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DYNAMIC MODELING, THEORY AND APPLICATION USING BOND GRAPH

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ABSTRACT

The paper describes the technique for presenting quantitative and systematic modeling and simulation using Bond Graph for the vehicle dynamic system. It is based on the relative contribution of the new generation of a system equation, expression, result analysis and simulation through graphical display. The portioning algorithm can be employed to the existing automated modeling techniques for efficient, accurate simulation towards the design of the vehicle dynamic system. The design of control oriented four wheeled vehicle is widely recognized to be a very challenging task. This allows accounting for the driver turn angle which necessitates about visualizing the real driving behavior and its effects on the overall vehicle dynamic system. The study also illustrates an introduction to vehicle dynamics with emphasis towards the influence of its various properties. It also discusses the steady–state behavior of simple automobile models and transient motion when small and large steering inputs and other disturbances are employed. The effect of various shape factors and type of characteristics on vehicle handling properties is analysed. In order to design a controller, a good model representing the dynamic system is needed. From the input parameters considered, the results of the modeling and simulation of vehicle dynamics through the Bond Graph are found efficient and more accurate.

Keywords: - Bond Graph, Four wheeled vehicle, Vehicle dynamics, Dynamic system model, Tire-road interaction, Simulator module.

1. INTRODUCTION

Thousands to Millions of car models have been produced by the automobile industry over the last century or so, but only meager section of people have influenced the business. The single most important attribute in the car buying process is that of design and its looks. Designers have played a very significant role in the history of the automobile. Over the years, there have been hundreds, perhaps thousands of designers, who have been involved in the activity of designing cars, but at the end of the day only a few dozen people have actually shaped the destiny of car design over the last eight decades. The size of the global automotive industry today is in excess of $ 1.6 trillion. Global automotive sales will exceed more than 100 million units in a year within next three years. Its size does matter, but besides size, the industry is also highly competitive. Global customers are well informed and highly demanding. People relate the car to their personality and many times the choice of car is driven by emotional preferences. This creates a compelling need for the industry to design and launch new products quickly with more innovative features [1]. Based on the industry evolutionary perspective, automobile vehicle development is in third generation and its development is briefly mentioned as under:

The *first generation automobile* is dominated by U.S. through industrialization and availability of capital. It led the way in the mass production of automobiles. During this period, Henry Ford pioneered the famous moving assembly line for his flagship model .The U.S. industry is also credited with a lot of innovations that included experimental designs front engine, internal combustion engine, rear storage space and automatic transmission. Factories became viable thanks to a revolution in equipment sophistication and process technology. The U.S. gained supremacy over Europe in industrialization as its technologically competent owner - investor capitalists were ready to invest in new technology. By the time of World War II, the U.S. had more large scale business enterprises than the rest of the world combined and these introduced modern accounting concepts and spawned managerial hierarchies.

The *second generation automobile* is dominated by Japan through its focus on quality and cost due to wages crawling up in the U.S. and lack of innovation in process technology. For Japan, that was hungry to prove itself after the defeat in the war, this provided a perfect platform to bounce back as an industrialized nation. The Japanese collaborated with the U.S. due to its geographical proximity and reverse engineered American products. This helped Japan become a new Industrial centre in Asia. A supportive government helped by keeping a close relationship with the industry, keeping the cost of capital low. All Japanese auto majors such as Toyota, Nissan, Honda and Mitsubishi invested in the supplier companies through kereitsu (a set of companies with interlocking business relationships and shareholdings) which bolstered the subsidiaries financial strength, product planning, parts rationalization, and overseas marketing capability.

