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Modeling and Simulation of Dynamic Half Car Using Bond Graph

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Abstract: This paper deals with the development of the so called half car models using Bond graph based on approaches to study the response of the vehicle while passing over a ramp or uneven surface. The first model has been evolved using a fairly standard suspension system attached between the wheels and the body of the vehicle. The second deals with the extension of the first model into a more complex hinged arm suspension with additional springs and dashpots, and some of it may be replaced by active control elements. This often translates into developing better models and increasing the use of onboard computers. The use of computers for control invariably requires models which execute faster and are reliable even in extreme conditions. Bond graph based techniques allow the development of continuously extensible models and easier integration with control systems. The results obtained from the model discussed in this paper, have been compared with existing published results and found in good agreement.

Keywords: Bond graph, Half car vehicle, Dynamic system model, Simulation model.

1. Introduction

Improvements in automobile technologies are continuing at ever increasing pace with the possibilities of putting more and more intelligence in the vehicles. The demand of making the automobiles safer and environmentally friendly is a universal one. Towards this research in the suspension systems is focused around improving the ride comfort and safety while the vehicle takes a turn, is applied with braking condition. Such of the improvements are being obtained through the use of sophisticated computer based controls along with more elaborate use of sensors. These invariably require better models for the automobiles and often models that can be executed in real time on computer for control purposes. For evaluating ride quality and control of the vehicles quarter car models are often enough but generally half car models are used for better results, as the heave and rocking motion can be kept in focus. There has been a trend to model the vehicle dynamics using Bondgraph based techniques as it allows easy up-gradation and merger with the development of control systems for the vehicles.

The present work deals with the modelling of a half car using Bondgraph techniques for heave and rocking motions as it goes over a ramp. Two different models have been developed. The first one is based on conventional suspension, well reported in literature. The results obtained are compared with the published literature. This validates the basic modelling approach adopted. Taking the ideas from this a second model is developed based on a hinged arm suspension, which could be suitable for active control systems. For an active control system the additional spring and dashpot may be replaced with the actuators. In the literature review, variety of papers have been studied and discussed the issues of independent suspension, full and half car models, using Bondgraphs for modelling the suspension systems etc. The actual development of the models using a Bondgraph package- SYMBOL SHAKTI has been described:

- The first model deals with conventional half car model, with a linearised proposition for the tire stiffness and assumption that the vehicle frame is a rigid body. The Bondgraph created are loaded with data from available sources and the results are verified. Additional results are also obtained from the model.
- The second model deals with a half car suspension through a hinged arm with a provision for providing active controllers. However, in the simulations another set of springs and dashpots have been used. This method is developed as in improvement over the first model with the additional of the hinged arm, and additional springs and dashpots.

Some results have been obtained for the vehicle performance as the vehicle goes over a ramp, using the vehicle data available in literature. Essentially it shows that how models can be easily evolved once the base model is prepared. The Results and Discussions shows the usefulness of the techniques adopted. At the end of concluding remarks, the possible areas of future work related to the present one, is also projected.

2. Literature Review

Many literatures have been reviewed pertaining to Bondgraph based modelling of vehicles. Andradottir et al. [1] has presented an overview of simulation modeling and analysis and critical issues are answered in the paper. Tseng and Ashrafi [2] established what are realistic subjects encountered in the challenge of achieving technology improvement in a vehicle stability control systems. The need of having a comprehensive model along with the components of an automobile properly represented and established by Louca et al [3]. Glass [4] has dealt an experimental evaluation of a prototype trailing-arm suspension for heavy trucks. Volvo Optimized Air Suspension-2 (VOAS-2), the prototype trailing-arm suspension. Kim et al [5] established that target cascading in product development is a systematic effort to propagate the desired top-level system design targets to appropriate specifications for subsystems and components in a consistent and efficient manner.

