for un-sprung mass3 (m)
x_5	-	car wheel displacement for un-sprung mass4 (m)
L_4, L_5	-	distance from the center of sprung mass to the front wheeland rear wheel (m)
L_7, L_8	-	distance from the center of sprung mass to left and right (m)
C_1, C_2, C_3 and C_4	-	damping coefficients of the suspension dampers (N-s/m)
K_1, K_2, K_3 and K_4	-	the stiffness of the suspension springs (N/m)
Φ	-	rolling angle (radians)
θ	-	pitching angle (radians)

III. THE OBJECTIVE OF THE WORK

To develop equations of motion for a 7 DOF full car model using equations of motion.

- To perform modal analysis on the above model to obtain un-damped natural frequencies and their mode shapes and compare them with damped natural frequencies for different values of damping.
- To find the response of the full car model using a semi-active control strategy for different road profiles.

IV. EQUATIONS OF MOTION FOR THE 7-DOF MODEL

Using Newton's second law the equations of motion are obtained for the the7-DOF model. It consists of a single sprung mass (M) free to heave, pitch, and roll, connected to four unsprung masses (M1, M2, M3,and M4) free to bounce vertically with respect to the sprung mass. Pitch and roll angles are assumed to be small. The four tires(front left, front right, rear right,and rear left) are modeled as four springs of stiffness KU1,KU2, KU3 and KU4 and dampers of damping coefficients CU1,CU2,CU3,and CU4 respectively. The suspensions between the sprung mass M and the un-sprung masses M1,M2, M3,and M4 are modeled as four linear springs of stiffness KS1,KS2, KS3,and KS4 respectively, and four linear dampers with damping coefficients of CS1,CS2, CS3,and CS4 respectively. The sprung mass has 3-DOF representing body bounce, roll,and pitch movement. The X is the vertical displacement of the sprung mass at the center of gravity, θ is the pitch angle and ϕ is the roll angle of the sprung mass, the un-sprung masses have 4-DOF due to vertical motions X1, X2, X3,X4. The input to the wheels is the road excitation X0. Thus there are a total of seven-second order differential equations governing the motion of the sprung and unsprung masses.

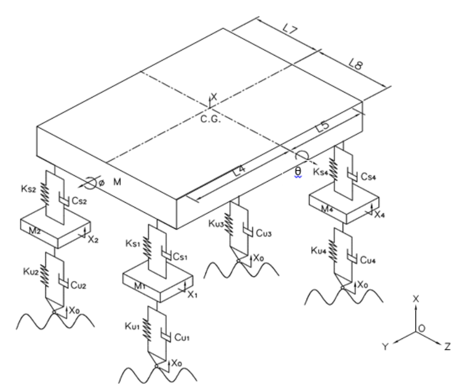

Figure 1A vertical full-Car Model with 7-DOF

V. MODELING OF FULL CAR MODEL

ANSYS is considered for the analysis of the full car vehicle suspension system. Modeling of a full car is done by using three types of elements described above. Sprung mass is assumed as a lumped mass in modeling, the set-1 element is taken as sprung mass and it is connected by MPC-184 elements to form a frame as shown in Figure 2. Wheels are also modeled as lumped masses by using set-2 for front wheels and set-3 for rear wheels.

Table 1 Real constant values for full-car model

Set number	Element type	Value
Set-1	MASS -21	M1 =656 kg, Ix=500 kg-m^2 Iy=1094 kg-m^2
Set-2	MASS-21	Mu = 41 kg
Set-3	MASS -21	Mu = 46 kg
Set-4	COMBIN-14	K_1,K_2=15000 N/m, C_1,C_2 = 1189 N-s/m
Set-5	COMBIN-14	K_3,K_4=15000 N/m, C_3,C_4 = 856 N-s/m
Set-6	COMBIN-14	K_u = 150,000 N/m C_u = 1500 N-s/m

Wheels stiffness and damping are also modeled using set-6 for both front and rear wheels. Finally, wheels and frame are connected by using set-4 and set-5 on front and rear wheels respectively. Finally, a full car model is modeled in ANSYS by following the above steps. The above-developed car model developed can be used for the study of the dynamicbehavior of the car.