The *third generation automobile* with the advent of electronics, computing and communication technologies, the world is now in the era of the “software cars” as General Motors (GM) calls it. With technology and innovation set to play a key role in the third generation automobile, India is uniquely placed to exploit this opportunity. The third generation automobile will be a high- tech car and a green car. The personal transport vehicles, especially cars are made more high-tech, intelligent and communicative powered by information and communication technology. In automobiles the scope of information technology (IT) utilizes intelligent systems, navigation control, infotainment and superior safety systems. Thus the automotives are moving from a mechanical platform to an electronic platform with more intelligence and communicative features. Technology shall play a significant and far reaching role in enabling the innovation towards the hi-tech, green car. Software and electronics are changing the concept of car design. To provide some numbers: The approximate cost of electronics in a luxury automobile is 23 percent of the total product cost. The average automotive electronic cost per vehicle is forecast to increase by 50 percent in 2010. Today, 80 percent of the innovations in automobiles come from electronics. Industry leader General Motors has unveiled the concept of ‘new Automotive DNA” where the car design will be driven by software and electronics. In the new DNA, GM talks about moving from internal combustion (IC) engines to electric propulsion, moving from mechanical systems to electronic systems for both steering and motion of the wheels. This means everything- how these systems are built, sold and serviced-will undergo a revolutionary change[2].

Thus the role of computerized modeling and simulation in engineering design continues to increase as companies strive to gain competitive advantage by reducing the time required to move from concept to final product. In this paper major emphasis has been given for computerized modeling and simulation of vehicle dynamics using Bond Graph. The paper describes a method for approaching an arbitrary parameter, initial, outline, and slider and simulation model, systematically and quantitatively. The bond graph of vehicle dynamic system illustrates typical object models using the basic modules of the software. For brevity, only small problems are considered in the simulation of vehicle dynamic system model, but Bond graph techniques reveal its strength and beauty in developing a clear and simplified model for vehicle dynamic model. Effort and flow variables in some physical domains are shown in Table 1.

NOMENCLATURE

dm/dt = Mass flow rate

dN/dt = Mole flow rate
dQ/dt = Volume flow rate
ds/dt = Entropy change rate
dV/dt = Volume change rate
e = Effort
e_m = Magneto-motive force
f = Flow
F = Force
h = Enthalpy
H = Height of ground excitation

i = Current

I = Inertial Element

K = Stiffness

L= Length of ground excitation

P = Pressure
R = Resistive Element

SE = Source of effort

SF = Source of flow

TF = Transformer

V = Voltage
v = Velocity
V = Velocity of the car

Greek Symbols

μ = Chemical potential
τ = Torque
φ = Magnetic flux
ω = Angular velocity

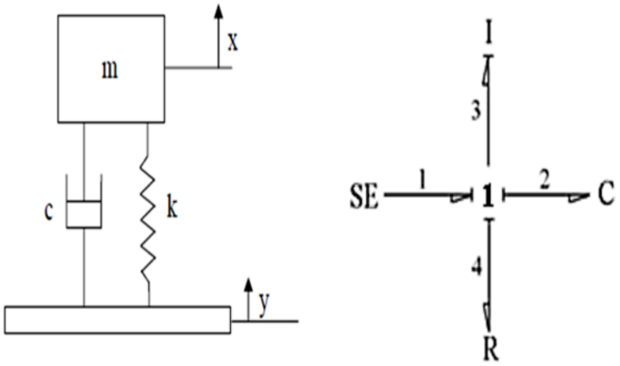
Table-1: Effort and flow variables in physical domains

Systems	Effort (e)	Flow (f)
Mechanical	Force (F)	Velocity (v)
	Torque (τ)	Angular velocity (ω)
Electrical	Voltage (V)	Current (i)
Hydraulic	Pressure (P)	Volume flow rate (dQ/dt)
Thermal	Temperature (T)	Entropy change rate (ds/dt)
	Pressure (P)	Volume change rate (dV/dt)
Chemical	Chemical potential (μ)	Mole flow rate (dN/dt)
	Enthalpy (h)	Mass flow rate (dm/dt)
Magnetic	Magneto-motive force (e_m)	Magnetic flux (φ)

2. DINAMICAL VEHICLE MODEL

2.1 Quarter Car Model

To model the vehicle as quarter car, vibration analysis of a single-degree of freedom system is presented in Fig. 1. In this model, only one-fourth of the vehicle's mass and suspension are considered.



