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Co-Simulation Procedure for PID and Fuzzy Logic Active Controls Strategies Applied to a Sprayers Boom Suspension

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1. Introduction

The boom sprayers are responsible for applying chemical products on cultures in order to maximize agricultural production. The spray is the fractionation of liquid droplets in order to distribute uniformly over the target. So smaller is the liquid volume to be distributed through the area, so smaller is the required drop diameter. The sprayers are designed just to generate drops and throwing them over the target with the required uniformity.

The spray distribution uniformity of sprayers boom is given by the assembly and operation conditions such as, nozzle spacing and opening angle, boom distance from soil, liquid pressure and dynamic stability of the boom. The liquid volume distributed along the boom should be as constant as possible, Sinfort (1994).

The vertical boom oscillations caused by irregularities in the terrain modifies the distance between each nozzle and the target, distorting the distribution. Moreover, when the oscillations are excessive the tips of the boom can touch the ground, causing damages. These oscillations may increase with walking speed of the tractor vehicle, Musillami (1977). The horizontal boom oscillations also change the sprays uniformity, but in a smaller proportion than the vertical ones.

Another fairly common problem that can also change the application uniformity is the error in the juxtaposition of culture bands covered by the spray. Insufficient or excessive spacing between these bands can cause a variation in liquid volume used up to 100%.

Various methods to study the quality of spray distribution under the dynamical aspects of the movement are known. These methods differ in the way of exciting the sprayer. One of them uses the excitation by a vehicle walking on a standard grass track prepared (POCHI et al., 2002, MILLER et al., 1989), or translating on a track prepared with artificial obstacles (CHAPLIN and WU, 1989). Other methods develop and use a shake driver to simulate a track with obstacles (SINFORT et al., 1997).

Herbst and Wolf (2001) developed a servo-mechanism to perform excitations on sprayers. They measured the sprays of various equipments, pulled sprayers and tractor mounted sprayers from different manufacturers. In these experiments they found coefficients of variation from 5 to 22%, depending of the boom length, the walking speed and excitation method used. According to these researchers a coefficient of variation in order of 15% would be an acceptable value for the usual ground conditions founded.

One procedure to minimize the coefficient of variation of spray distribution is to design and use mechanisms to stabilize the boom within acceptable parameters. These mechanisms are known as boom suspensions for sprayers.

On many sprayers there are control of spray mean height and systems of boom movement management with passive boom suspensions. The active controls are still less used. However unstable movements have been characterized as a great limitation for chemical products applications with precision and good uniformity, (RAMON and BAERDEMAEKER 1997, POCHI and VANNUCCI, 2001).

Womac et al. (2001) investigated the effect of nozzle height and the equipment walking speed in the uniformity of chemical products application in field conditions. The coefficient of variation founded stays from 5% to 17% for boom static conditions and 6% to 37% for boom in motion (6 to 26 $km.h^{-1}$).

Sinfort and Herbst (1996) studied the boom movement and the spray pattern in terms of practical use. The movements of the spray boom were evaluated by a simulator with hydraulic cylinders and the spray pattern was simulated by software. It is concluded that the roll motions are responsible for major non-uniformity of liquid application.

Ramon et al. (1997) developed a polynomial model to predict the distribution of a single spray nozzle that moves on a channels table 15 meters long. The difference founded between the measured and the simulated values was below 7%. They observed also that the boom downward movements affect the liquid distribution more than the boom upward movements.

Speelman and Jansen (1974) determined that the amount of vibrations on the sprayer boom is influenced by the structure of the boom, ground surface irregularities and walking speed. Using an initial condition of 0.5 meters spray height, they observed that as amplitudes of boom vertical motion increase, the uniformity of spray distribution decreases.

On cereals spraying, Nation (1980) determined that the spray deposit variation is proportional to the movement of the sprayer boom end. He also observed that random vertical movements of the sprayer boom are more influenced by roll movements than vertical translation motions of the boom.

Considering a boom as rigid body subjected to sinusoidal inputs, Iyer and Wills (1978) proved that the bigest source of the spray distribution variation comes from the own movement of the boom

Langenakens et al. (1999) founded that increasing the vehicle translation speed, the boom oscillation amplitude also increases. They obtained for applied liquid volume coefficients of variation from 2% to 173%, caused mainly by boom rolling movement resulting from vehicle translation.

2. Models, simulations and results comparisons

We used a calibrated virtual model that was developed for some simulations to test control strategies. The performances of these strategies are compared with the performance of a passive suspension model. Following a brief description of the models and all the simulations are presented.

2.1 Description of the models used in simulations

This part will show the main configurations of the models used in simulations with the rigid body software (ADAMS).

2.1.1 Passive model

Figure 2.1 shows a trapezoidal type passive boom suspension model with its main dimensions.

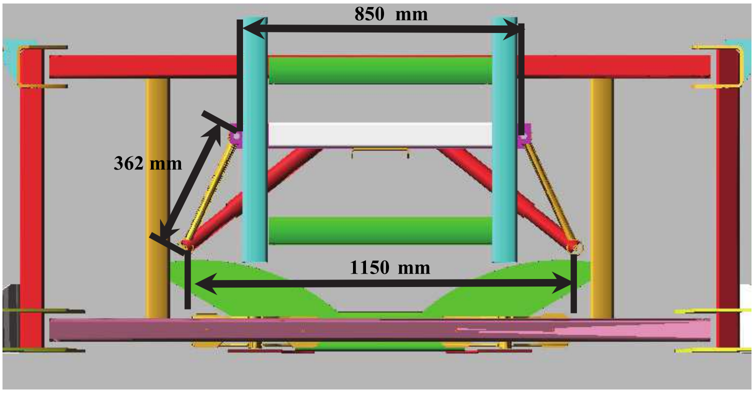

Fig. 2.1. Passive suspension model with its main dimensions.

2.1.2 Model with sensor fusion and proportional control

We used a boom suspension of trapezoidal type with the same dimensions listed in Figure 2.1. We used three position measurement sensors uniformily distributed along the length of the boom. The sensor 1 was placed at 4 meters from the center of the equipment, the sensor 2 at 8 meters from the center and the sensor 3 at 12 meters from the center, as illustrated in Figure 2.2.

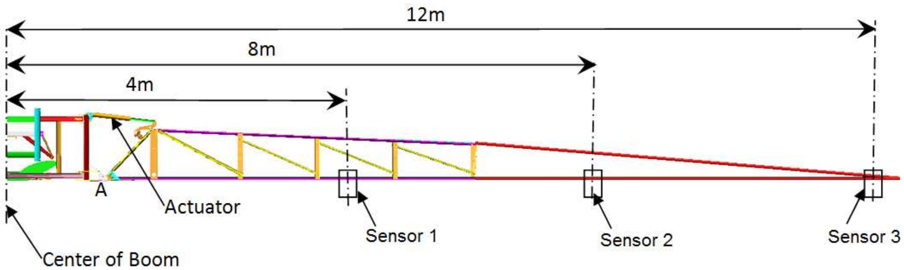

Fig. 2.2. Boom model with 3 sensors for fusion and proportional control.

The control strategy we used takes information from three position sensors making an weighted average with coefficients related to the distance from the center of the equipment. These coefficients increase from sensor 1 to sensor 3 to give more weight on rolling motion, because the boom pivoted at the point A. To keep the boom at a constant height of 500 mm from the ground is the main target. Therefore the control equation, using the force variable, is:

$$Fa = -Fe + k\left[-500 + \left(\frac{1}{6}\right)sensor\,1 + \left(\frac{1}{3}\right)sensor\,2 + \left(\frac{1}{2}\right)sensor\,3\right] \quad (1)$$

where:

Fa: actuator force (N);
Fe: actuator static force relative to the weight of the boom (N)
k: gain
sensor 1: ground position measurement (mm) - 4 m from equipment center
sensor 2: ground position measurement (mm) - 8 m from equipment center
sensor 3: ground position measurement (mm) - 12 m from equipment center

2.1.3 Model with sensor fusion and fuzzy logic

We used a boom suspension of trapezoidal type with the dimensions listed in Figure 2.1. We used three position measurement sensors uniformly distributed along the length of the boom. The first sensor is placed at 4 meters from the center of the equipment, the second at 8 meters from the center and the third at 12 meters from the center, as illustrated in Figure 2.2.

Here we used a procedure identified as a co-simulation method between ADAMS and MATLAB softwares, with the goal of the model of interacting rigid body capabilities of Adams software with the control plant capabilities of fuzzy system simulations in Matlab software. This procedure is showed schematically in Figure 2.3.

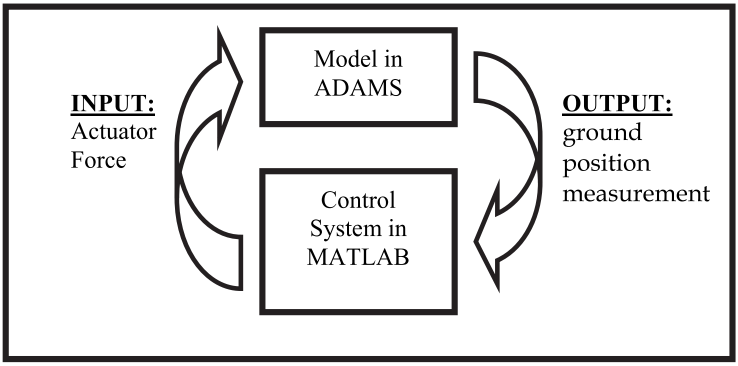

Fig. 2.3. Co-Simulation between ADAMS and MATLAB software.

Figure 2.3 is a simple diagram that shows how co-simulation is performed. The output variables of the model of Adams are exported to the plant control in Matlab. The actuator forces are calculated according to strategy and then applied to a control designed into the Adams. The first step is to define what are the input and output variables for the Adams model. Here the input variable is the force law and force the actuator to the actuator left. The output variables are the right sensor position 1, the right sensor position 2, the right sensor position 3 (at the boom right tip), the left sensor position 1, the left sensor position 2, the left sensor position 3 (at the boom left tip).

