REDUCED SIMULATION'S MODEL OF A WHEEL LOADER BY USING THE BOND GRAPH TECHNIQUE TO USE IN TRAINING SIMULATORS.

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KEYWORDS

Bond Graph, earth moving machines, steering system, mechanism.

ABSTRACT

This paper presents a model developed for simulating earth moving machines like wheel loaders. The developed model is used for real time simulation and is included in a full machinery simulator designated for the training..

The model includes a mechanical model of the chassis, axles, suspension systems, hydraulic actuators and mechanical models of the arms. All the models have been simulated using Bond Graph elements (Karnopp et al. 1990). The complete model has been developed as a modular system, using sub-models of each of the above-mentioned components. This approach helps to minimize both the number and complexity of the system equations obtained from the overall model.

Some simulation examples and results are also included.

INTRODUCTION

Real time simulation is an indispensable requirement or models whose purpose is to test vehicle handling, since the driver expects to get an immediate response, as is the case in real life. Sometimes, when a vehicle's engineer decides to analyze the quality or safety, or to design controllers for ABS systems, normally rely on multibody dynamic models and each question requires a model of suitable complexity. The existing models span a wide range in the complexity spectrum. For instance, the design of a controller it might be enough to represent the vehicle as a point mass (Liang and Peng 1999); when we study suspensions we can use a quarter car model (Ando and Suzuki 1996); a half car model may be preferred when analyzing ABS performance (Alleyne 1997); finally, a full car and higher-order multibody models may be necessary (King and Ro 2002) for more advanced studies.

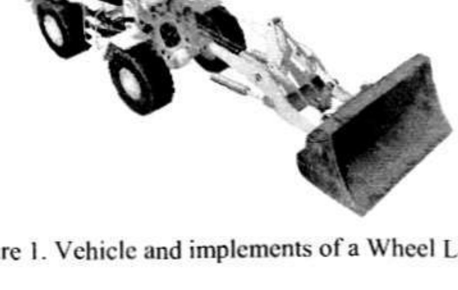

Figure 1. Vehicle and implements of a Wheel Loader

A framework for a modular approach to modeling 3D multibody systems is available in the literature (Pacejka 1985, Bos 1986, Ersal 2009) but there are not literatures about optimized earthmoving machines models in the items presented here.

When it comes to simulating machinery such as excavators or wheel loaders, the part corresponding to the vehicle's own dynamics is joined to the part related to the movement of implements, such as buckets, arms or actuators (fig. 1). Unlike traditional vehicles, these are lacking in suspension and need to incorporate an oscillating axle, located in the front or rear axle depending on the machine, so that the machine can be adapted to the unevenness of the terrain. In a traditional vehicle, it is the front wheels that turn the vehicle with no relative turn whatsoever being produced in the rear wheels with respect to the center of gravity. However, in the particular case of Wheel Loaders (fig. 2), all four wheels turn with respect to the center of gravity, which means that this phenomenon must be taken into account, as well as the specific way in which these machines produce the turn.

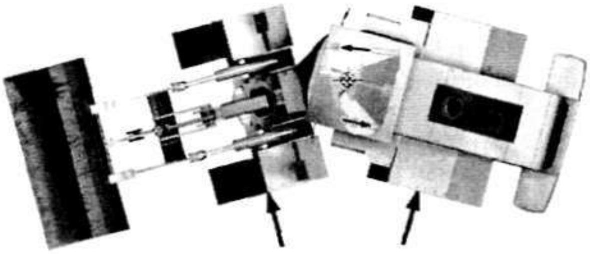

Figure 2. Turn in a Wheel Loader

As to the movements of the different implements, these are performed using the joint action of several hydraulic actuators and integrated mechanisms. These mechanisms are partially supported on the chassis of the machine. Since the main aim is to load, unload and move material using a scoop or a bucket, one of the objects of the simulation is to see the reaction occurring on the chassis of the machine when the different implements are being moved, as this involves a displacement of mass (Margolis and Shim 2002).

The aim of this paper is to demonstrate the validity of implementing kinematic or equivalent equations in cases where a dynamic simulation is not strictly necessary. The Bond Graph (Karnopp et al. 1990) technique enables systems belonging to the different areas of physics to be modelled in a way that is both intuitive and close to reality. It is a perfect technique for representing elements belonging to the area dealt with in this paper.