(a) (b)

Figure 1: A quarter car (a) model having single degree of freedom and (b) Bond graph model

Tires and suspensions are considered in two degrees of freedom quarter car model as shown in Fig. 2. This model is more realistic than a quarter car model with single degree of freedom [3, 4].

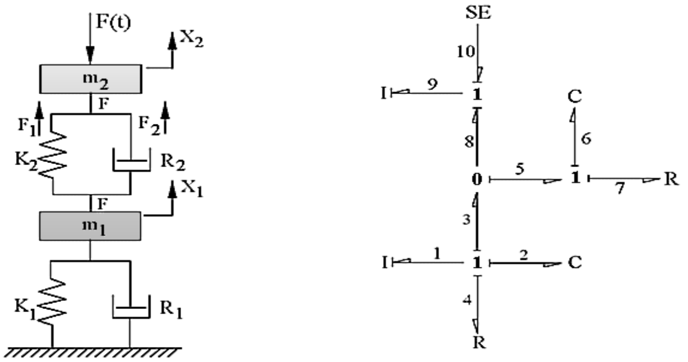


Figure 2: A quarter car (a) Model having two degree of freedom and (b) Bond graph model

2.2 Bicycle Car Model

Quarter car model is excellent to examine and optimize the body bounce mode of vibrations. However, vibration model of vehicle must be expanded for including pitch and other modes of vibrations [4, 5]. Bicycle model includes body bounce and body pitch which are shown in Fig. 3.

2.3 Half Car Model

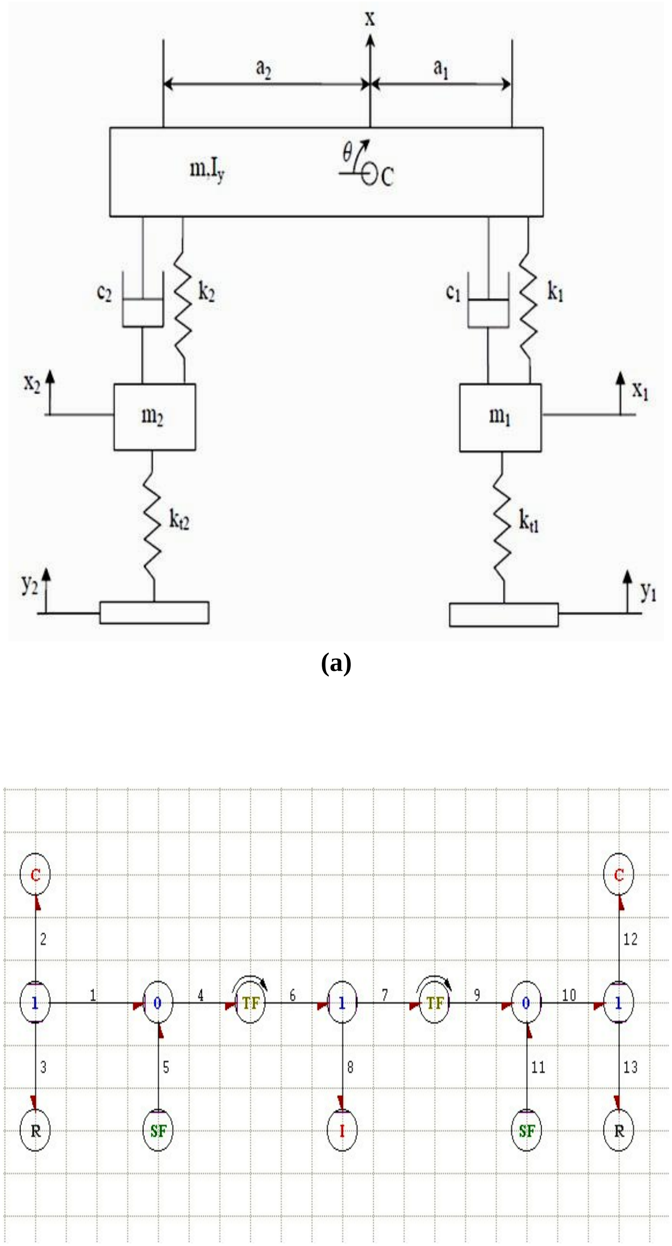
To examine and optimize the roll vibration of a vehicle, half car vibrating model must be used. This model includes the body bounce and body roll. The half car model may be different for the front and rear half due to different suspension and mass distribution. Furthermore, different antiroll bars with different torsional stiffness may be used in the front and rear halves [6, 7]. Half car model is shown in Fig. 4.