The second step is to create these variables in the Adams; so we need to create one variable for each state variable. To create a new state variable we need to select in the menu, following the instructions: Build, System Elements - state variability - New. Then insert the name and it will measure this variable, as shown in Figure 2.4.

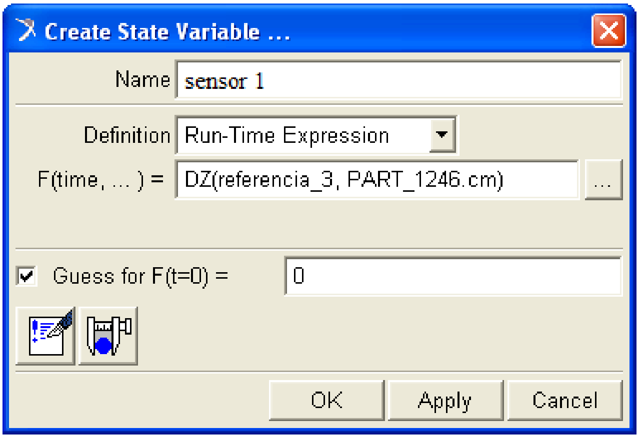

Fig. 2.4. Box dialog for creating an input state variable.

For the output variables follow the same steps except that F (time ,...) should be maintained the zero default value, as shown in Figure 2.5.

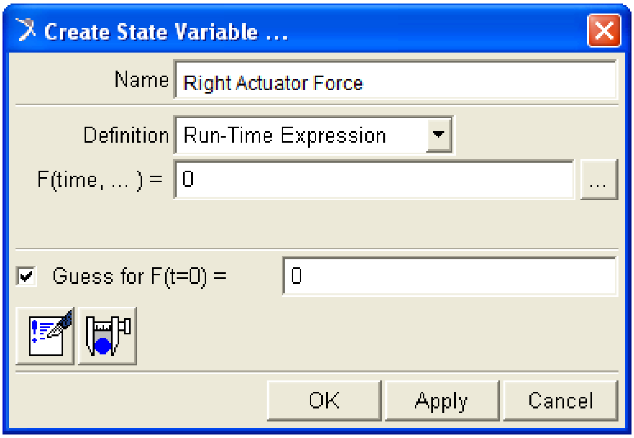

Fig. 2.5. Dialog box for creating an output state variable.

With the input and output variables defined, the values of input variables obtained from Simulink must to be applied (referenced) in the model components of the Adams. In this case, the intensity of the actuator force obtained in Simulink must be referenced to its respective force in the Adams model. To reference the input variable, we should select the menu Edit - Modify and open the right force variable. This will open a dialog box as shown in Figure 2.6.

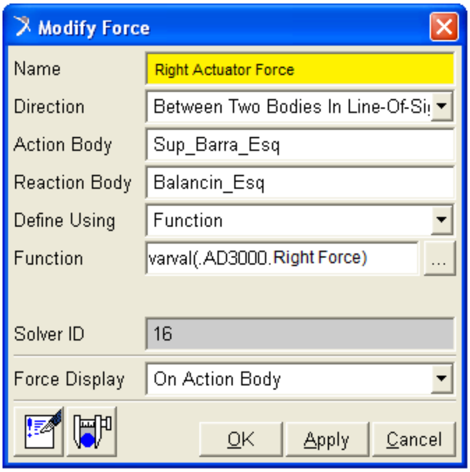

Fig. 2.6. Dialog box for an input variable allocation as a force component of the Adams.

The next step is the creation of the control plant to be exported to Simulink. To export the model, we select the Controls menu - Export Plant. A dialog box, shown in Figure 2.7, opens.

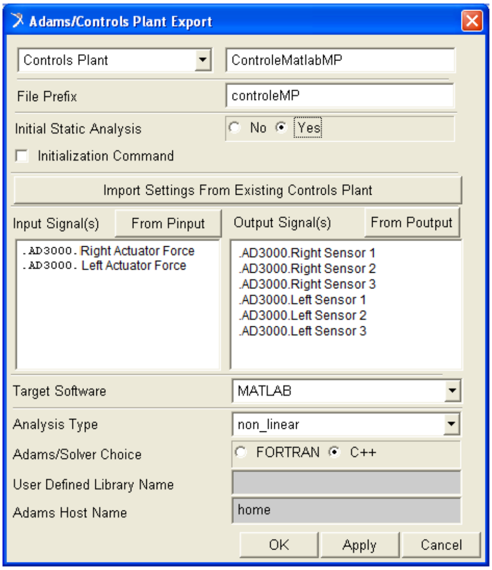

Fig. 2.7. Dialog box for export control plant to Adams.

The input and output variables are listed in the same order in which the respective connecting pins will appear in the control block. It is necessary that input and output pins are connected correctly each other to assure the proper simulation of the control systems applied to the boom.

This export process will show three kinds of files, each one with a prefix defined in the dialog box of Figure 2.7. In this case we can see the files controleMP.adm, controleMP.cmd and controleMP.m. These files will be saved in the working directory of the Adams.

The next step is to connect the block generated at the Adams model to the Simulink control plant. To adjust the control system with the Adams model we must first open the Adams block diagram in Matlab. To do this we must start Matlab and change the Matlab working directory to the same one used by Adams, that is, at the same location where the files are generated in the previous step. Once this is done we should write at the Matlab prompt the extension of the file we have created, in this case controleMP. This initializes the Adams input and output variables as Matlab variables. The next command used is Adams_sys, that opens a window with a block diagram of Adams as shown in Figure 2.8.

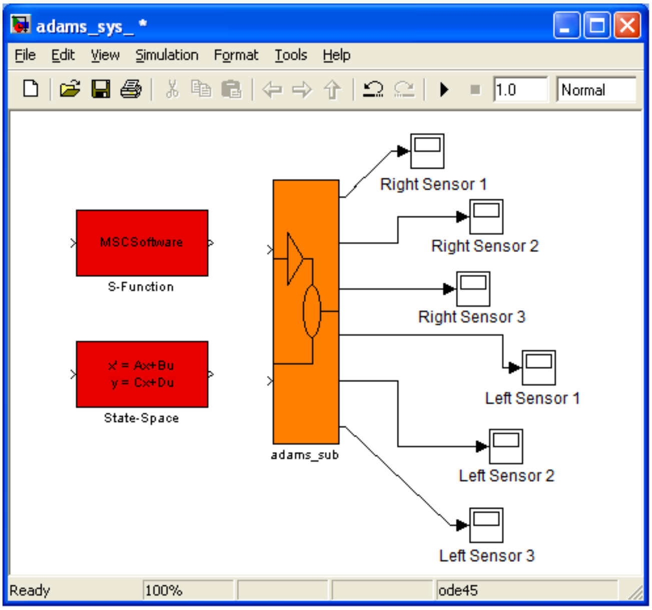

Fig. 2.8. Block diagram of Adams in the Simulink.

A double click on the block subsystem at Adams_Sub opens a new window that shows the available components, as seen in Figure 2.9.

A double click on the block plant at Adams opens a dialog box with the parameters that must be adjusted. The communication interval field specifies how often the Adams communicates with Simulink and the number of communications between them for each step of writing output. The animation mode field can be adjusted to be interactive, that is, the simulation can be shown graphically as the model is computed. These parameters can be seen in Figure 2.10.

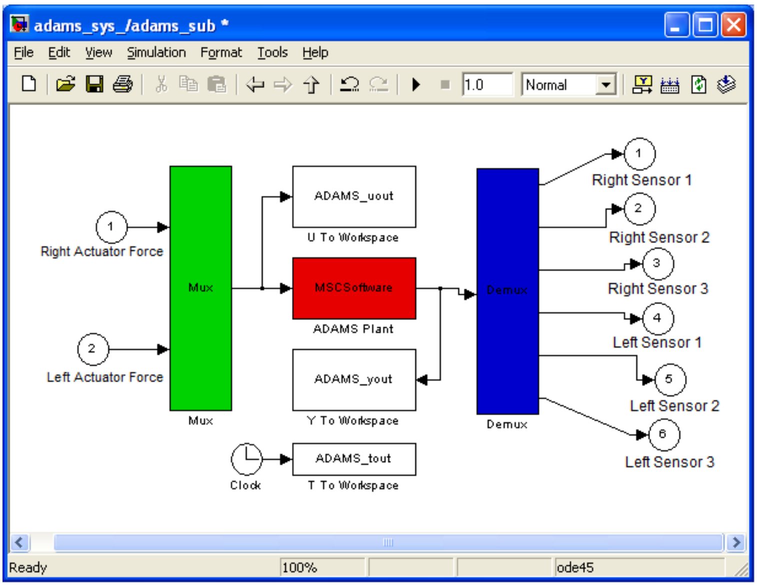

Fig. 2.9. Subsystem model in Adams.