Kim et al [6] describe a hydraulic system design and vehicle dynamic modelling for development of tire roller traction and essential aspect in the system analysis of tire rollers. Maxim and Nguyen [7] have dealt the modelling suspension of an automobile is of interest for many automotive and vibrations engineers. Rideout et al [8] proposed a technique for decoupling among elements of a dynamic system model by quantitatively and systematically search to partition models. Granda [9] established the basic theoretical principles in vehicle dynamics and design combined with a practical approach-using computer aided techniques that allow students to build and analyze vehicle dynamics and mechatronics systems used in vehicles using computer models for analysis and design. Zoroofi [10] established that due to the limitations in the availability of fossil fuels and the high consumption rate of this energy for transportation, inclination of vehicle industry toward other sources of energy is inevitable. Silva et al [11] presented the model-based analytical reduction relationships. Pertaining to active suspension systems, Adibi and Rideout [12] have dealt the significant study of subject over the last two decades. Currently, many active suspension systems could be found to the commercial available automobiles. Milner et al [13] presented a study of the development of a prototype autonomous vehicle developed and validated by the U.S. Army (TACOM-TARDEC) for high-fidelity six-degree-of-freedom model. Gauchia and Sanz [14] observed that the current energy scenario is continued to be dominated by fossil fuels, especially by oil. Creed et al [15] discussed the creation of a full car model, for a standard road going vehicle. Lyons et al. [16] established that the practice of mechanical engineering requires an ability to investigate and analyze the modeling. Wakeham and Rideout [17] investigated an appropriate level of model complexity for designing optimal vehicle active suspension controllers by using the Linear Quadratic Regulator (LQR) method, complex thermal and mechanical systems.

3. The Actual Development of the Model Using Bondgraph Package Symbol-Shakti

3.1. Overview

The review in the previous section shows that modelling of an automobile is an important field of study. Further it shows that new modelling techniques, like the one based on the use of Bond graph is becoming popular, as it helps in several ways, like flexibility and extensibility of models and automatic generation and solution of the system equations etc. The study of literature by Louca et al [3] shows that for various purposes like quick evaluation of specific features and configurations and real time running of the models for controls.

Simple models are desirable and are adequate, as compared to full models. Four wheeled automobiles have been modeled in a variety of ways, to study stability controllability, of environmental friendliness and self navigation etc. Many of these studies show Kim et al [5] that the most common requirement is to have a relatively simple but responsive model at hand which may be run in real- time during the vehicle operation. Recent studies particularly Granda [9] and Silva et al [11] show that while the full blown vehicle models may be needed to be used in some application a plane two wheeled half car like model and even a single wheel quarter model have a role in evaluating the active ride control system of a vehicles. Further, the controlling system itself may need to run a vehicle model to provide more advanced type of vehicle control.

These models may also form a basis of crisis control in the event of any damage of the vehicle. Keeping the above observation in mind the present work has concentrated on building a half car vehicle model and its validation and evaluation for road un-evenness. Further, a Bondgraph based approach has been adopted as it easily permits evaluation of variety of parameters and also in principle run time versions if needed can be derived.

3.2 Development of the Model

The proposed Bondgraph based study has been carried out by University developed software called SYMBOL-Shakti. The concept of Bondgraphs based on power flow in various elements of a system (I, C, R, TF, SE, and SF) and the concept of junctions (0, 1) is shown in Table 1. If the roll of the vehicle is not important (often the case) the normal 4 wheeled vehicle as mentioned earlier can be reduced to a 2 wheeled model and various parameters can be identified for a front wheel or rear wheel drive vehicles.

Since the role of modeling and simulation in engineering design continues to gain competitive advantage, it is desirable to reduce the time required to move from concept to the final product. All the standard assumptions requiring linearity in tire stiffness rigidity of the body and lack of lateral motion of the tire etc have been adopted. As a model complexity increases in step with advances in computer software and hardware, the engineer remains well served to use "proper models simulation". Proper modeling can be defined as the systematic determination of the model with minimum complexity.

3.3. Modeling the Dynamics of an Automobile with Road Excitation

a). Outline of the Plan of Studies

The studies here have been divided into two parts:

- The first one deal with the modeling of half car with simple spring dashpot suspension on the front end rear wheels as it goes over a road bump, Various responses are studies through a bond graph model.
- The second study deals with development of a more elaborate suspension model with a hinged arm between the wheels and the chassis with spring and dash pots on both sides of the pivot.

The first model is relatively standard one and has been studied widely with the simplifying assumptions of rigidity of the chassis and linearity of tire stiffness etc. The Bondgraph developed for it is to be verified with the one reported in Mukherjee et al [18] by selecting the parameters reported there. The rocking and heaving motions of the vehicle have to be obtained and then validated with the reported one.

The half car model is to be used further to study the performance of the vehicle in terms of other parameters as it passes over the bump. The model of a hinged arm suspension (often used for active control) is to be developed next. The performance of this suspension is to be modeled as the vehicle goes over a bump on the road.