2.4 Full Car Model

Figure 5, shows the model of the vehicle as full car and vibration analysis of seven-degree of freedom system is presented [8-10].

In this model, full vehicle's mass and suspension are considered where Front damper is R_{2f}, Rear stiffness is K_{2r}, Front stiffness is K_{2f}, Mass of the car is Mc ,Rear damper is R_{2r}, Moment of inertia of the car is Mcg ,Rear damper is R_{1r}, Front damper is R_{1f}, Rear stiffness is K_{1r}, Front stiffness is K_{1f}, Mass of the car is Jc , Front Moment of inertia of the car is

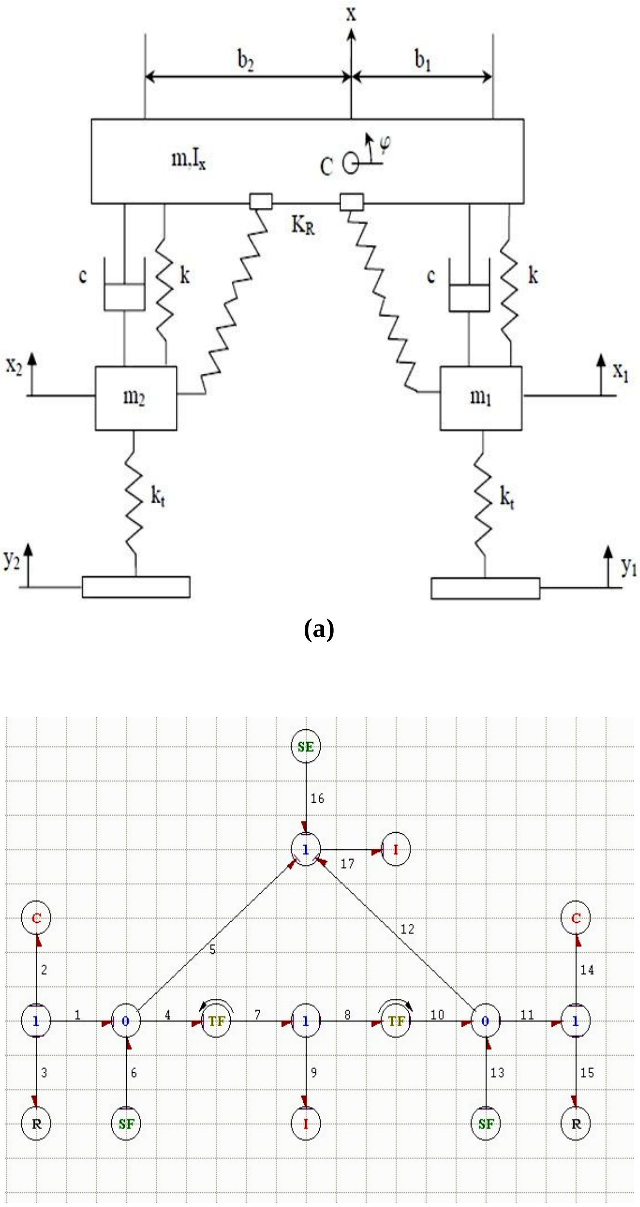
Mbfg , Rear Moment of inertia of the car is Mbrg , Front Mass of the car is Mbf, Rear Mass of the car is Mbr , Rear Mass of the car is Jbr ,Front Mass of the car is Jbf , Front stiffness is K_{3f} , Rear stiffness is K_{3r} ,Front damper is R_{3f} , Rear damper is R_{3r} , Front Velocity of the car is $V_1(t)$, and Rear velocity of the car is $V_2(t)$.