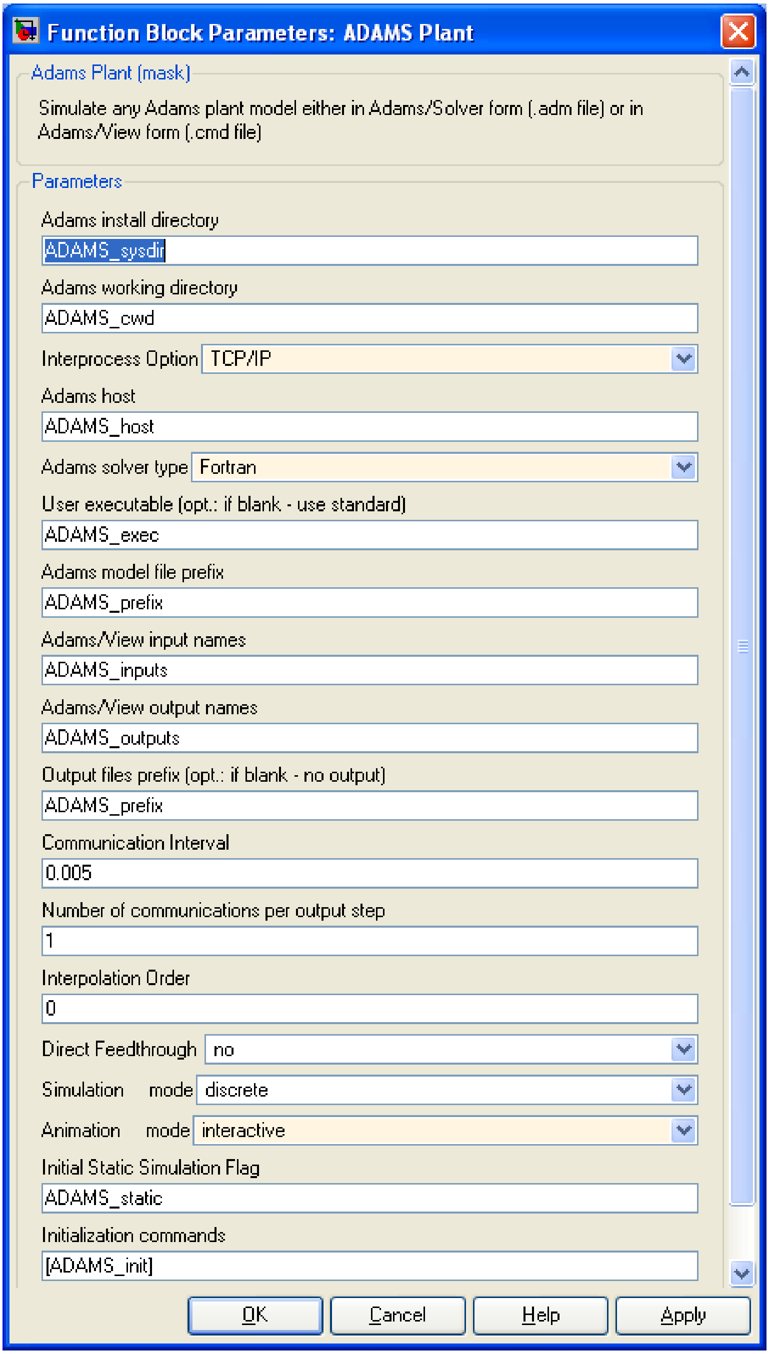

Fig. 2.10. Dialog box of function block parameters.

After the necessary adjustments they should be copied into the block Adams_sub plant control Simulink and then connect the inputs and outputs properly. Figure 2.11 shows an overview of the control system.

To construct the fuzzy system block we used a model with the method of centroid defuzzification Mamdani type. The weighted average height obtained from the sensors was used as input as follows:

$$A = \left[-500 + \left(\frac{1}{6} \right) sensor\,1 + \left(\frac{1}{3} \right) sensor\,2 + \left(\frac{1}{2} \right) sensor\,3 \right] \tag{2}$$

where:
A: value of weighted average height from the three sensors [mm].

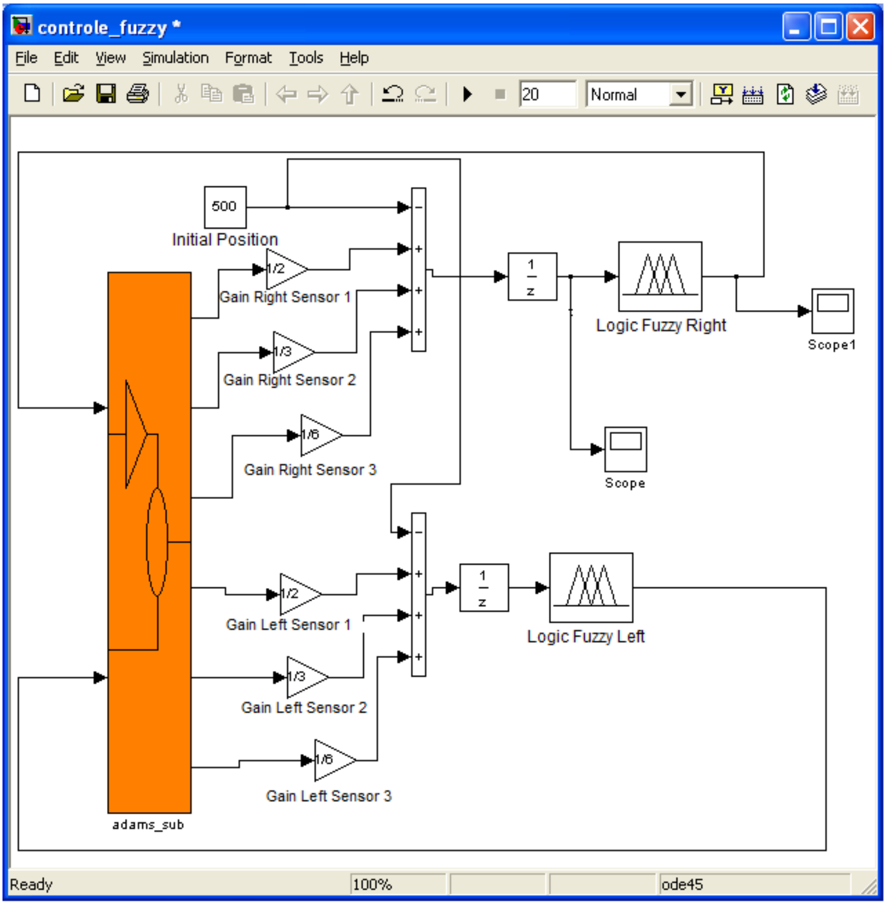

Fig. 2.11. Fuzzy control system integrated with Adams.

The Figure 2.12 shows a graphic of input inference, where the variable is the weighted average height obtained from equation 2.

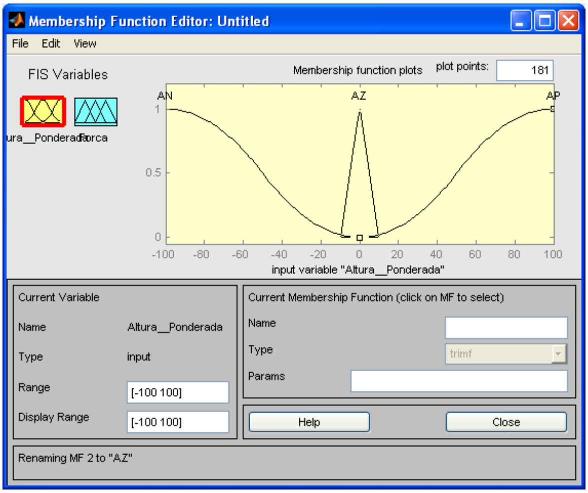

Fig. 2.12. Input inference of weighted average height.

The input linguistic variables are:

AN: Negative Height;
AZ: Zero Height;
AP: Positive Height;

The Figure 2.13 shows a graphic of output inference, where the variable is the force applied to the system.

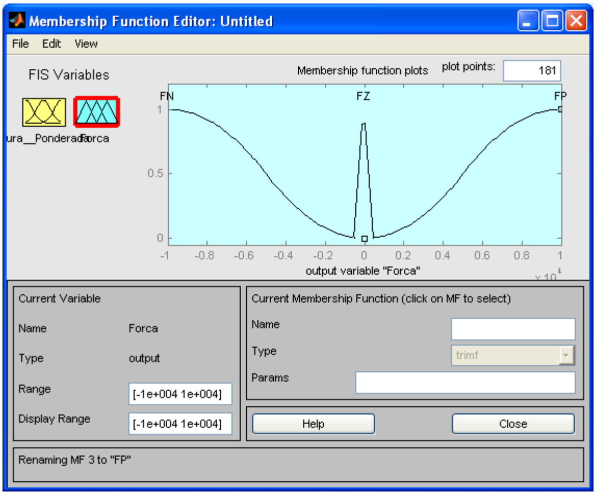

Fig. 2.13. Force output inference.

The output linguistic variables are:

FN: Negative Force;
ZP: Zero Force;
FP: Positive Force;

We find the rules for defuzzification of the input variables on output variables though the bos shown in Figure 2.14.

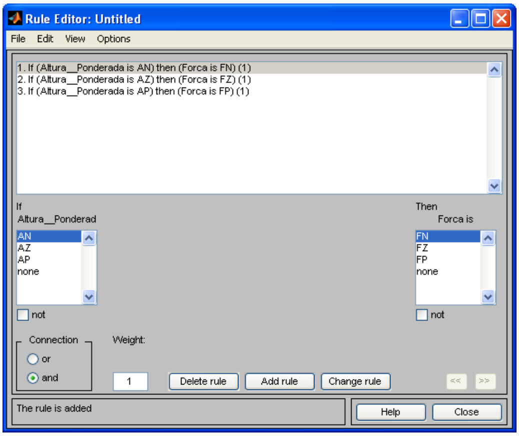

Fig. 2.14. Box of fuzzy rules used in the equipment model.

We can also define the curve of relationship between output and input using the rules previously established, as shown in Figure 2.15.

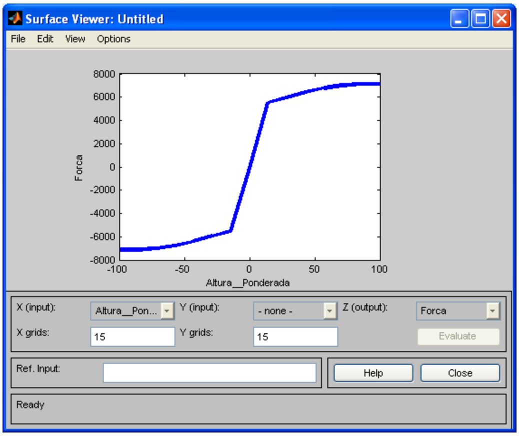

Fig. 2.15. Input versus output curve.

Therefore the control equation, using the fuzzy control power variable is:

$$Fa = -Fe + f(fuzzy) \tag{3}$$

where:

Fa: actuator force (N);
Fe: actuator static force relative to the weight of the boom (N)
f (fuzzy): the function obtained by defuzzification of the fuzzy model shown in Figure 2.15.