STRUCTURE OF THE CHASSIS

In a Wheel Loader, the chassis is typically comprised of two front and rear parts joined in the middle by an axle which lets one part turn with respect to the other (fig. 2). The front part supports the front differential, arms and bucket, as well as the hydraulic actuators, while the rear part supports the cab, the rear differential, oscillating axle, engine, transmission and fluid tanks. The turning movement of the front part of the chassis with respect to the rear is performed by opening or closing the angle formed between both parts by activating two hydraulic cylinders, the turn being proportional to the angle turned by the steering wheel.

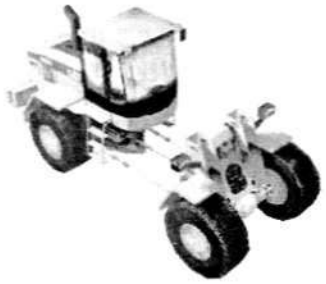

Figure 3. Wheel Loader chassis structure

As we have stated, unlike traditional vehicles, this type of machine incorporates an oscillating axle so that the machine can be adapted to the unevenness of the terrain (fig. 3).

On first inspection, the way to model the whole chassis would seem to be by introducing three rigid solids and then assembling them using the two axles. Since each of the rigid solids has its own reference system, a single global system must be worked with where all the velocities of the different points can be referenced, thereby making it possible to form the final set of equations (fig. 4).

Since the driver's cab is located over the rear chassis, it is the reference system of this part that must be used for calculating the velocities in the different points where the parts are joined.

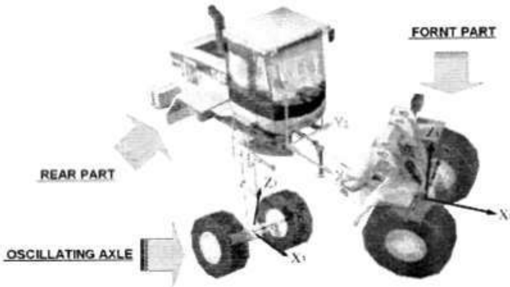

Figure 4. Chassis reference system

By observing the two joints where this change of reference needs to be made, it can be seen that in the first of these, a turn is made about the Z_1 axis parallel to Z, which means it would be sufficient to simply make a change on the XY_1 plane. Likewise, in the second joint, a turn is produced about the X_3 axis, which is parallel to X, it only being necessary to make the change of reference on the YZ_3 plane. Therefore, it is not necessary to work with three-dimensional coordinate transformations, but with planes, with all the simplification that this implies.

Turning Movement

As is the case with a traditional vehicle with power steering, the power steering takes charge of changing the wheel directions with practically no effort by the driver, the pump has sufficient energy to change and maintain the direction of the wheels during the driving process. It is for this reason that it can be supposed that the angle formed between the front and rear part of the machine is proportional to the angle turned by the steering wheel.

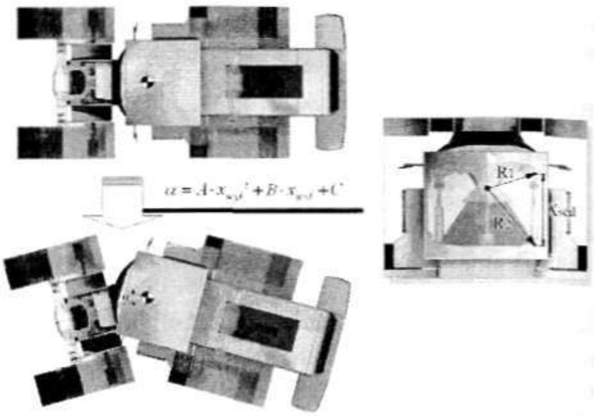

Figure 5. Re-positioning of the wheels in a Wheel Loader

If the positioning of each wheel is analyzed when a turn is being made, it can be seen how these relocate in accordance with the angle "α" (fig. 5) (max. ±40°) formed between the front and rear part of the machine; hence in accordance with the angle turned by the steering wheel. In each of the parts, the angle is distributed equally in both the front and the rear part.

Regarding the positioning of the wheels, it is possible to model a single rigid chassis instead of having to connect the two corresponding solids to the front and rear parts of the chassis and having to make a change of reference at its anchorage point. It will subsequently be necessary to change the position of the wheels on this chassis in respect of the centre of gravity, depending on the "α" angle which would be formed by the front and rear parts.