(a)

(b)

Figure 3: A bicycle car (a) model having four degree of freedom and (b) Bond graph model



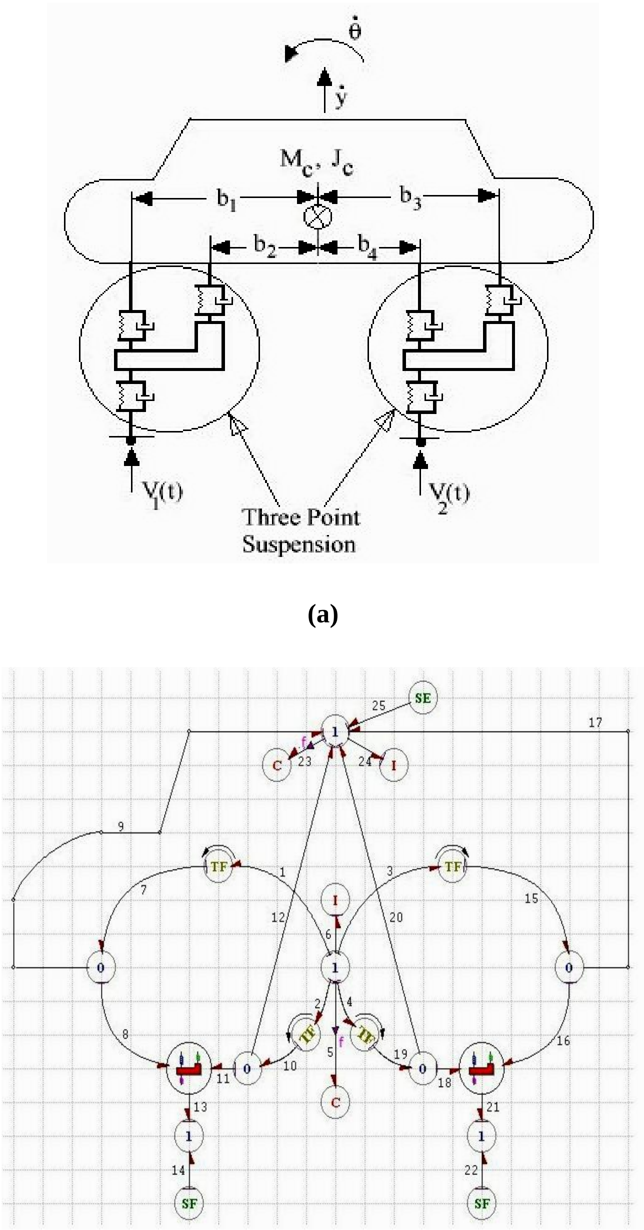
(a)

(b)

Figure 4: A half car (a) model having four degree of freedom and (b) Bond graph model

3. APPLICATION OF BOND GRAPH

In the bond graph formalism energy is conserved, power flow paths can be identified, and power flow associated with elements and their connections can be readily determined. Generalized inertia ‘I’ and capacitance ‘C’ store energy as a function of the system state variables, which are generalized momentum and displacements.



(a)

(b)

Figure 5: A full car (a) Model having seven degree of freedom and (b) Bond graph model

The time derivatives of generalized momentum P and displacement q (Q) are generalized effort ‘e’ and flow ‘f’, the product of which is power. Generalized resistor R remove energy from the system, and have a constitutive law relating generalized effort to generalized flow. Sources of effort and flow (SE and SF) represent ports through which the system interacts with its environment. Energy is transported among source, storage and dissipative elements through power-conserving “Junction structure” elements. Such elements include power- continuous generalized transformers (TF) are functions of external variables for example co-ordinates. Kirchhoff’s loop and mode laws are modeled by power conserving, 1 and 0 junctions respectively [10]. Elements bounded to a 1 Junction have common flow, and their efforts algebraically sum to zero. Elements bounded to a 0 junction have common effort, and their flows algebraically sum to zero.