2.2 Simulations

The simulations were conducted in order to evaluate the three kinds of suspension in analysis, that are a passive suspension, an active PID control suspension and active Fuzzy control suspension.

The input conditions were grouped into three sets: the first set corresponds to step type input, the second to harmonic type input and the third to random type of input.

In the first set of inputs, we used two step sizes. With this kind of analysis we expected to evaluate the system overshoot, settling time and the power consumed for each type of control.

In the second set of inputs, we used two amplitudes and two frequencies in order to be able to measure the conditions of the boom oscillations and the power consumed by each type of control.

In the third set of inputs, we used random signals, taking from tractors standards (ASABE / ISO 5008, 2002) to evaluate the conditions of boom oscillation and power consumed for each type of control.

2.2.1 Step inputs

In this first set of simulation analysis we used a step type input with angle amplitudes of 5 and 10 degrees, which corresponds to the equipment transposing a 160 and 320 mm step obstacles, respectively, with a 1800 mm distance between tires, as shown in Figure 2.16.

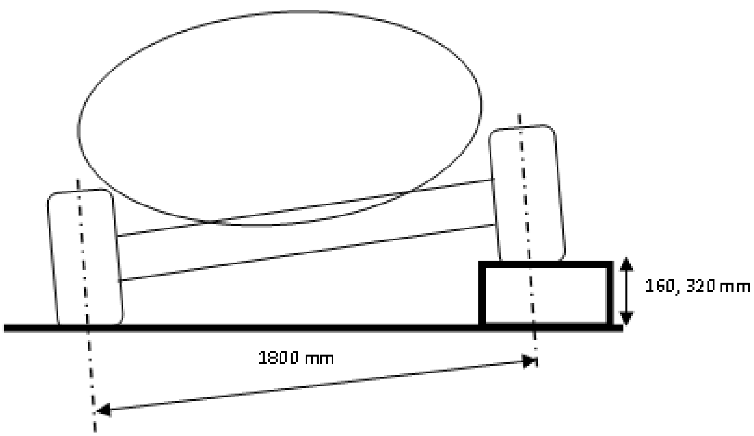

Fig. 2.16. Model for step type input.

The Figure 2.17 shows the displacement behavior of the three positions of the boom right side with the passive system, active PID system and active Fuzzy system, all subjected to a step type input with an angle amplitude of 5 degrees. It is also shown the power consumed by each suspension system used.

From the analysis of Figure 2.17 it is possible to note a great advantage of active systems when compared with passive system considering boom displacements, independently of the sensor position.

The Figure 2.18 shows the behaviors of active systems. We can observe that the Fuzzy active system stabilizes the boom quicker than the active PID system, but it has a larger overshoot signal for all the three sensors than PID. The RMS power value of active PID system is 0.30 kW and for Fuzzy active system is 0.32 kW.

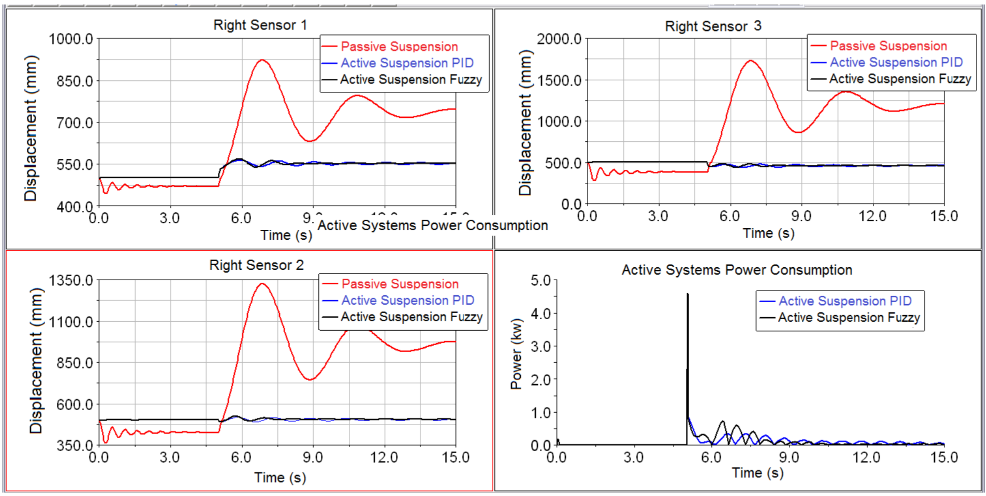

Fig. 2.17. Behavior of suspension systems subjected to a step input amplitude of 5 degrees.

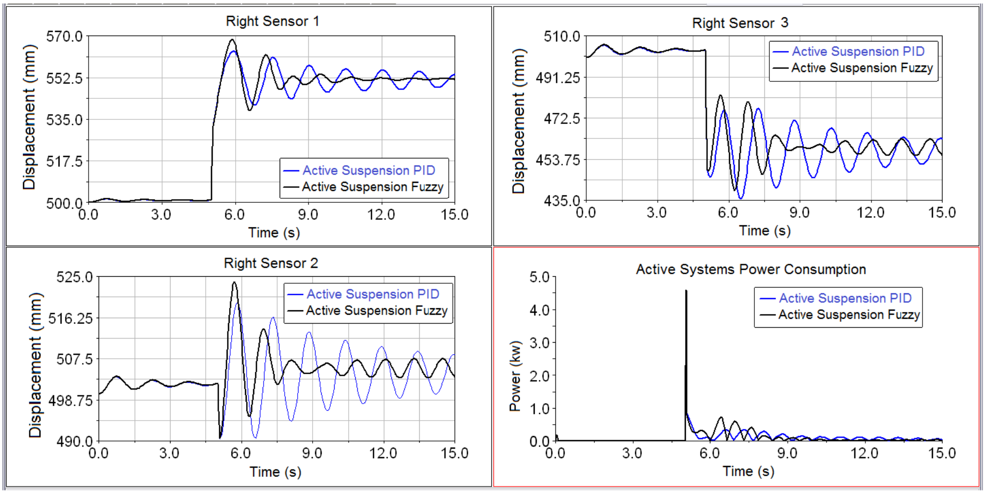

Fig. 2.18. Behavior of active systems subjected to a 5 degrees step input amplitude.

The Figure 2.19 shows the displacement behavior of the three positions of the boom right side of the passive system, active PID system and active Fuzzy system subjected to a step type input with angle amplitude of 10 degrees. It is also shown the power consumed by each suspension system used.

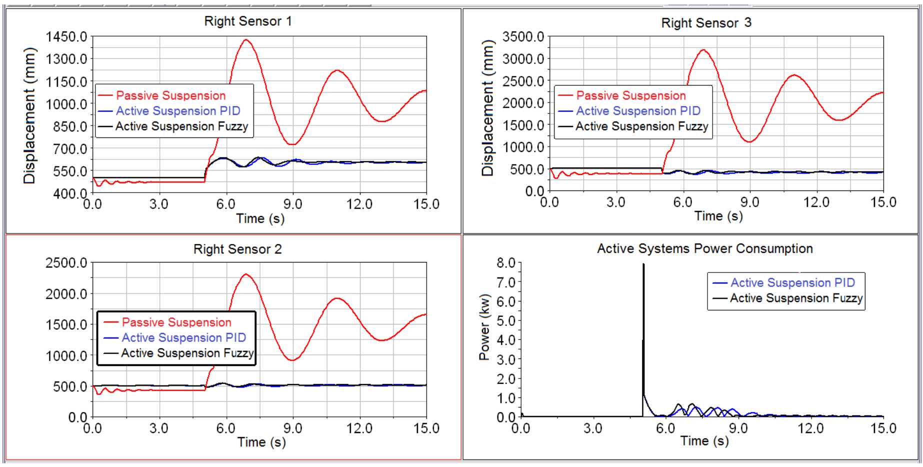

Fig. 2.19. Behavior of suspension systems subjected to a step input amplitude of 10 degrees.

From the analysis of Figure 2.19 it is possible to note the great advantage of active systems when compared with passive system considering boom displacements, independently of the sensor position.

Figure 2.20 shows the behaviors of active systems. We can observe that the active Fuzzy system stabilizes in less time interval than the active PID system but has a larger overshoot signal for all three sensors. The RMS power value of the active PID system is 0.49 kW and for Fuzzy active system is 0.50 kW.

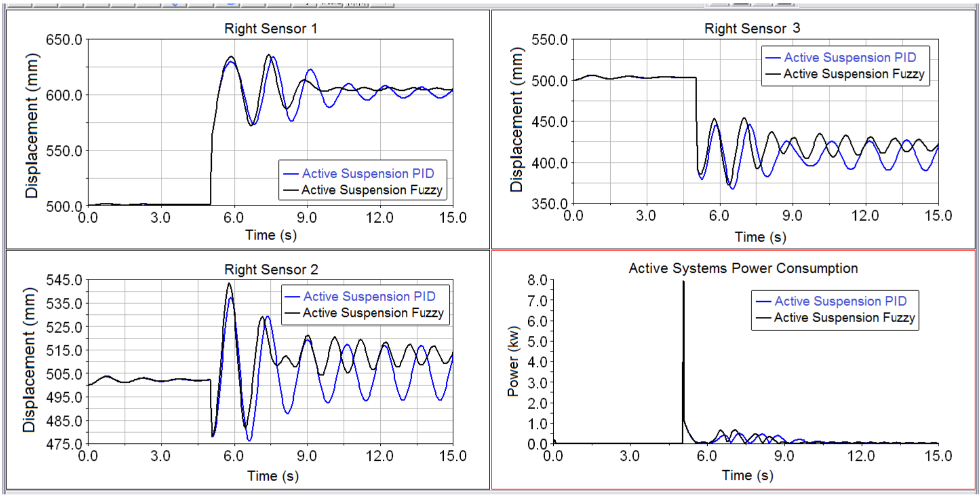

Fig. 2.20. Behavior of active systems subjected to a 10 degrees step input amplitude.