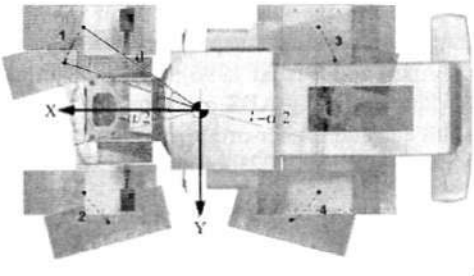

Figure 6. Re-positioning of wheel anchorage points

As a result of this change, a model with fewer equations is obtained, since the equations referring to one of the solids and to the change of reference have been eliminated. Thus, the points shown in the figure 6 corresponding to the wheels can be positioning depending on angle between front and rear parts "α" (table I):

WHEEL	X	Y
- *(1) Right Front*	$+d\cdot\cos(\beta-\frac{\alpha}{2})$	$-d\cdot\sin(\beta-\frac{\alpha}{2})$
- *(2) Left Front*	$+d\cdot\cos(\beta+\frac{\alpha}{2})$	$+d\cdot\sin(\beta+\frac{\alpha}{2})$
- *(3) Right Rear*	$-d\cdot\cos(\beta-\frac{\alpha}{2})$	$-d\cdot\sin(\beta-\frac{\alpha}{2})$
- *(4) Left Rear*	$-d\cdot\cos(\beta+\frac{\alpha}{2})$	$+d\cdot\sin(\beta+\frac{\alpha}{2})$

Table I. Calculation of wheel anchorage points

where "d" is the distance from the anchorage point to the center of gravity and "β" the angle initially formed respect of the horizontal. It must be said, that subsequently, in each of the wheels, the engine or braking torque needs to be separated into components taken about the global X and Y axes of the chassis, which is why it is essential to have information on the three linear and two angular velocity components at the wheel anchorage points.

Fig. 7 shows the Bond-Graph model corresponding to a three-dimensional solid (Karnopp and Margolis. 1993, Asgari and Hrovat 1991), expressed in local coordinates, with the information about V_x, V_y, V_z, ω_x and ω_y contained in one of the wheel anchorage points located at one of the coordinates referring to the X_1, Y_1 and Z_1 center of gravity. As can be seen in the fig. 7, the effect of the machine's weight has been included into the different local axes, instead of implementing equivalent changes of reference using TF type elements.

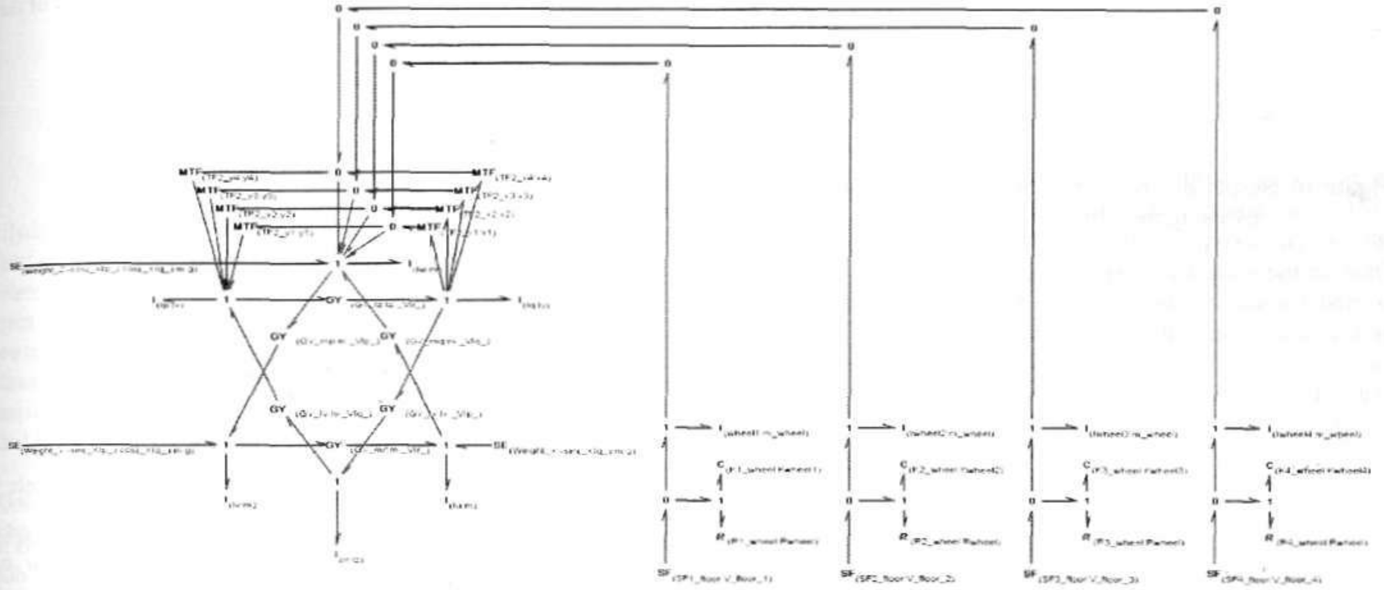

Figure 7. Chassis solid with anchorage points to the four wheels by means of a Bond-Graph.