3.4. Half Car Models

a). Half Car Model with a Fixed Suspension

The distance between the front and back suspension from C.G., was selected as 'b' and 'a' respectively.

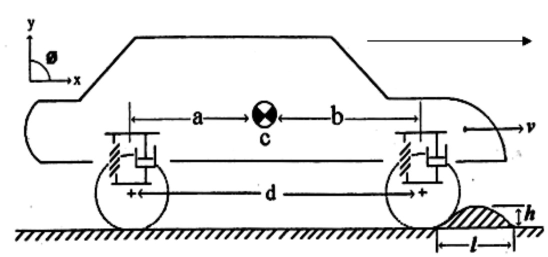

Figure 1: Half car model with fixed suspension

The vertical motion of the car is modeled by spring and dashpots suspensions at the front and the back wheels (Fig.1). The vehicle model was given a velocity step input of 1 m/s, lasting for 10 seconds for simulation. The model allows heave and pitching motion of the vehicle to be studied.

b). Description of the Elements of the Bondgraph

The description of the elements of the Bondgraph shown in Table 1.car is Vr (t) [12, 13].

Table 1: The description of the elements of the Bondgraph

Name of the element	Symbol
Flow equalizing junction	1
Effort equalizing junction	0
Inertial element	I
Compliant element	C
Resistive element	R
Transformer	TF
Source of effort	SE
Source of flow	SF

c). Parameters of a Half Car Model with Fixed Suspension

Parameters of a half car model with fixed suspension as given in Table 2.

Table 2 Parameters of a half car model with fixed suspension

Description	Parameter name	Values used
Velocity of the half car	v	1 m/s
Height of ground excitation	h	0.1 m
Length of ground excitation	l	0.3 m
Rear damper	REAR_DM	100 n.s/m
Rear stiffness	REAR_ST	20000 n/s
Front damper	FRONT_DM	100 n.s/s
Front stiffness	FRONT_ST	20000 n/s
Mass of the half car	CAR_MASS	1080 kg
Distance of rear wheel from C.G	a	1.1 m
Distance of front wheel from C.G.	b	0.9 m
Moment of inertia of the half car	J_CAR	250 kgm^2

d). Development of the Bondgraph

Bond graph based model have been developed using the notation and ideas from the Mukherjee et al [18]. The properties and the utilities of the junction can be brought about as follows:

In Bondgraph there are only two kinds of junctions, the **1** and the **0** junction. They conserve power and are reversible. They simply represent system topology and '1' junction represents a common mass point in a mechanical system, a series connection (with same current flowing in all elements) in a electrical network and a hydraulic pipeline representing flow continuity, etc. Two such junctions with four bonds are shown in the Fig.2. Using the inward power sign convention, the constitutive relation (for power conservation at the junctions) for the figure above may be written as follows;

$e_1 f_1 + e_2 f_2 + e_3 f_3 + e_4 f_4 = 0.$

As **1** junction is a flow equalizing junction,

$f_1 = f_2 = f_3 = f_4$.

This leads to, $e_1 + e_2 + e_3 + e_4 = 0.$

Now considering the other bond graph, the constitutive relation becomes,

$e_1 f_1 - e_2 f_2 + e_3 f_3 - e_4 f_4 = 0$, and, $f_1 = f_2 = f_3 = f_4$.

Thus, $e_1 - e_2 + e_3 - e_4 = 0.$

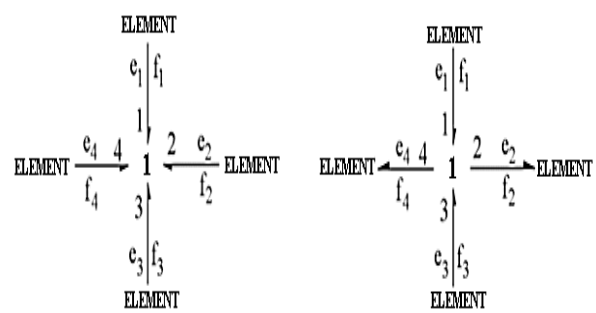

Figure 2: '**1**' Junction element models

So, a **1** junction is governed by the following rules: The flows on the bonds attached to a **1**-junction are equal and the algebraic sum of the efforts is zero. The signs in the algebraic sum are determined by the half-arrow directions in a bond graph.