2.2.2 Harmonics inputs

The following Table 2.1 shows the harmonic parameters of the simulation signal used. We use two amplitudes and two frequencies for sinusoidal signals. Therefore four sinusoidal inputs were used in the systems simulations developed, as shown in Table 2.1.

Simulations	Amplitude (degree)	Frequency (Hz)	Simulation Code
1	5	0,1	A5F0,1
2	5	2,0	A5F2
3	10	0,1	A10F0,1
4	10	2,0	A10F2

Table 2.1. Amplitudes and frequencies of 4 sinusoidal inputs.

The Figure 2.21 shows the displacement behavior of the three positions of the boom right side of passive system, active PID system and active Fuzzy system subjected to a harmonic input with amplitude of 5 degrees and frequency of 0.1 Hz. It is also shown the power consumed by each suspension system used.

From the analysis of Figure 2.21 it is possible to note the great advantage of the active systems when compared with the passive system considering boom displacements, independently of the sensor position.

In Figure 2.22 we can see that there are no significant differences between the active system PID and fuzzy active system behavior for any simulated positions.

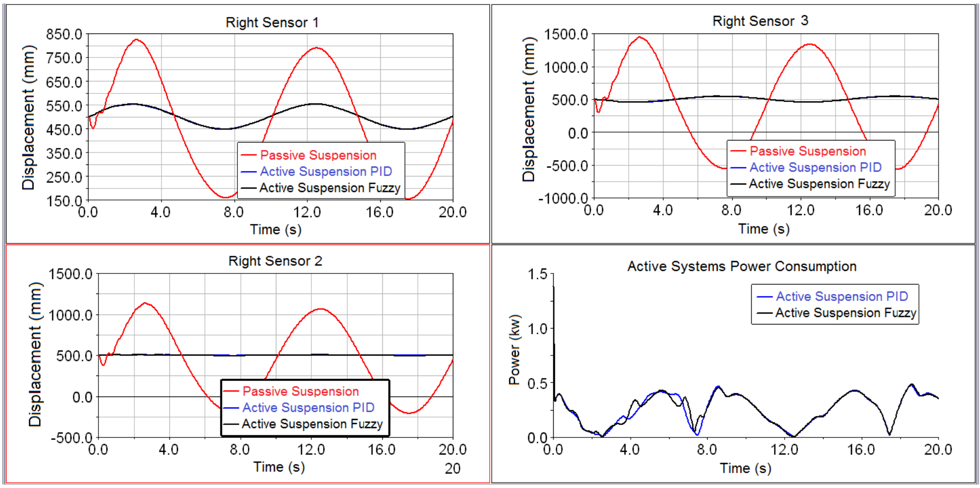

Fig. 2.21. Behavior of suspension systems subjected to harmonic input with 5 degrees amplitude and 0.1 Hz frequency.

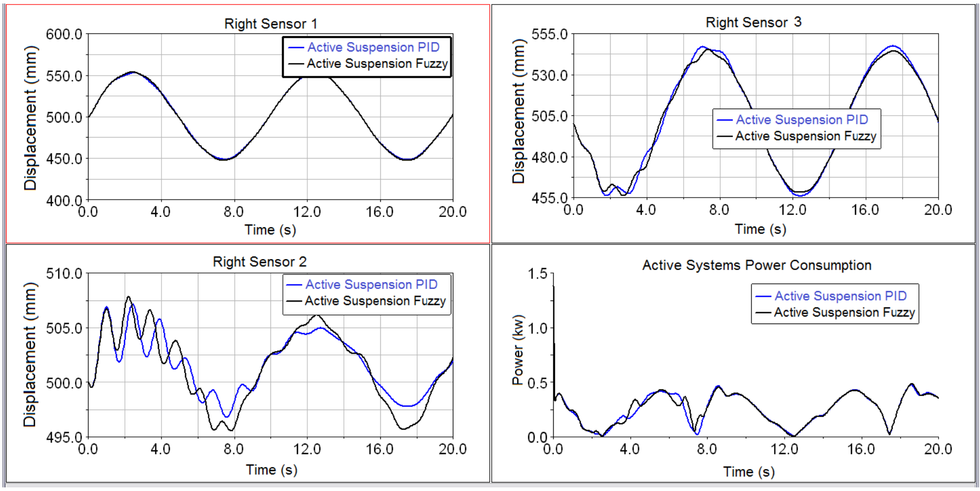

Fig. 2.22. Behavior of active suspension systems subjected to harmonic input of 5 degrees amplitude and 0.1 Hz frequency.

Figure 2.23 shows the displacement behavior of the three positions of the boom right side of the passive system, active PID system and active Fuzzy system subjected to a harmonic input with amplitude of 5 degrees and frequency of 2 Hz. It is also shown the power consumed by each suspension system used.

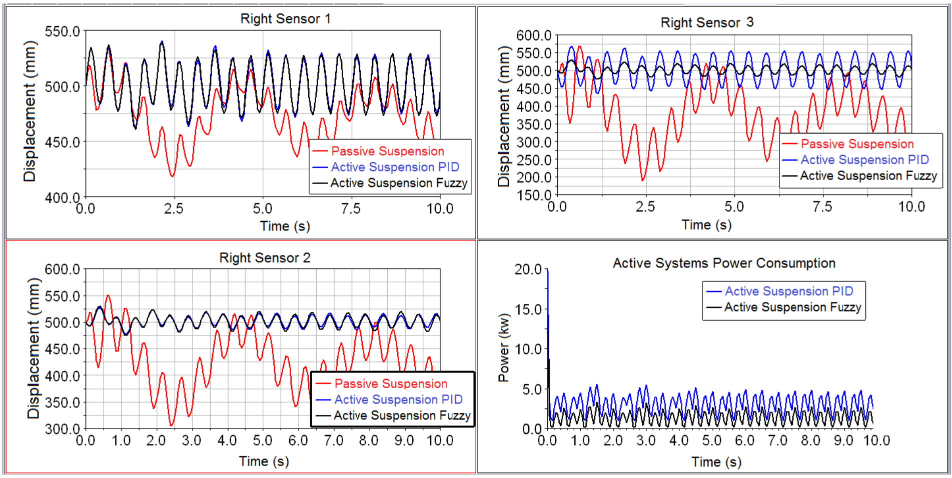

Fig. 2.23. Behavior of suspension systems subjected to harmonic input with 5 degrees amplitude and 2 Hz frequency.

From the analysis of Figure 2.23 we can see that active control systems are more efficient than passive system for all positions simulated.

From Figure 2.24 we can see that there are significant differences between active PID system and active Fuzzy system at position 3, the tip of the boom. The RMS value of power consumed by the active PID system is 3.32 kW while the RMS value of power consumed by active Fuzzy system is 1.57 kW.

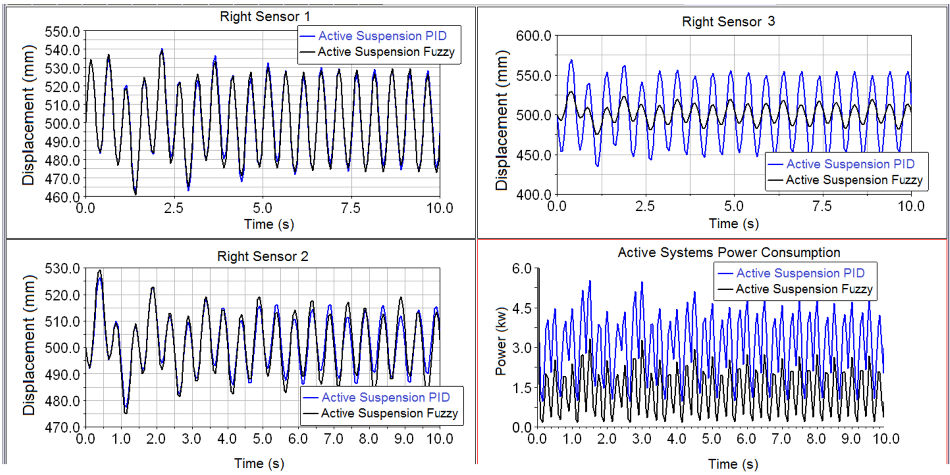

Fig. 2.24. Behavior of active systems subjected to harmonic input with 5 degrees amplitude and 2 Hz frequency.

Figure 2.25 shows the displacement behavior of the three positions of the boom right side of passive system, active PID system and active Fuzzy system subjected to a harmonic input with amplitude of 10 degrees and a frequency of 0.1 Hz. It is also shown the power consumed by each active system used.

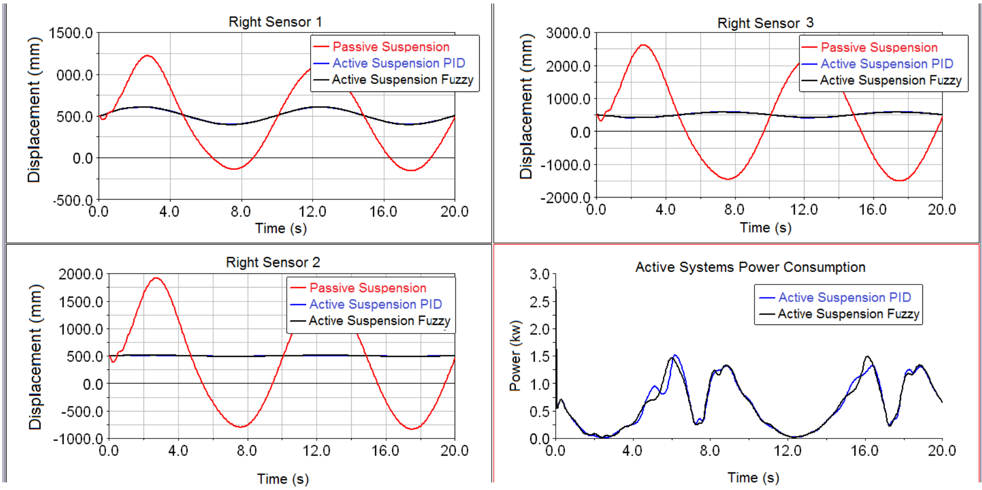

Fig. 2.25. Behavior of suspension systems subjected to harmonic input with 10 degrees amplitude and 0.1 Hz frequency.