Movement Of The Oscillating Axis

As for the chassis, it is also essential to model the behavior of the oscillating axis with the object of adapting the machine to the unevenness of the terrain.

Figure 8. Movement of the oscillating axle

Firstly, it must be said that the maximum permitted movement is approximately since ±15°, the lateral movement of the wheels and all that entails, may be ignored, so that the vertical displacement of the wheels is all that is significant (fig.8).

Moreover, compared to the rest of the machine and due to the low maneuvering speed of these machines, the dynamic behavior of this axle may also be ignored.

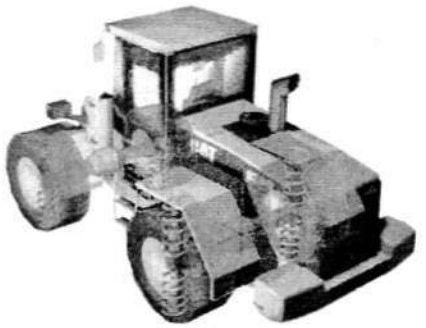

Figure 9. Dynamic model of the oscillating axle + suspension

However, it can be seen that due to the existence of the anchorage point, its movement is the average of that corresponding to the two wheels, and the movement of the suspension adjacent to one of the wheels is the opposite to that at the other (fig. 8 and fig. 9).

Fig. 7 showed the typical model for studying vehicle transversal dynamics where the suspension of each of the wheels can be seen as well as their inertias and rigidities. It can also be seen how the wheels has an excitation at its base, caused by a change in terrain (V_floor_1, 2, 3 or 4).

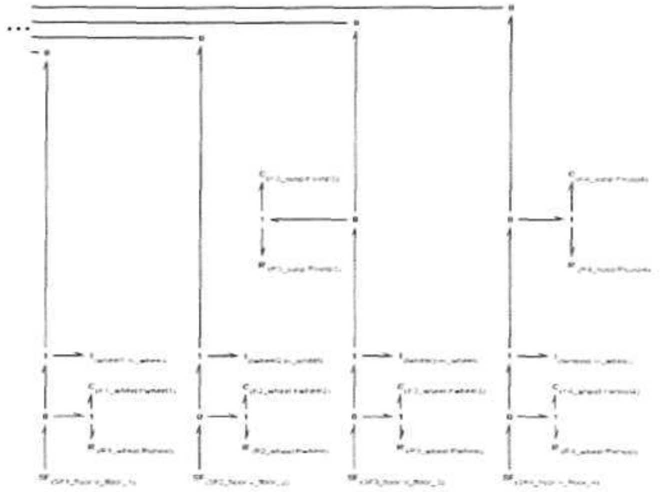

Figure 10. Suspension of a traditional vehicle (only rear part) by using the Bond Graph technique.

Thus, in the wheels corresponding to this axle, it will suffice to model a similar suspension to that of traditional vehicles (in the other wheels there is no suspension whatsoever), as is shown in figure 10, and then associate the movement at the point of anchorage as a combination of the movements of the wheels and the movement of the suspension with one another:

$$X_{left\_suspension} = -X_{right\_suspension} \qquad [1]$$

Fig. 11 shows the interrelation between the inertia velocities corresponding to each of the rear wheels of the machine ('Iwheel3' and 'Iwheel4', Right and Left wheels respectively) and the displacements existing in each of the suspension springs introduced (K3_susp and K4_susp) according to expressions [1].

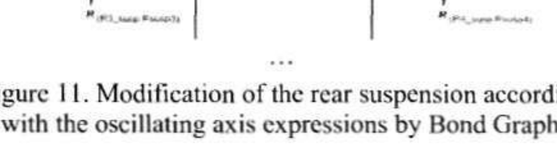

Figure 11. Modification of the rear suspension according with the oscillating axis expressions by Bond Graph.