0 - junctions have equality of efforts while the flows sum up to zero, if power orientations are taken positive toward the junction. This junction represents a mechanical, electrical node point and hydraulic pressure distribution point or Pascalian point. Two such junctions with four bonds are shown in the Fig 3.

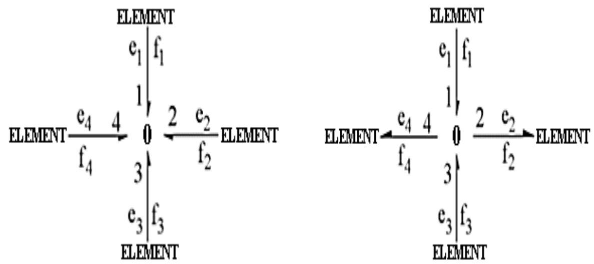

Figure 3: **'0'** Junction element models

In case of the model in the left, the constitutive relation becomes $e_1 f_1 + e_2 f_2 + e_3 f_3 + e_4 f_4 = 0.$

Whereas, the model in the right is governed by the following relation,

$e_1 f_1 - e_2 f_2 + e_3 f_3 - e_4 f_4 = 0.$

As **0** junction is an effort equalizing junction,

$e_1 = e_2 = e_3 = e_4$.

This leads to, $f_1 + f_2 + f_3 + f_4 = 0$ and $f_1 - f_2 + f_3 - f_4 = 0$, for the left and the right models, respectively.

e). Input Excitation for the Vehicle

A sinusoidal bump has been selected for the vehicle excitation with the following details:
Where h is the height (m), of the ground excitation of the bump, l is the length (m), of ground excitation of the bump, v is velocity (m/s), of half car, d is the diameter (mm), of the wheel and t is time (s).

The bump excitation for front wheel is

$$y = h * \sin\left(\pi * \frac{v}{l} * t\right)$$

for $0 \leq t \leq \frac{1}{v}$ = 0,

for $t > \frac{1}{v}$

and for rear wheel is

$$y = h * \sin\left(\pi * \frac{v}{l} * \left(t - \frac{d}{v}\right)\right)$$

for $\frac{d}{v} \leq t \leq \frac{d+l}{v}$ = 0,

for $t > \frac{d+l}{v}$

f). Creating the Bondgraph Model

A modeling scheme for the half car model as shown in Fig.4, is visualized, using the literature and the Bondgraph logic with two '**0**' junctions and 4 numbers of '**1**' junctions with relevant transformers.
Entering into the Bondgraph Software, Symbol Shakti is carried out through the entry module called Bond Pad. Entry has been started with the typical flow equalizing '**1**' junction structure shown in Fig.2. The Software assists in various activities which include numbering, causality checks etc. For example the inertial element (I17) is depicted as rotational inertia of the vehicle, compliant element (C18) is the suspension spring of the vehicle.

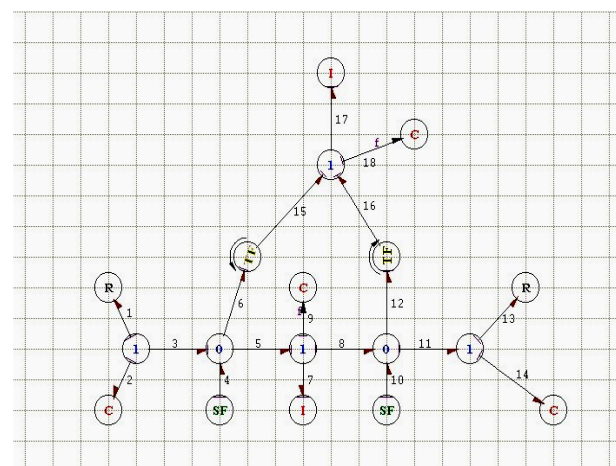

Figure 4: Bondgraph model of half car model with a fixed suspension

For the rear portion of the vehicle, resistive element (R1) is the suspension damper and the compliant element is (C2). Effort equalizing junction (0) shows real suspension of the half car, Source of flow (SF4) shows ground excitation of the car of a real wheel, Transformer (TF6) a mass less lever is connected to the rear wheel of the half car, Flow equalizing junction (1) is given the vertical motion of C.G. of the half car , Inertial element (I7) is mass of the vehicle, compliant element (C9) is heave motion of the half car.