The power bonds contain a half-arrow that indicates the direction of algebraically positive power flow, and a causal stroke normal to the bond that indicates whether the effort or flow variable is the input or output from the constitutive law of the connected element. Full arrows are reserved for modulating signals they represent powerless information flows, such orientation angels for co-ordinate transformation matrices. Table 1 defines the symbols and constitutive laws for energy storage and dissipative elements (“energetic’ elements), source, and power-conserving elements. The constitutive laws are written in an input –output- form consisted- with the placement of the causal strokes.

The deeper study is done from Mukherjee A., [9, 10] for the development of bond graph and statements are as under:

SE ➔ The source of effort is external to a system in the sense of that the system does not influence its output. The source of effort determines the effort in the bond associated with it.

F (t): SE
F (t, Pm, Qn): SE

SF ➔The source of flow determines the flow variables in the bond associated with it. For source, the effort variable is an extra system entity and does not influence the output of this source.

V (t): SF
V (t, P_m, Q_n): SF

The P_m and Q_n in the arguments indicate that the corresponding functions are functions of system state as well.

3.1 The Inertia element (I)

Creation of this element is motivated by the idea of a mass point in mechanics. This element relates effort or its integration (the impulse) to the rate of change of momentum or the velocity. The relations for a simple linear inertial element may be written in the following forms:

$$e(t) = \frac{d(m(t)f)}{dt} \qquad (1)$$

or;

$$f(t) = \frac{1}{m(t)} \int_{-\propto}^{t} e(\varepsilon)\, d\varepsilon \tag{2}$$

In these expressions the generalized inertia m (t) is taken as function of time.

$$e(t) = \frac{d(p)}{d(t)} \tag{3}$$

$$p(t) = \int_{-\propto}^{t} e(\varepsilon)\, d\varepsilon \tag{4}$$

3.2 The Compliant element (C)

The compliant elements role model is a Hookian spring or an electrical capacitor, which stored energy depending on their configurations. The basic constitutive relation of a single port compliant element in the bond graph maps is written as:

$$e(t) = F\left(t_1 \iint_{-\propto}^{t} (\varepsilon)\, d\varepsilon\right) \tag{5}$$

$$f(t) = \frac{dG(t_1\, e(t))}{dt} \tag{6}$$

where F and G are single value functions of their arguments. G is of course respect to its arguments. In bond graph theory the integration of flow is called generalized displacement or charge of the C element.

$$Q(t) = \int_{-\propto}^{t} f(\varepsilon) d\varepsilon \tag{7}$$

The above relation may thus be written as:

$$e(t) = F\big(t_1\, Q(t)\big) \tag{8}$$

$$\frac{dQ(t)}{dt} = \frac{dG(t_1\, e(t))}{dt} \tag{9}$$

$$Q(t) = G\big(t\,, e(t)\big) \tag{10}$$

$$e(t) = k(t) \int_{-\propto}^{t} f(F)\, d\varepsilon = k\big(t\,, Q(t)\big) \tag{11}$$

Or

$$f(t) = \frac{d\big(e(t)/k(t)\big)}{dt} \tag{12}$$

This is linear Hookian spring this has a constitutive relations. The variations in compliant parameters **k** and **c** in these linear models indicate function of the stiffness or capacitance with time.

3.3 The Resistive element (R)

Unlike I and C element which relate essentially the integration of effort or flow variables to flow or effort on a bond, the resistive element involves no integration and directly relates the efforts to flow or vice-versa:

$$e = \varphi(f) \tag{13}$$

or,

$$f = \psi(e) \tag{14}$$

In their linear forms may be

$$e = Rf \tag{15}$$

$$f = \frac{1}{R} e \tag{16}$$

where φ and Ψ are simple valued functions of flow or effort respectively.