If we apply a excitation at the base of one of the rear wheels caused by a change in terrain, such as can be seen in the graphs showing the results, the displacement of the suspension on one of the sides is the opposite to that of the other side (fig. 12).

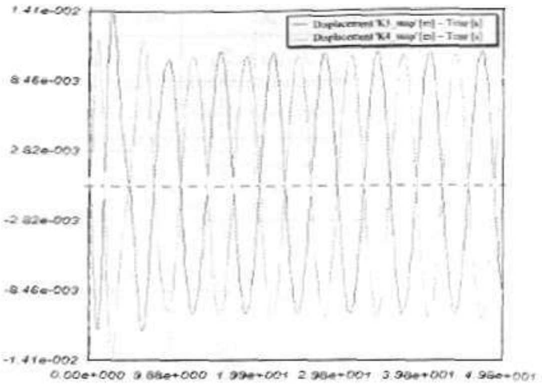

Figure 12. Displacements in the suspension

If we study the movement of the machine, the vertical velocity of the machine is the average of the movement of the wheels, such as we can see in next figure.

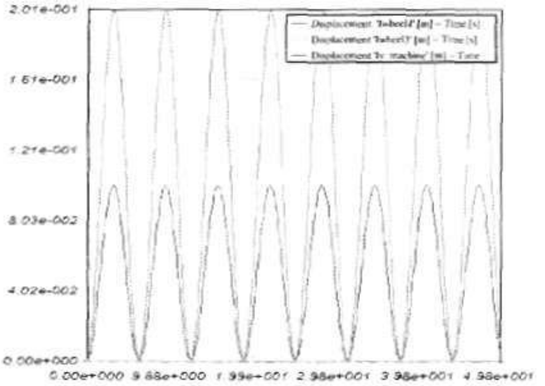

Figure 13. Vertical displacements of the machine's wheels

Fig. 14 shows that the difference between the two models is that the one with the oscillating axle has no displacement due to the vehicle's own weight, which is exactly what happens in reality.

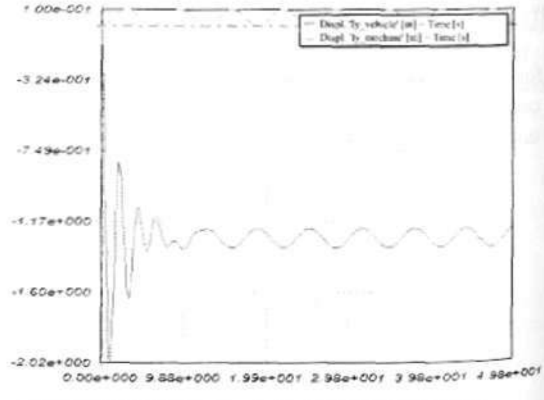

Figure 14. Displacements in the suspension

Under normal conditions, the values of the spring and damping of the suspension in the oscillating axle model will be small (just sufficient to quickly stabilize the machine), while they will be very great when the maximum turning angle of the oscillating axle is attained or superceded by ±15°.

BUCKET HANDLING

The scoop or bucket is moved by using hydraulic actuators and one or several interlinked mechanisms (fig. 15). The functioning of these actuators is controlled by the machine operator handling the appropriate levers. This handling regulates the speed and direction in which the hydraulic actuators are required to work.

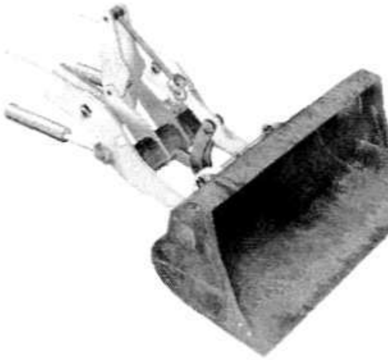

Figure 15. Implements of a Wheel Loader

Hydraulic systems modelling and simulation has been performed using a whole range of techniques, although currently a lot of territory remains to be researched in this area of Engineering. Traditionally, algebraic differential equations have been proposed based on the corresponding laws of physics (Cobo et al. 1998.). They have then been solved in various environments like MATLAB, Simulink, and MAPLE, to name but a few.

One of the drawbacks of this procedure lies in the fact that obtaining algebraic-differential equations is usually complex as well as the procedure for solving them, and on many occasions so much time is spent that real time simulation cannot be performed while costs also increase significantly.