Similarly for front suspension of the half car the effort equalizing junction (0) shows the front suspension of the car, Source of flow (SF10) shows ground excitation of the car at the front wheel, Transformer (TF12) a mass less lever connected to the front wheel of the half car, Flow equalizing junction for the front wheel is (1), resistive element is (R13) the front suspension damper, compliant element is (C14). The efforts on the bonds attached to a 0-junction are equal and the algebraic sum of the flows is zero. The signs in the algebraic sum are determined by the half-arrow directions in a bond graph

g). Simulation and the Results Obtained

The half car model with fixed suspension has been tested with the parameters shown in the

Table 2, along with the road bump described in section e) above.

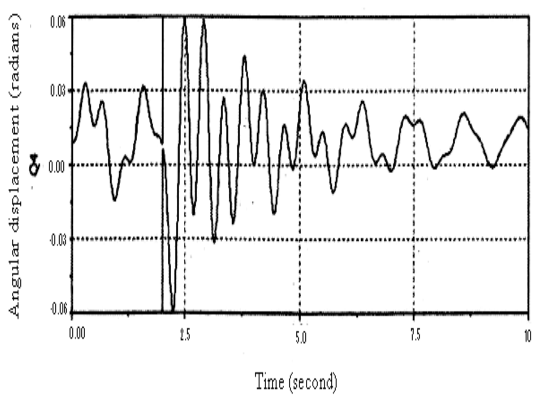

Figure 5: Rocking motion of the half car model at front suspension with vertical angular displacement at C.G., Input parameters to Symbol Shakti, Displacement-(Q4 m), Speed - 1m/s, Time-10 seconds

Fig. 5, shows the rocking motion of the half car when the half car is driven at 1 m/s speed.

These results match almost exactly with the results for this reported in Mukherjee et al [18].

Fig.6 shows the heaving motion of the half car under the same conditions. These results also match the ones reported in Mukherjee et al [18].

These two validate the model and also proper appreciation and the use of the Software Symbol Shakti.

Further studies have been carried out using the Bondgraph Model created. Motion of only the front wheel is simulated in terms of rocking and heaving as it passes over the bump in terms of time and shown in Fig. 7, and Fig.8.

Results show that the behaviour of the individual wheels may be significantly different when taken alone, as compared to over all model.

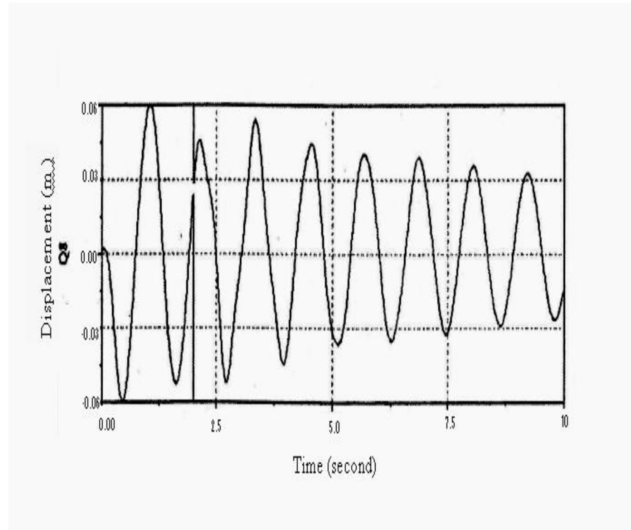

Figure 6: Heaving motion of the half car model at rear suspension with vertical displacement at C.G., Input parameters to Symbol Shakti, Displacement- (Q8 m), Speed - 1m/s, Time -10 seconds

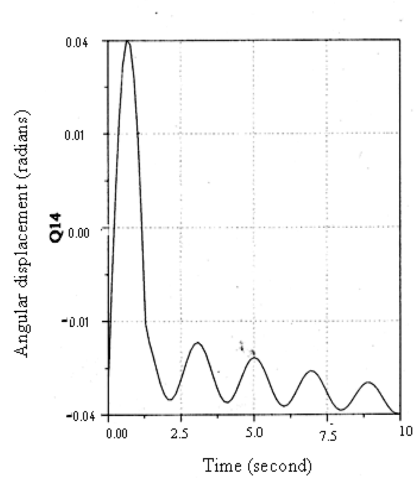

Figure 7: Rocking motion of the half car model at front suspension with vertical angular displacement, Input parameters to Symbol Shakti, Displacement- (Q14 m), Speed - 1m/s, Time- 10 seconds