From the analysis of Figure 2.25 is possible to note the great advantage of active systems when compared with passive system considering boom displacements, independently of the sensor position.

In Figure 2.26 we can see that there are no significant differences between active PID system and active Fuzzy system for any position simulated.

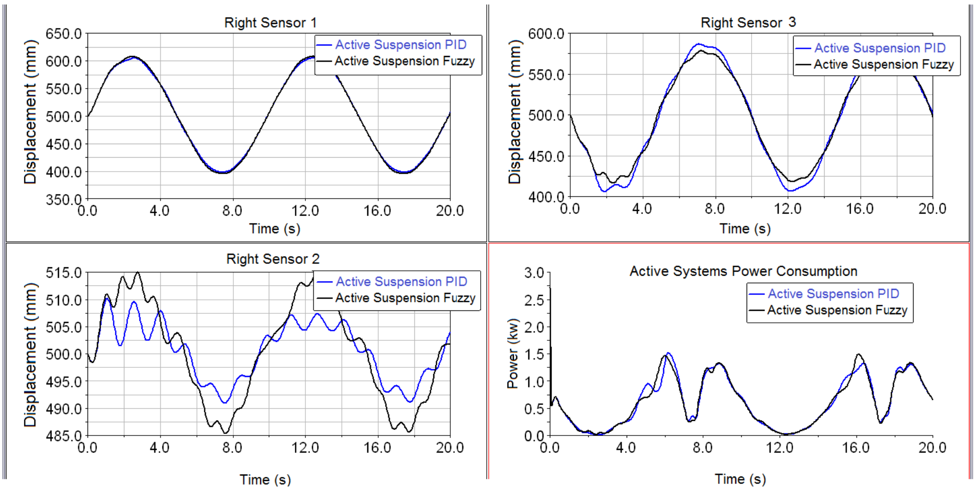

Fig. 2.26. Behavior of active systems subjected to harmonic input with 10 degrees amplitude and 0.1 Hz frequency.

From the analysis of Figure 2.27 it is possible to see the best performance of active systems when compared with passive system considering boom displacements, independently regardless of sensor position.

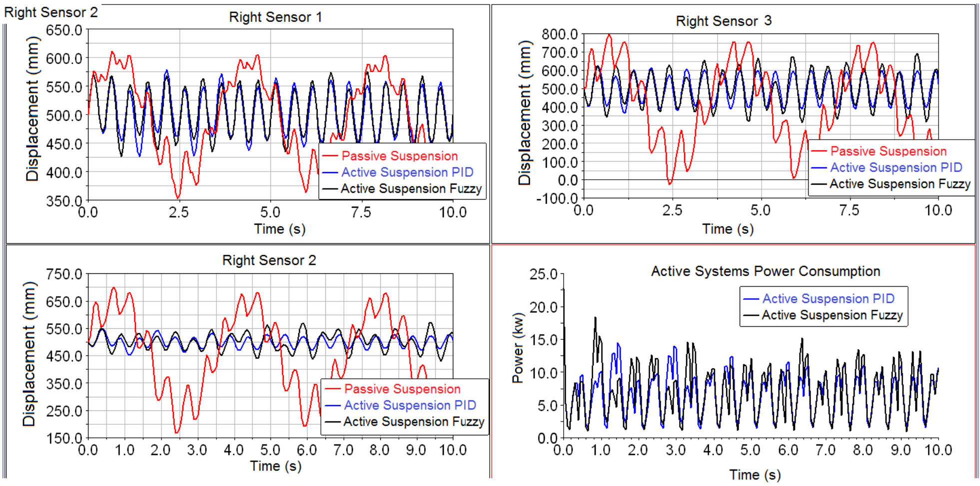

Fig. 2.27. Behavior of suspension systems subjected to a harmonic input of 10 degrees amplitude and frequency of 2 Hz.

In Figure 2.28 we can see that there are no significant differences between active PID system and active Fuzzy system for any position simulated.

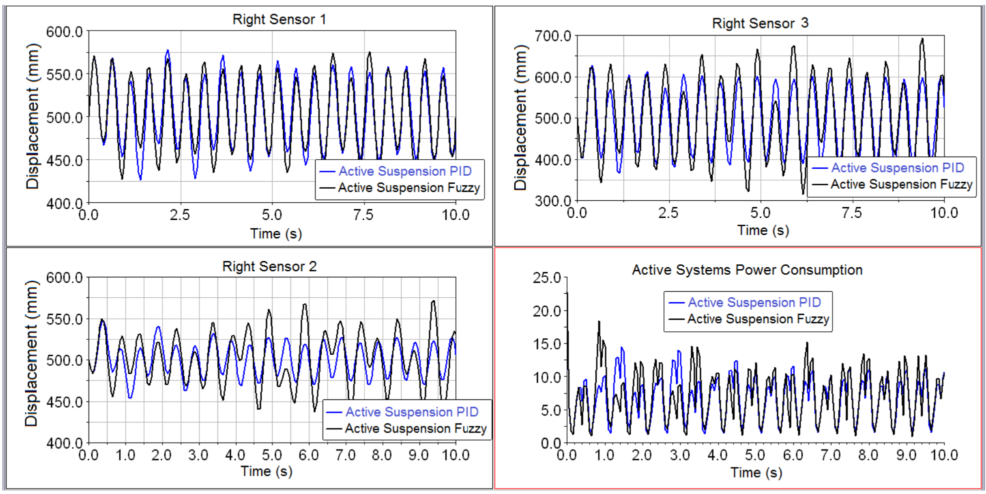

Fig. 2.28. Behavior of active systems subjected to a harmonic input range of 10 degrees amplitude and 2 Hz frequency.

2.2.3 Random inputs

For this simulation set, we use input signals from a vibration analysis of tractors standard (ASABE / ISO 5008, 2002). This standard establishes two pavement types (smooth and rough), and gives the Cartesian coordinates for each type of track. These coordinates are put through ADAMS software and then the simulations can be run.

Figure 2.29 shows the smooth pavement condition with equipment travel speed of 5 km/h. It also shows the boom displacement at the three sensor positions (1, 2 and 3).

From the analysis of Figure 2.29 it is possible to note the efficiency of active control to keep constant the distance between the boom and the ground.

In Figure 2.30 it is possible to note the equivalence of both active control systems, ie, there are no significant differences in maintaining the height of the boom from the ground.

Figure 2.31 shows the smooth condition of pavement with equipment travel speed of 7.5 km/h. It also shows the boom displacement at the three sensor positions (1, 2 and 3).

From the analysis of Figure 2.31 it is possible to note the efficiency of active control to keep constant the distance between the boom and the ground.

In Figure 2.32 it is possible to note the equivalence of both active control systems, ie, there are no significant differences in maintaining the height of the boom from the ground.

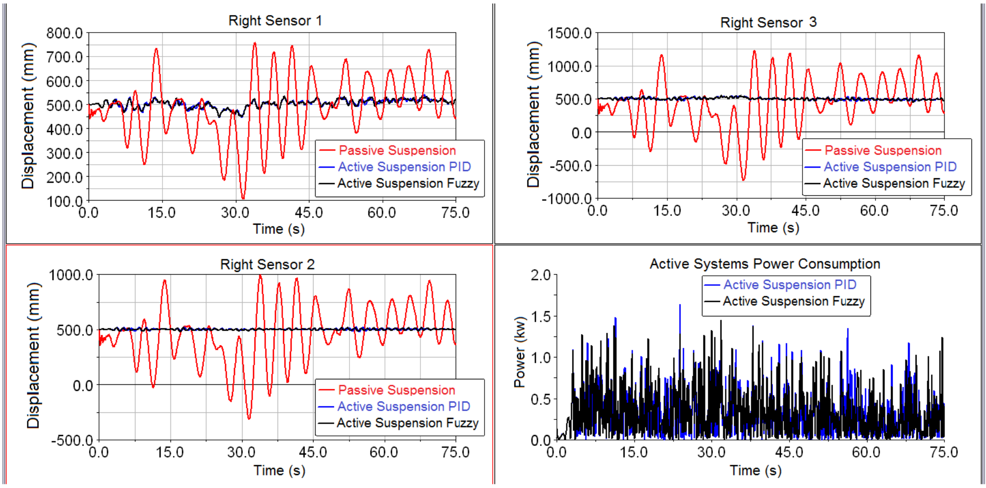

Fig. 2.29. Suspension systems submitted to a smooth track at 5 km/h.

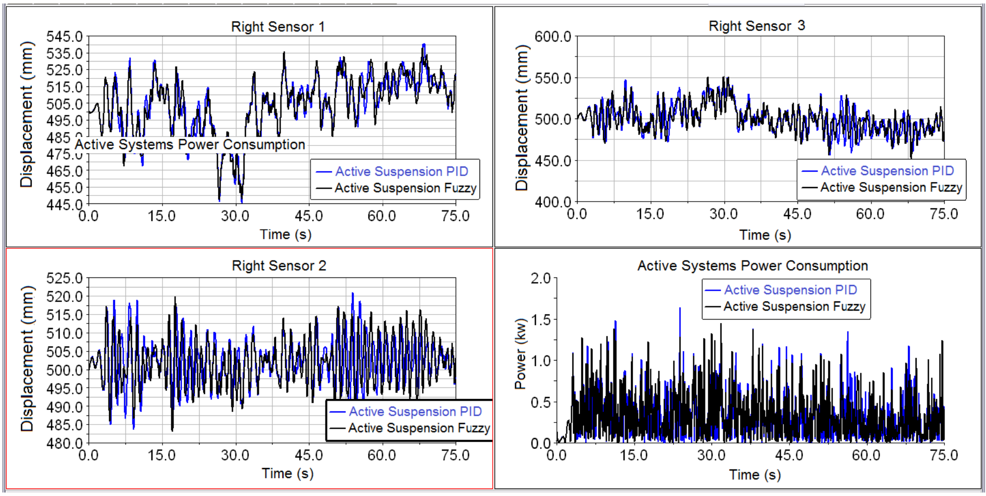

Fig. 2.30. Active suspension systems submitted to a smooth track at 5 km/h.