Another possible option is to generate the model from zero using specific software, either by the finite elements method, using block diagrams, or using graphic techniques. These types of simulations are often oriented towards specific applications, frequently technological ones, and are therefore mainly focused on obtaining graphic or numerical results (Hydro+Pneu, OHC-Sim, HOPSAN, LVSIM) and move away from obtaining equations for the model.

Normally, in these machines, since the hydraulic circuit pump has enough power and there are intermediate hydropneumatic accumulators, the working velocity of the hydraulic actuators remains more or less constant for a constant lever position, and only varies as a function of the load in the bucket.

For this reason, we may assume that the velocity in the actuator pistons is proportional to the position of the control levers and the load in the bucket. To know the values of this velocity, it is necessary to simulate the hydraulic circuit and obtain the law of pressure and forces appearing in the piston, which considerably simplifies the complexity of this subsystem's model (Romero et al. 2008).

The mechanisms present in machines such as Backhoes and Wheel Loaders work on a single plane, which means a planar model can be studied instead of a three-dimensional one.

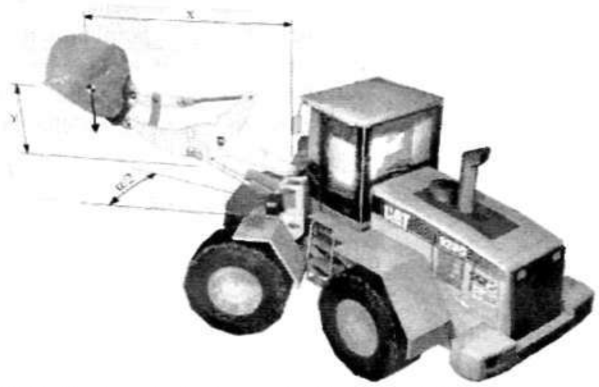

Figure 16. Reaction of the arm on the machine chassis

In order to be able to simulate the different implements, it is essential to develop a model of each hydraulic actuator, and assemble the different bars and actuators so as to obtain the equivalent mechanism (Romero et al. 2006; Romero et al. 2009) and incorporate it into the machine chassis so that the relevant actions and reactions will be produced on the chassis.

Reactions On The Machine Chassis

As a general rule, it may be stated that the most important reaction that takes place in the machine chassis is that caused by the displacement of the load in the bucket, since it is the only mass that varies, either in volume or density, and to which the driver must be accustomed. Thus, it is essential to drive a Wheel Loader with the load as low as possible and avoid sudden braking, since this can cause the machine to overturn.

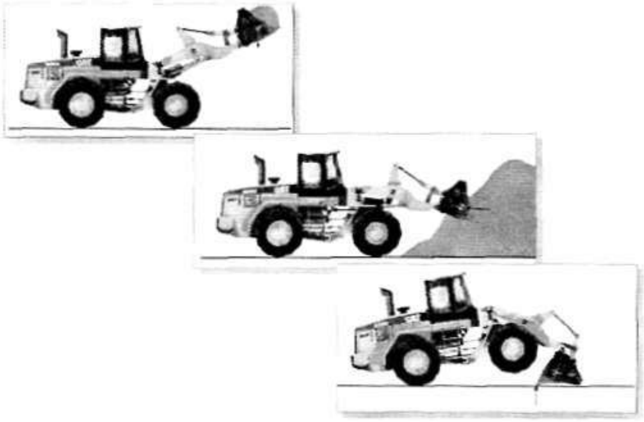

Figure 17. Reactions of the arm on the machine chassis

However, instead of anchoring the planar mechanism to some points located on the three-dimensional solid and thus, work with a single model where the reactions themselves would act directly on the chassis, we have preferred to isolate the mechanism.

So, when its kinematic simulation has been obtained, not only the angles in each of the arms can be obtained, but also the position of the point where the load acts.

When the coordinates of this point have been obtained, the resulting torque on the chassis can be quickly calculated, bearing in mind that the load at this point acts vertically and that the chassis may have a different orientation from the horizontal plane.

In this way, in order to obtain the behaviour caused by the reaction of the load on the chassis, it will only be necessary to introduce a point and a force into the three-dimensional solid.