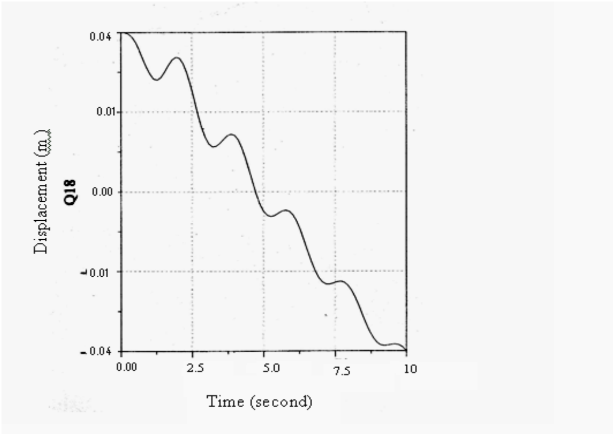

Figure 8: Heaving motion of the half car model at rear suspension with vertical displacement, Input parameters to Symbol Shakti, Displacement- (Q18 m) , Speed - 1m/s, Time – 10 seconds

h). Validation of Results and Possibilities of further Studies

Validation of the results obtained was carried out (as explained earlier) with the help of results reported in Mukherjee et al [18]. The first two graphs plotted using the data from Mukherjee et al [18] dealing with rocking and heaving motion of the half car identical values. This validates proper use of the Software and use of correct units and values. Using the model created has been further used to study the individual behaviour of the front and rear suspensions.

The behaviour of the suspension for going over a bump can be further studied by changing over the parameters in the model developed. It has been further evolved to study hinged arm suspension as shown in the next section.

3.5. Modeling Hinged Suspension through Bondgraph based Half Car Model

a). Overview

As discussed in literature review suspensions for automobiles have been continuously advancing and newer configurations permitting on line control have become practical. These require real time computation and thus simpler but robust models permitting control, where Bondgraph models have become well adopted. Suspensions have evolved with trailing and leading arms, Glass [4] helping in providing control elements besides affecting the dynamics. Present effort is about a hinged arm suspension as suggested by Mukherjee et al [18] where basic configuration is of a leading arm (value of lead is a variable). This has to be modeled for a sinusoidal bump (as in the earlier section), and the heave and rocking motion (pitch) have to be studied.

b). Development of the Vehicle Model

The configuration of the vehicle elements adopted is shown in Fig.9, which has considerably more elements than the earlier model. Basically two more hinged platforms have been added which are connected to chassis of the vehicle. Sets of springs and dashpots between the hinged arm and the vehicle are part of the proposition Mukherjee et al [18]. Various elements and their nomenclature is also shown in the Fig.10. There three hinged points for the half car also shown. To simulate the half car, the model was made geometrically symmetric by setting distance (A_{f} + a_{f}) for front wheel and (A_r+a_r) for real wheel effectively placing the models centre of gravity between front and rear wheel of the vehicle. Most of the values for the physical elements of the vehicle have been taken from the vehicle describe in the previous section.

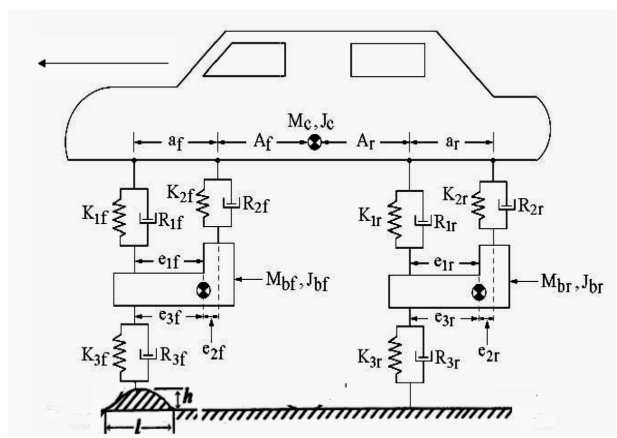

Figure 9: Half car model with hinged suspension

In the proposed model the distance of rear wheel from C.G is 1.1m, the. ,Distance of front wheel from C.G is 0.9 m ,Front damper is R_{2f} , Rear stiffness is K_{2r} , Front stiffness is K_{2f}, Rear damper is R_{2r} , Mass of the half car is Mc, Rear damper is R_{1r} , Front damper is R_{1f} , Rear stiffness is K_{1r}, Front stiffness is K_{1f} , Moment of Inertia of the half car is Jc , Weight of the hinged arm suspension of the half car is Mbfg , Weight of the rear arm suspension of the half car is Mbrg , Mass of the hinged arm suspension of the half car is Mbf, Mass of rear arm suspension of the half car is Mbr, Moment of Inertia of the rear arm suspension is Jbr, Moment of Inertia of the hinged arm suspension of the half car is Jbf , Front stiffness is K_{3f} , Rear stiffness is K_{3r} ,Front damper is R_{3f} , Rear damper is R_{3r} , Velocity of the car is v.