3.4 Constitutive laws of basic 2-port elements

The bond graphic transformer can represent an ideal electrical transformer, a mass less lever; etc. The transformer (TF) does not create, store or destroy energy. It conserves power and transmits the flow of power with proper scaling as defined by the transformer modules.

4. ALGORITHM FOR ASSIGNING CAUSALITY

A systematic way of assigning causality to a bond graph model was suggested by Karnopp and Rosenberg [11, 12].Their algorithm is very effective for manual assignment of causalities. We follow basically the Karnopp-Rosenberg in the following steps:

i). Select any source either SE of SF. The source types have fixed causalities which cannot be altered. Thus in case of SE give a stroke at the junction end of the bond and in case of SF give a stroke at the end of the element (i.e. SF) end of the bond.

ii). If the bond newly causal becomes strong bond of a junction the weak causalities (i.e. a stroke for a bond on 1-junction and open for a bond on o-junction) may immediately be assigned to all other bonds of the junction which are unassigned.

iii). If a newly causal bond happens to be one of the ports of TF then causality may be assigned to the other part in accordance with the causality structures of these elements.

iv). If any of the causal bonds through step I to III happen to be the strong bond on a junction then causality may be immediately assigned to other bond of the junction.

v). If through I to IV any bond becomes last but one bond is causal on a junction then the last one should be causal to be a strong bond on that junction.

vi). If a stage is reached when causality cannot propagate further then select the next source element which is still un-causal and repeat the steps I through V.

vii). If no other source element is left then select a storage element (I or C) which is not causal, assign to it proper or integral causality then repeat steps II through V.

viii). In the event that the causality cannot be propagated further select the next un-causal (I or C) element and repeat the step II through V.

ix). If no storage element is left un-causal then choose any unassigned R element and assign it to any causality(either resistive or conductive) then repeat the steps from I through V.

x). In case this leads to change of causality of an already assigned storage element and brings it to differential causality, reverse the causality of the R element and again propagate this, following the steps from II through V.

xi). If the step-X leads to new occurrences of differential causalities which are more in number then those after step X then retain the earlier one (assigned in step IX with propagation).If the present step leads to lesser number or no differential causality then consolidate this causality. In case occurrences of differential causalities cannot be avoided by either causalities of the R element then either the model should be reformulated or the one with minimum differential causalities should be retained.

xii). If the causality cannot be propagated further after steps IX, X or XI then select the next unassigned R element and repeat the steps IX through XI.

xiii). After the step XII only some of the internal bonds (bonds joining the junctions either directly or through two port elements) may remain unassigned. Select one such bond and assign arbitrary causality to it. Repeat the steps from II through V.

xiv). If the step XIII demands reverting causality of a previously integrally causal storage element (I or C) then find out if this situation may be avoided by reversing causality of an R element. If this can be done then the causality of that R element should be reversed and propagated.

xv). If no such R elements in step XIV exist then the causality of the internal bonds should be reversed and step XIII and XIV should be repeated.

xvi). If causal internal bond both ways produces differential causalities then either system model should be reformulated or one producing minimum occurrences of differential causalities should be retained.

xvii). Now the next un-causal internal bond should be selected and step from XIII through XVI should be repeated.

xviii). Even if everything goes well after step XII is completed and all the bonds get assigned without any occurrences of differential causalities, one should check for what is known as a causal loop. A causal loop is a set of junction elements so connected that they form a closed loop and each junction in such a loop has strong bond which is an internal bond in this loop. If causal loop is detected then one should examine reversal of any R element averts such a loop without if introducing differential causality. When this can be done the system graph has been successfully causal otherwise the model should reformulate.