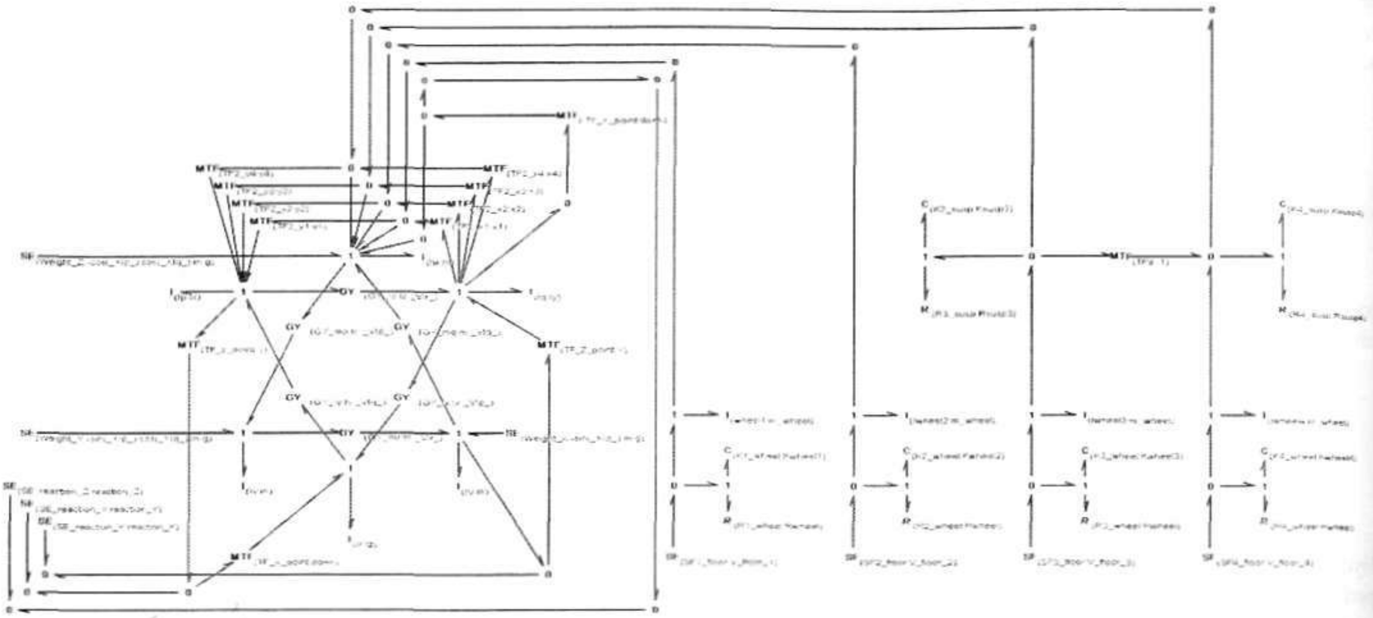

Figure 18. Chassis solid with anchorage points to the four wheels and one reaction forces by means of a Bond-Graph.

In fig. 18 it can be seen how the existence of a vertical load located at a point of local coordinates (do+X,Y,0) influences a three-dimensional solid. The coordinates of this point will constantly vary as the arm is extended or retracted and will be the result of the kinematic study of the arm.

The force will correspond to the weight of the load in the bucket, the reaction when the bucket load material or the reaction with the floor, once it has been resolved into the local coordinate axes of the chassis of the chassis.

Therefore, if we move the bucket away from the machine and unload the content of bucket to reduce the force due to it a few seconds after starting the simulation, the chassis of the machine undergoes a slight initial pitching until it stabilizes and then gradually acquires a different angle and the deformation of the wheel's, rear or front, are different (fig. 19).

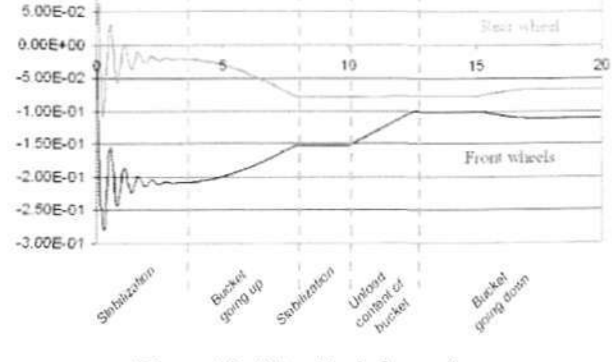

Figure 19. Wheel´s deformation

CONCLUSIONS

As a final conclusion, it may be stated that in general it is possible to translate the results due to the action of external elements such as servopumps or hydraulic actuators to a model by using expressions according to the different parameters being handled (steering wheel, pedals, levers,...) or through the resolution of kinematic models (mechanisms) instead of trying to group everything together in a single model.