c). Development of the Bondgraph Model

The basic effort towards starting a Bondgraph model is similar to what has been shown for a non hinged suspension vehicle. The details of the road bump have also been adopted from the previous section. For the proposed configuration two additional hinges along with masses and moment of inertias have been introduced and two sets of additional springs and dashpots between the hinged platform and the body of the vehicle have been introduced. To develop a feasible system transformers have been introduced as shown in the Fig.11. As the two halves are symmetrical only half of the diagram has to be kept in focus.

d). Development of the Actual Bondgraph

To draw the model of the half car with hinged arm suspension the activities started by invoking the Bond Pad of the Bondgraph software Symbol Shakti. Towards developing the Bondgraph description (Fig.10) the software itself provides supports for a variety of activities like numbering the Bonds, displaying direction of causality, power and effort flows etc. In fact the software checks the feasibility of the system modeled by displaying zero errors in end if it is logically correct.

Inspite of this fact, it does not insure that it is Bondgraph of the system that was actually to be modeled. To gain further confidence some numerical results have also been obtained as shown in the next section. In the Bondgraph, Mc is the mass of the car body and Jc is the Moment of inertia (as shown in the Fig.10). Description of bonds and associated elements is as follows.

For the rear suspension compliant element is (C15) rear stiffness is $K_{2r,}$ For the resistive element is (R16) rear damper is R_{2r} , Resistive element is (R27) rear damper is R_{1r} , Compliant element (C30) the stiffness is K_{1r} and also for the resistive element of the rear damper is $R_{1r,}$ Source of effort is (SE54), Mass of the rear arm suspension of the half car (M53) is Mbr, Moment of Inertia of the rear arm suspension (M57) is Jbr, For the resistive element (R78) rear stiffness is K_{3r} , Source of flow is (SF73) for the velocity of the half car is v.

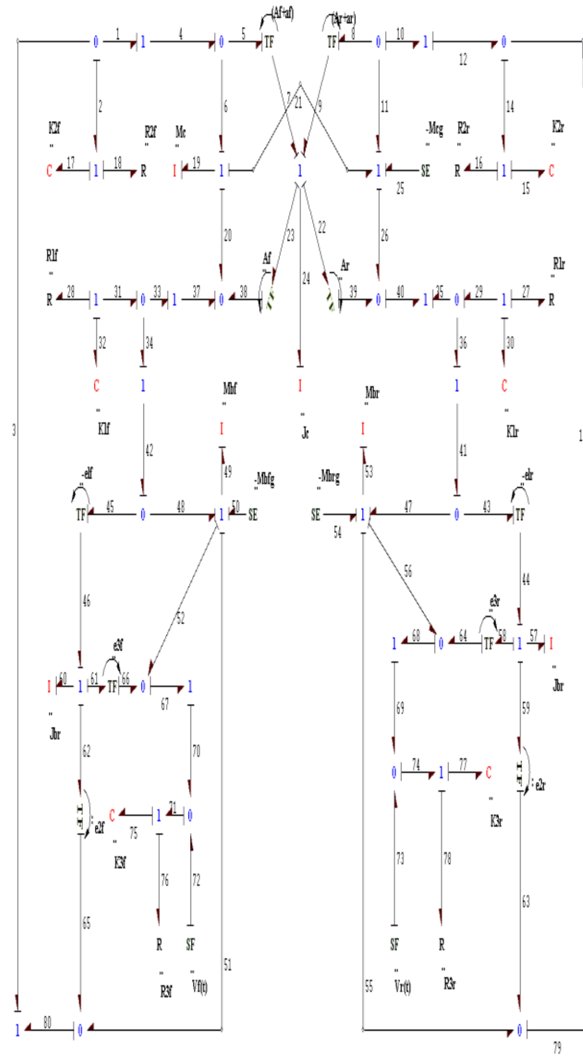

Figure 10: Bondgraph model of half car model with a hinged suspension

For the front suspension resistive element (R18) is for the front damper is $R_{2f,}$ Complian element (C17) is for front stiffness is $K_{2f,}$ Complian element (C32) is for front stiffness $K_{1f,}$ Source of effort is (SE54), Mass of the hinged arm suspension (M49) is Mbf, Moment of Inertia of the hinged arm suspension (M60) is Jbf, Resistive element (R76) front damper is R_{3f} , Source of flow (SF72) for the velocity of the car is v.