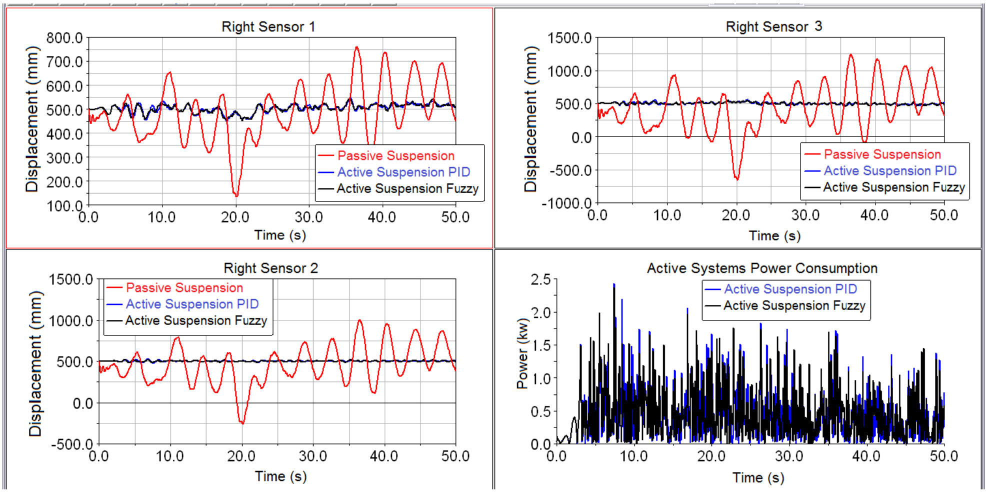

Fig. 2.31. Suspensions submitted to a smooth track at 7.5 km/h.

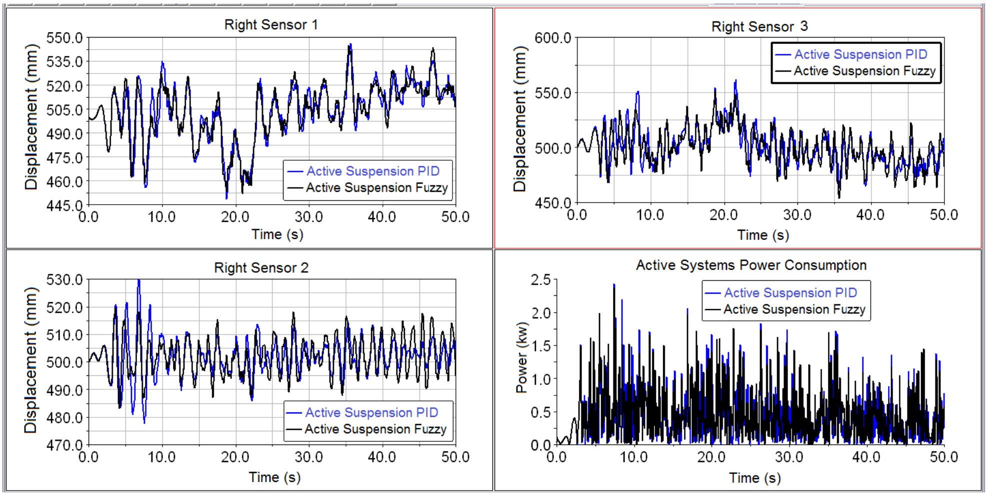

Fig. 2.32. Active suspension systems submitted to a smooth track at 7.5 km/h.

Figure 2.33 shows the smooth condition of pavement with equipment travel speed of 10 km/h. It also shows the boom displacement at the three sensor positions (1, 2 and 3).

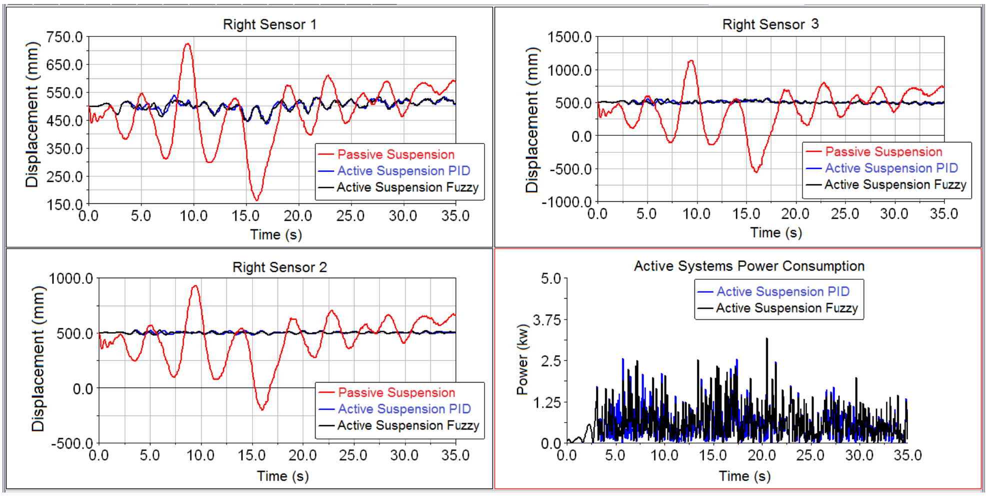

Fig. 2.33. Suspension systems submitted to a smooth track at 10 km/h.

From the analysis of Figure 2.33 it is possible to note the efficiency of active control to keep constant the distance between the boom and the ground.

In Figure 2.34 it is possible to note the equivalence of both active control systems, ie, there are no significant differences in maintaining the height of the boom from the ground.

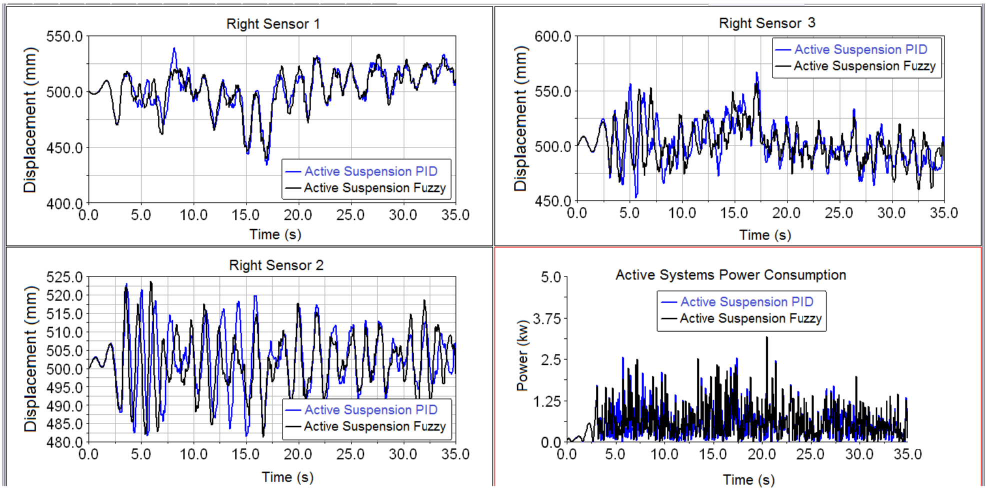

Fig. 2.34. Active suspension systems submitted to a smooth track at 10 km/h.

Figure 2.35 shows the rough condition of pavement with equipment travel speed of 5 km/h. It also shows the boom displacement at the three sensor positions (1, 2 and 3).

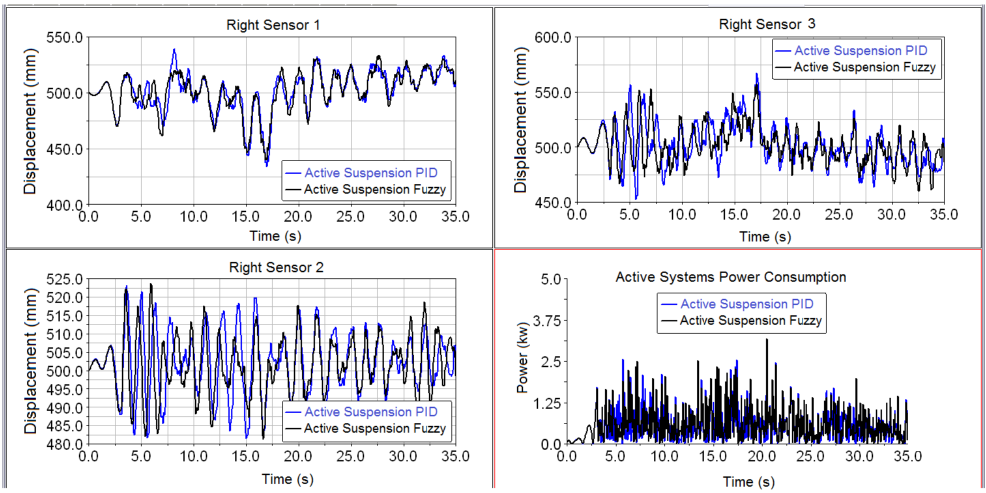

Fig. 2.35. Suspension systems submitted to a rough track at 5 km/h.

From the analysis of Figure 2.35 it is possible to note the efficiency of active control to keep constant the distance between the boom and the ground.

In Figure 2.36 it is possible to note the equivalence of both active control systems, ie, there are no significant differences in maintaining the height of the boom from the ground.