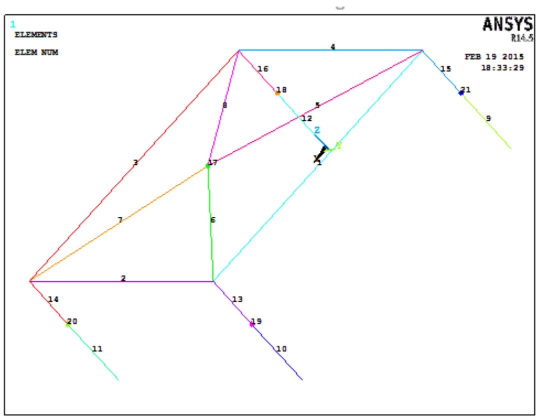

Figure 2Full-car model developed in ANSYS

Modal analysis: Finite Element Method

Un-damped natural frequencies and mode shapes: Block Lanczos method

Damped natural frequencies and mode shapes: Q-R Damped method

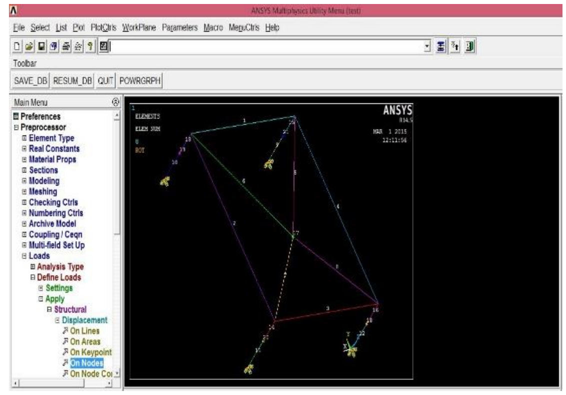

Figure 3 Constraining of all DOF for the wheels

VI. MODE SHAPES OF THE 7 DOF FULL-CAR MODEL FOR VARIOUS DAMPING COEFFICIENTS

Modal analysis is performed for 7 DOF full car model using finite element method using ANSYS software package, Un-damped and damped modal analysis of the system for various damping coefficients ranging from 500-2000 N-s/m is carried out.