e). Running the Model on Symbol Shakti

A model that has been successfully compiled can also be run on the system and results obtained. Symbol Shakti also allows the provision of obtaining various plots by specifying the relationships. Activation of the bonds can be done to obtain specific details of the variation of the values.

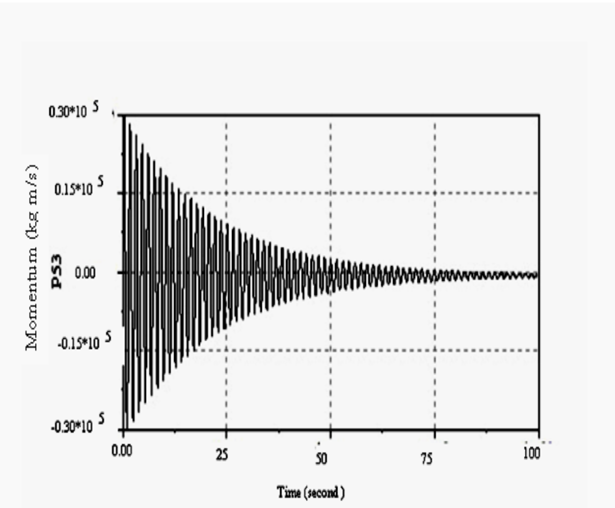

Figure 11: Heaving motion of the half car model at rear suspension. Observed through Momentum in bonds, Speed-15 m/s, Time- 100 seconds, Numerical data is taken from Table 2.

Equation as generated by the system for the half car model with a hinged suspension. These equations have been automatically solved by the Symbol Shakti solver for specific case as shown in Fig.11. Results show that it the basic characteristics are not very different then the model may have to be tuned to drift towards any specific desirable objectives.

4. Results and Discussion

Bondgraph based modeling of various systems of an automobiles has been carried out in large number of investigations, reported in literature. The present work attempts to model a car suspension through a half car model approach. A hinged arm suspension selected has been modeled for a case when the vehicle goes over a bump of the shape of a sine wave. Efforts have been concentrated on evolving the model, as once the model is obtained a variety of results can be obtained. The study has been carried out in two parts. The first part models a half car with a simple suspension. The results of this simulation have been successfully verified with the data available in the literature. The second part is an effort to model a hinged suspension with a half car model as an extension to the first model. A bond graph model for this has been successfully compiled. A few trail results for specific situations have been obtained.

5. Conclusion

Automobiles continue to be central to present day human activities and a vast literature exists on their evolution and adaptation. However, the pace of developments has not slowed down. Newer tools such as Bondgraphs make it possible to model more and more complex systems. The efforts here examine the modeling of automobile suspensions especially that may be useful in future to bring in active control systems etc. A half car model of a conventional suspension using Bondgraphs has been created first for modeling heave and rocking motion of a car as it passes over a bump on the road. The results are specially obtained for a case where published value is available. A close match with that has validated the modeling strategy and the use of the Bondgraph package. This model has then been extended to a hinged arm suspension half car model with two sets of springs and dashpots across the hinge. The model has been successfully compiled showing the logical correctness of the model. A few results have also been obtained more results from the model created can be obtained by giving relevant *inputs.*

6.0 Possibilities of Future Work

Hinged arm suspensions have been around for quite some time. However, they become important for introducing active computerized control of vehicles. The present work has used a model without active elements but two sets of springs and dashpots. While a successful compilation of the Bondgraph on the software (Symbol Shakti) of the proposed model validates a logically correct modeling, it does not insure that at worthwhile model has been created. It may be verified with further efforts in that direction. A more systematic activity can be carried out of study the benefit of the hinged arm suspension under various conditions, through the model created. The work can be extended by bringing in the control systems through Bondgraphs model towards developing an active suspension model.

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