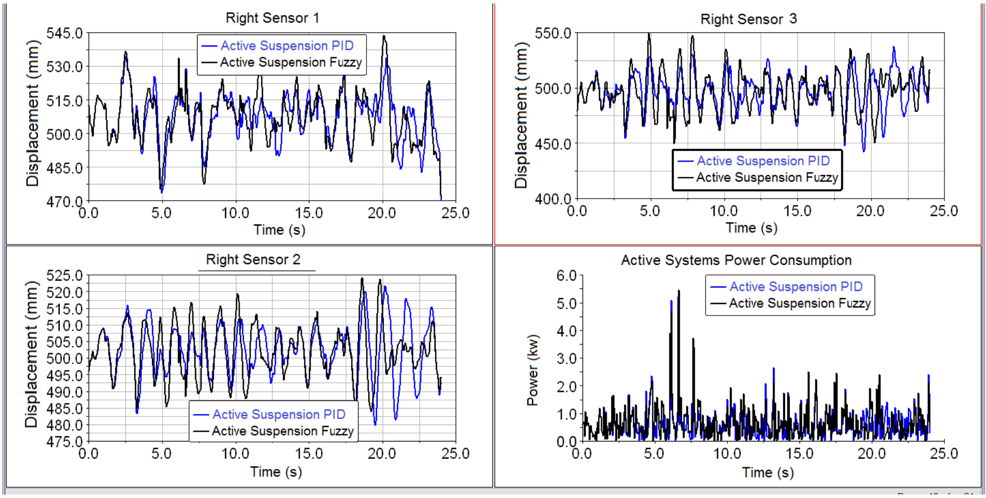

Fig. 2.36. Active suspension systems submitted to a rough track at 5 km/h.

Figure 2.37 shows the rough condition of pavement with equipment travel speed of 7.5 km/h. It also shows the boom displacement at the three sensor positions (1, 2 and 3).

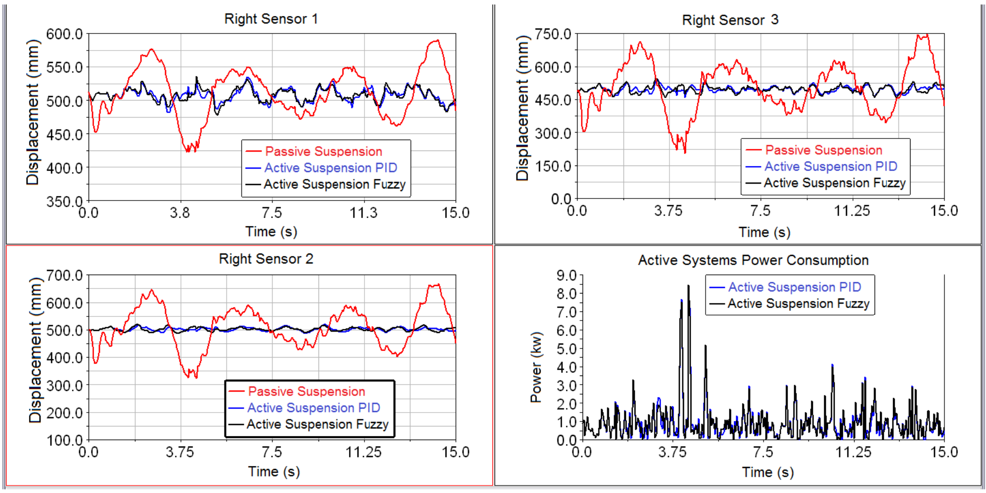

Fig. 2.37. Suspension systems submitted to a rough track at 7.5 km/h.

From the analysis of Figure 2.37 it is possible to note the efficiency of active control to keep constant the distance between the boom and the ground.

In Figure 2.38 it is possible to note the equivalence of both active control systems, i.e., there are no significant differences in maintaining the height of the boom from the ground.

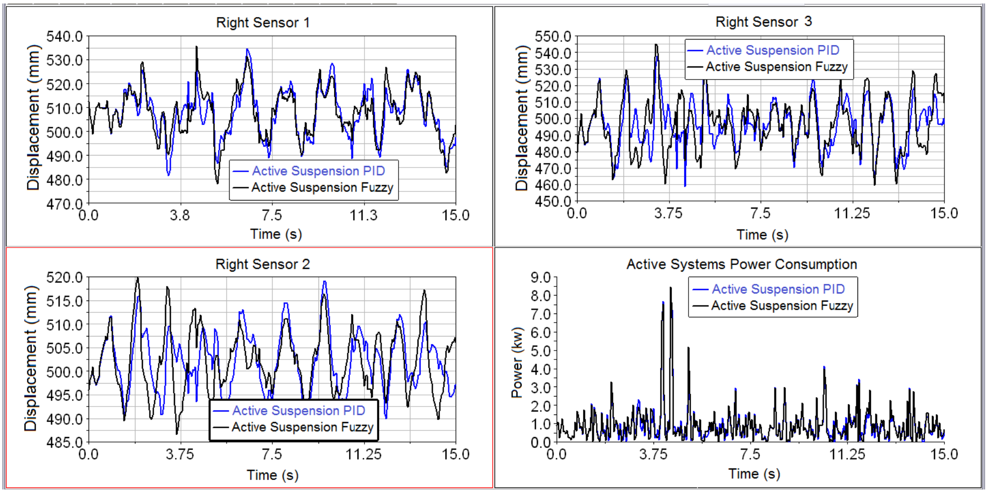

Fig. 2.38. Active suspension systems submitted to a rough track at 7.5 km/h.

Figure 2.39 shows the rough condition of pavement with equipment travel speed of 10 km/h. It also shows the boom displacement at the three sensor positions (1, 2 and 3).

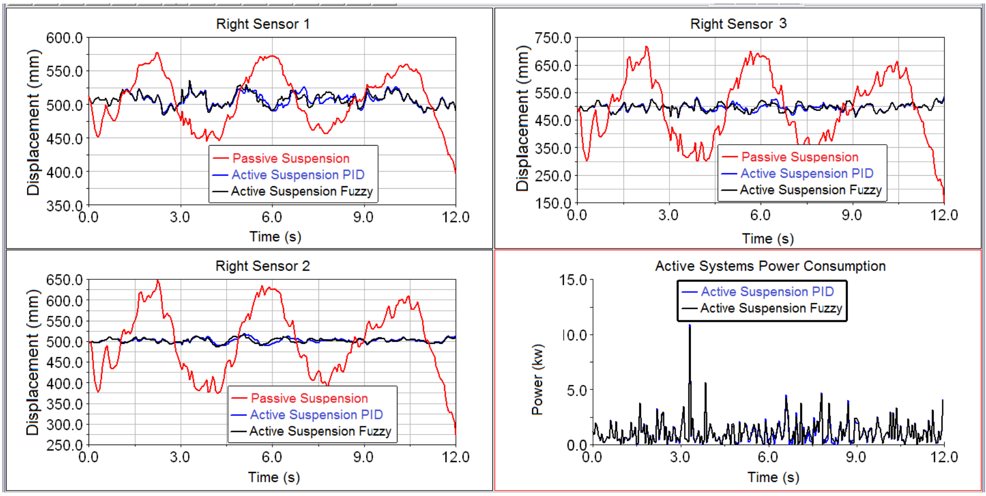

Fig. 2.39. Suspension systems submitted to rough track at 10 km/h.

From the analysis of Figure 2.39 it is possible to note the efficiency of active control to keep constant the distance between the boom and the ground.

In Figure 2.40 it is possible to note the equivalence of both active control systems, i.e., there are no significant differences in maintaining the height of the boom from the ground.

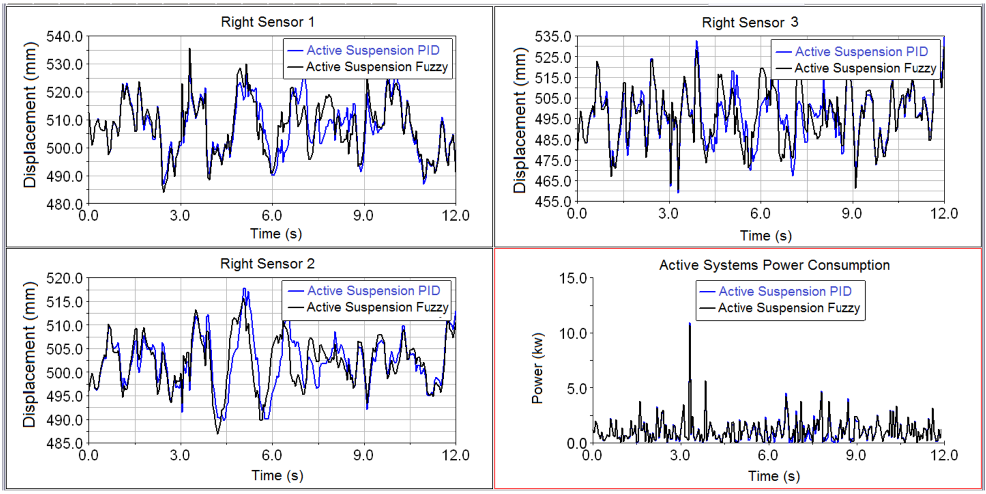

Fig. 2.40. Active suspension systems submitted to a rough track at 10 km/h.

3. Conclusion

We can conclude that independently of control strategy adopted, PID or Fuzzy control, the input signals are significantly attenuated if compared to a passive suspension.

The PID control strategy has a practical advantage of being more easily implemented than the Fuzzy control strategy in sprayer booms.

The power consumed by the active Fuzzy system was slightly lower than the PID controller, what presents no significant advantage in our practical design.

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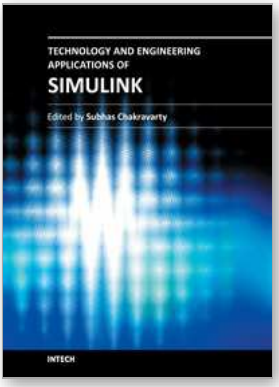

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Building on MATLAB (the language of technical computing), Simulink provides a platform for engineers to plan, model, design, simulate, test and implement complex electromechanical, dynamic control, signal processing and communication systems. Simulink-Matlab combination is very useful for developing algorithms, GUI assisted creation of block diagrams and realisation of interactive simulation based designs. The eleven chapters of the book demonstrate the power and capabilities of Simulink to solve engineering problems with varied degree of complexity in the virtual environment.

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