VII. MODE SHAPES OF 7 DOF FULL-CAR MODEL AT DAMPING COEFFICIENT C =500 N-S/M

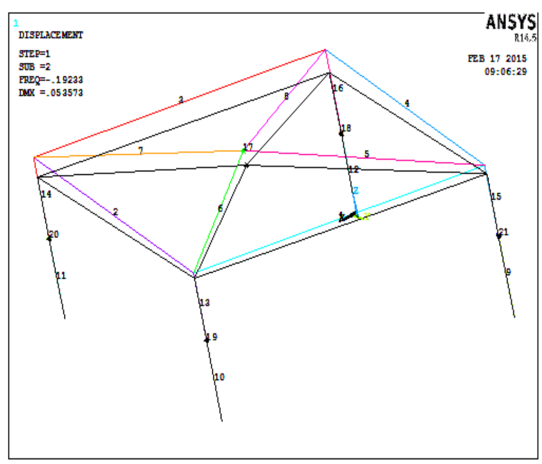

Figure 4 Sprung mass bounce at 1.18 Hz

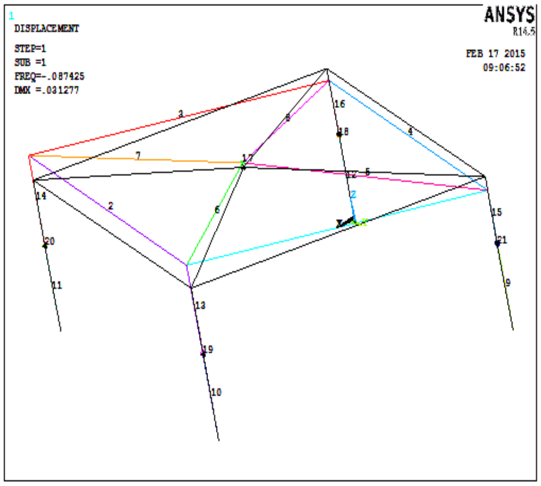

Figure 5 Sprung mass pitch at 1.57 Hz

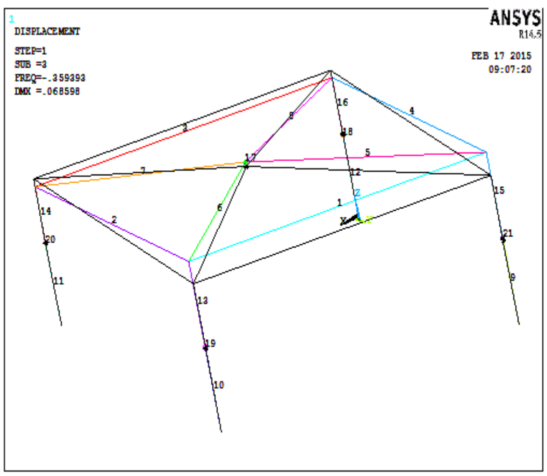

Figure 6 Sprung mass rolling at 0.74Hz

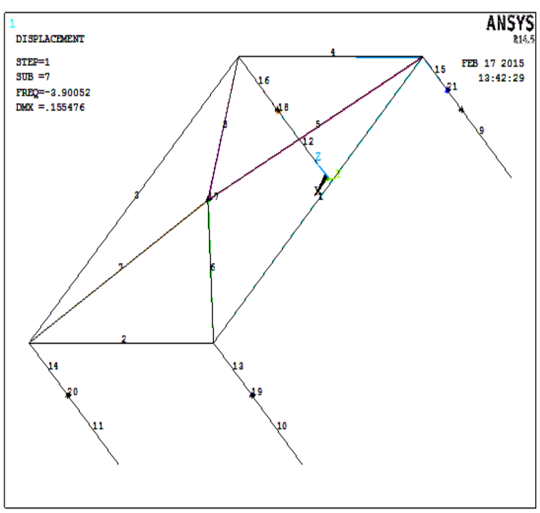

Figure 7 Un-sprung mass 1 bounce at 9.81Hz

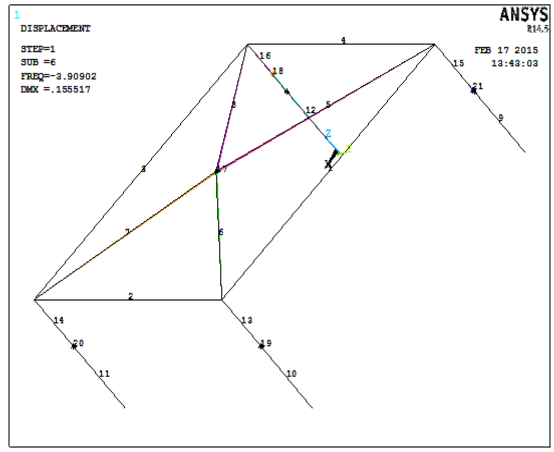

Figure 8 Un-sprung mass 2 bounce at 9.81Hz

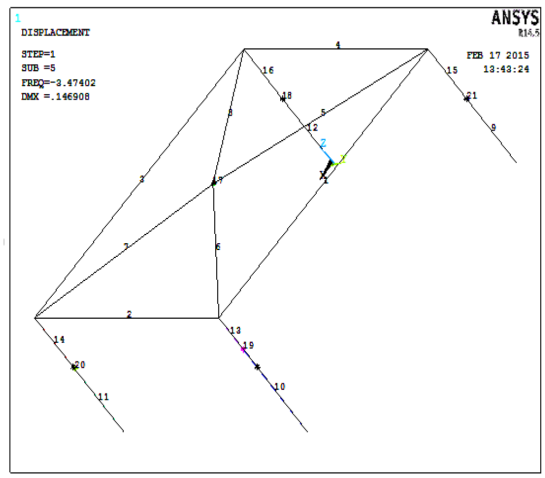

Figure 9 Un-sprung mass3 bounce at 9.16Hz

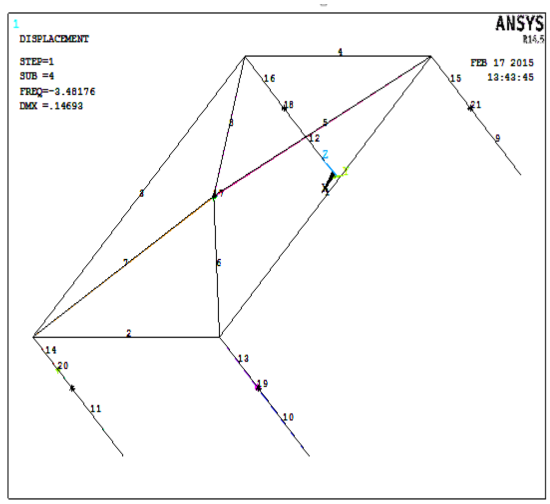

Figure 10 Un-sprung mass 4 bounce at 9.16Hz

VIII. RESULTS

Similarly, the natural frequencies of the 7 DOF full car model for various damping coefficients C=0, 500, 1000, 1500 and 2000 N-s/m in ANSYS are done and tabulated in Table 2.