4.1. Creation of System Equation

Method of generation of system equations is an augmented (power directed and causalled) bond graph, using a step by step procedure, system equations may be generated. The difference between equations derived from bond graphs and otherwise is that there will be a set of N first order differential equations, where N is the number of states. The total number of lumped elements (I and C) with integral causality present in a system [13, 14].

A system or a part of it, changes from one configuration to another because there have been, or there are causes which act on it, and the system or a part of it absorbs a part of these causes. The amounts of absorbed causes may be good measures of the states of the system and the way these absorbed causes are changing with time contains the description of its dynamics. The system variables in which the equations are derived are thus the absorbed causes in storage element with integral causalities. The spring or capacitor element (with integral causality) receives flow and thus displacement or total charge is the associated with this element as:

$$Q = \int_{-\infty}^{t} f dt \tag{17}$$

Q is the general symbol which is used for displacement as well as charge.

An inertia or inductance with integral causality receives effort as cause. Thus the system variable associated with this element is a generalized momentum as given by,

$$P = \int_{-\infty}^{t} e dt \tag{18}$$

System Variables for Bond graph based analysis is,

$$\int_{-\infty}^{t} (cause)\, dt \tag{19}$$

where Cause is the information going to storage elements with integral causality.

4.2 Generation of System Equation

The system equations may be generated by answering the following two equations:

- What do the elements (all) give to the system expressed in terms of system variables and sources? It is known as expanded method [15, 16].
- What does the system give to storage elements with integral causality? It is known as matrix method.

(Note: All the ID (identity) terms created in this method are dimensionless).

In this method the equation may be written in Matrix form as shown below:

$$\frac{d}{dt}\{X\} = [A][X] + [B]\{U\} \qquad (20)$$

where *{X} is state vector, {U} is input vector, [A] is system matrix and [B] is input matrix.*

In this section the method of generation of system equations is discussed. The differential equations describing the dynamics of the system are written in terms of the states of the system. All storage elements (I and C) correspond to stored state variables (P for Momentum and Q for displacement respectively) and equations are written for their time derivatives (i.e. effort and flow).

4.3 Creation of System Bond Graph

The impressions or models of nature are produced by human facilities and pieces of art. Such modeling of nature or any part of it can never be complete. Each model is a creation of mind, thus incomplete due to limitations of understanding, due to the purpose for which it is created or due to limitations of the mediums used. Each system bond graph is a piece of art. Like any other art, the art of creating system bond graphs may be acquired through a proper combination of learning processes.

5.0 RESULTS AND DISCUSSION

It is seen from Figures that the vibration amplitude of sprung mass of the quarter car model is highly affected by the base excitation frequency. However, the vibration amplitude of the unsprung mass is lightly affected from the road profiles. For quarter car and bicycle car model, it is seen from Figs. 1-3, that the translational vibration amplitude of the body is acceptable level. However, similar to quarter car model, the amplitude of unsprung mass is lightly affected from the road profiles. For half car model, the similar tendencies to other car models can be seen from above Figs. 4 and 5. The mean square value of the response of the sprung mass is less than the mean square value of the response of the unsprung mass for bicycle half car models and full car but not for quarter car model.

6.0 CONCLUSIONS

Analysis of a road vehicle is investigated using different car models which are quarter car model, bicycle car model, and half car model. Computer programs in Mathematica are developed for all car models to understand the base excitation response behaviors of the sprung mass in all car models and to simplify the calculations, proportional damping is considered for damping properties in car models. For the sake of completeness and semi-numerical results for random vibration analysis, different car models are presented.

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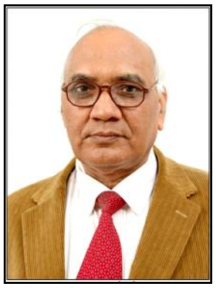

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(ii) The Impact of Air Pollution on Health, Agriculture and Technology; ISBN: 978-953-307-528-0, Full Chapter: Influence of the Air Engine on Global Warming Issues - 21st Century Fuel Technology, InTech Open Access Publisher, Rijeka, Croatia.

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