Also, the end model would only be left with those elements that it would be impossible to separate because they interact, such as the wheels, for instance, not dealt with here. On the other hand, we have seen the advantage of dealing with elements such as implement bars and actuators using a Bond-Graph approach.

It has thus been seen how a simulation model can be created starting out from simplifications and subdividing a large model into smaller ones.

It has also been seen how it is not necessary to simulate the dynamics associated with a mechanism at every instant, but only in cases where this information is really needed.

Finally, it should be pointed out that the equations so obtained are not only fewer in number but also in complexity, making a real time simulation possible by having reduced the time needed to perform it.

As an professional application of the developed model, it has been used to create a training simulator for a spanish simulation company.

REFERENCES

Alleyne, A. 1997. "Improved Vehicle Performance Using Combined Suspension and Braking Forces". Vehicle System Dynamics, Vol. 27, Is. 4, pp. 235-265.

Ando, Y. and Suzuki, M. 1996. "Control of Active Suspension Systems Using the Singular Perturbation Method". Control Engineering Practice, Vol. 4, Is. 3, pp. 287-293.

Asgari, J. and Hrovat, D. 1991. "Bond graph models of vehicle 2D ride and handling dynamics" Proc. Of the 1991 ASME Winter Annual Meeting.

Bos, A. M. 1986. "Modelling Multibody Systems in Terms of Multibond Graphs with Application to a Motorcycle", Ph.D. Dissertation, University of Twente, Enschede, Netherlands.

Cobo, M., Ingram, R., Cetinkunt, S. 1998. "Modeling, Identification and real-time control of bucket hydraulic system for a Wheel type loader earth moving equipment". Journal Mechatronics, Vol. 8, pp. 863-885.

Ersal, T., Kittirungsi, B., Fathy, H.K., Stein, J.L. 2009. "Model reduction in vehicle dynamics using importance analysis". Vehicle System Dynamics, Vol. 47, Is. 7, pp. 851 – 865.

Karnopp, D.C., Margolis, D.L. and Rosemberg, R.C. 1990. "System Dynamics: A Unified Approach". John Wiley & Sons, Inc., Second edition.

Karnopp, D.C. and Margolis, D.L. 1993. "Analysis and simulation of planar mechanism systems using BG". J. of Mechanism Design. Vol. 101, Is.2, pp.187-191.

Kim, C. and Ro, P. I. 2002. "An Accurate Full Car Ride Model Using Model Reducing Techniques". Journal of Mechanical Design, Vol. 124, No. 4, pp. 697-705.

Liang, C.-Y. and Peng, H. 1999. "Optimal Adaptive Cruise Control with Guaranteed String Stability", Vehicle System Dynamics, Vol. 32, Is. 4, pp. 313-330.

Margolis, D. and Shim, T. 2002. "Instability Due to Interacting Hydraulic and Mechanical Dynamic in Backhoes", ASME International Symposium on "Advanced Vehicle Technologies".

Pacejka, H. B. 1985. "Modelling Complex Vehicle Systems Using Bond Graphs", Journal of the Franklin Institute, Vol. 319, Is. 1, pp. 67-81.

Romero, G., Félez, J., Martínez, M.L. and Maroto, J. 2006. "Kinematic analysis of mechanism by using Bond-graph language". Proc. of 2006 European Conference on Modeling and Simulation ECMS'06, pp. 193-202.

Romero, G., Félez, J., Martínez, M.L. and del Vas, J. J. 2008. "Simulation of the hydraulic circuit of a wheel loader by using the Bond Graph technique ".Proc. of 2008 European Conference on Modelling and Simulation ECMS'08, pp. 313 a 321.

Romero, G., Félez, J., Mera, J. M. and Maroto, J. 2009. "Efficient simulation of mechanism kinematics using bond graphs". Simulation Modelling Practice and Theory. Vol. 17, Is. 1, pp. 293-308.

BIOGRAPHY

GREGORIO ROMERO received his Mechanical Engineering from the UNED (Spain) in 2000. He got his PhD Degree from the Technical University of Madrid in Spain in 2005 working on simulation and virtual reality, optimizing equations systems. He started as Assistant Professor at the Technical University of Madrid in Spain (UPM) in 2001 and became Associated Professor in 2008. He is developing his research in the field of simulation and virtual reality including simulation techniques based on bond graph methodology and virtual reality techniques to simulation in real time. He has published more than 35 technical papers and has been actively involved in over 20 research and development projects and different educational projects.

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