Table 2 Natural frequencies of the 7 DOF full car model for various damping coefficients in ANSYS

S. No	Modes of vibration	Natural Frequencies (Hz) and mass normalized amplitudes at various damping coefficients (N-s/m)									
		C = 0		C = 500		C = 1000		C = 1500		C = 2000	
		FREQ	AMP	FREQ	AMP	FREQ	AMP	FREQ	AMP	FREQ	AMP
1	Rolling of sprungmass	0.76	-1	0.74	1	0.73	1	0.72	0.9	0.77	-0.6
2	Bounce of sprungmass	1.24	1	1.18	0.95	1.14	0.9	1.06	0.8	0.9	0.8
3	Pitching of sprungmass	1.56	-1	1.57	-1	1.47	1	1.23	1	1.23	1
4	Bounce of un-sprung mass1	10.03	0.75	9.81	0.75	8.66	0.6	7.11	0.6	6.73	0.6
5	Bounce of un-sprung mass2	10.03	0.75	9.81	0.75	8.62	0.6	7.9	0.6	6.73	0.6
6	Bounce of un-sprung mass3	9.35	0.75	9.16	0.7	8.17	0.6	7.86	0.6	6.4	0.6
7	Bounce of un-sprung mass4	9.35	0.75	9.16	0.6	8.09	0.6	7.4	0.6	6.4	0.6

Table 3 Un-damped Natural Frequencies of 7 DOF full-car model

S. No	Mode of vibration	Literature Freq (Hz)	ANSYS	
			Freq(Hz)	Amp(mm)
1	Rolling	0.8	0.769	-1
2	Car Bounce	1.2	1.2408	1
3	Pitching	1.5	1.5101	-1
4	Wheel-1 bounce	9.4	10.03	0.75
5	Wheel-2 bounce	9.4	10.03	0.75
6	Wheel-3 bounce	9.4	9.35	0.75
7	Wheel-4 bounce	9.4	9.35	0.75

IX. CONCLUSION

Un-damped and damped natural frequencies and the corresponding mode shapes for the 7 DOF full car model have been found using equations of motion and finite element method. The natural frequencies thus found by both the methods are in good agreement with those in literature. The following are conclusions can be drawn from modal analysis of 7DOF full car model.

- From un-damped modal analysis, mode shape of bounce of the sprung mass is associated with roll of the sprung mass due to the coupling of the system. Pitching of the sprung mass is independent of the roll and bounce of the sprung mass.
- Damped modal analysis is carried for different values of damping that is from 500 to 2000 N-s/m in steps with step size 500 and corresponding natural frequencies are found.

From, analytical analysis the natural frequencies of roll, pitch and bounce of sprung masses are obtained are shifted from 0.76-0.78 Hz, 1.24-1.37 Hz, 1.5-1.59 Hz, where un-sprung mass bounces 1, 2, 3 and 4 are shifted from 10.03- 6.74 Hz, 10.03- 6.73 Hz, 9.35- 7.45 Hz and 9.34- 7.24 Hz respectively. From, numerical analysis the natural frequencies of roll, pitch and bounce of sprung masses are obtained are shifted from 0.76-0.77 Hz, 1.24-1.34 Hz, 1.5-1.53 Hz, where un-sprung mass bounces 1, 2, 3 and 4 are shifted from 10.03- 6.73 Hz, 10.03- 6.73 Hz, 9.35- 6.74 Hz and 9.34- 6.74 Hz respectively.

- From damped modal analysis, it is observed that natural frequencies of the full car model are shifting which will help us in avoiding the resonance of the system with road excitation during active/semi-active suspension systems.
- From the damped modal analysis, it is found out that peak amplitude of mode shapes are decreasing but increasing amplitudes of others.

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