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DYNAMIC ANALYSIS OF THE INTELLIGENT SPRAYER BOOM

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Abstract. *As part of the 3 year project "The intelligent Sprayer Boom", financed by The Danish National Advanced Technology Foundation, the dynamics of the sprayer boom is to be analysed.*

In order to minimize the amount of herbicides used to kill the weeds in agriculture a new sprayer boom is being developed called "The intelligent sprayer boom". For the sprayer boom the primary challenge is to hit the weeds with precision from a movable platform. Since the sprayer boom is mounted on a tractor the system will react to bumps in the field.

The intelligent sprayer boom has an integrated camera technology, a vision system and an image editing module, which in the same working process can distinguishes weeds from crops, the decision system will monitor the state of the field and at the same time spray the observed weed. Hereby the amount of used herbicides is minimized since only the weeds will be sprayed and not the surroundings. However this requires that the boom movements are predictable and based on data from field tests.

At field tests a first version of the newly developed camera system was tested in 2010. At the field test it was found that the vertical boom movements where too big for the camera weed prediction system to work properly. At the University of Southern Denmark (SDU) a patent for an active damping system of the sprayer boom has been obtained.

The subject of this paper is analysis of the dynamics of the Sprayer boom. The analysis is based on a Multibody Dynamics model of the sprayer boom and is made in Matlab. The model is made in order to analyse the boom movements. The purpose of the model is to support the development of the patented active damping system for the sprayer boom. The Multibody Dynamics model has been made based on data retrieved from a CAD model and a Finite Element model of the sprayer boom.

The project "The intelligent Sprayer Boom" is made in cooperation between two industrial companies (T&O Stelectric A/S, CLAAS Agrosystems A/S) and three Danish universities (AU, KU and SDU).

1 INTRODUCTION

Agricultural fields are often sprayed with various chemical solutions, including fertilizers, herbicides, insecticides, etc. Various types of equipment are available for applying such chemical solutions.

Sprayers used in farming for spraying crops, have wide spray booms in operating position. The spray boom is extended outwardly transverse to the direction of travel of a vehicle adapted for moving the spray boom. The width of the sprayer may be as wide as 30 metres or more see Figure 1.

Figure 1: Spray boom UX-5200 from Amazone [9].

The tendency towards the use of low volume spraying techniques, leading to a necessary reduction in spray droplet size, the cost of chemicals and increasing concern with environmental pollution demand more sophisticated spraying.

A problem with boom spraying equipment relates to difficulties in conforming the spray booms in their field positions to the terrain. These problems are exacerbated by sloping and uneven field conditions, and are further exacerbated by relatively wide-span spray booms which can create relatively large moment arms at the vehicles. For spray chemical coverage, the spray nozzles mounted on the booms should preferably be positioned at uniform heights above the field or crop surface. However, when traversing a sloping field, the boom on one side of the vehicle may need to be raised while the other boom may need to be lowered to maintain a relatively uniform spraying height for effective coverage. This problem has been addressed by providing boom elevation controls, which can be operated for each boom independently from the vehicle cab. However, manually controlled boom elevation systems are susceptible to human error factors in operation. For example, operators may have difficulty adjusting the elevations of a pair of spray booms in response to changing field contours while keeping the vehicle on a straight course.

Figure 2 shows “The intelligent spray boom” which is equipped with a robust camera that distinguishes weeds form crops, regardless of the weather; and finally that information from the local systems is integrated into an overall decision system monitoring the state of the field in order to minimise use of herbicides.

In the project with “The intelligent spray boom” two patents have been filed: one for active damping of the sprayer boom and another concerns detection of weeds from a digital camera. The present paper regards the active damping system installed on the spray boom.

The patented damping system of the spray boom (Section 2, [1]) describes a boom suspension including both a passive and an active suspension arrangement. The passive suspension arrangement maintains the boom in a set relation to the vehicle and stabilises the boom against displacement from a desired position when the vehicle moves over uneven ground.

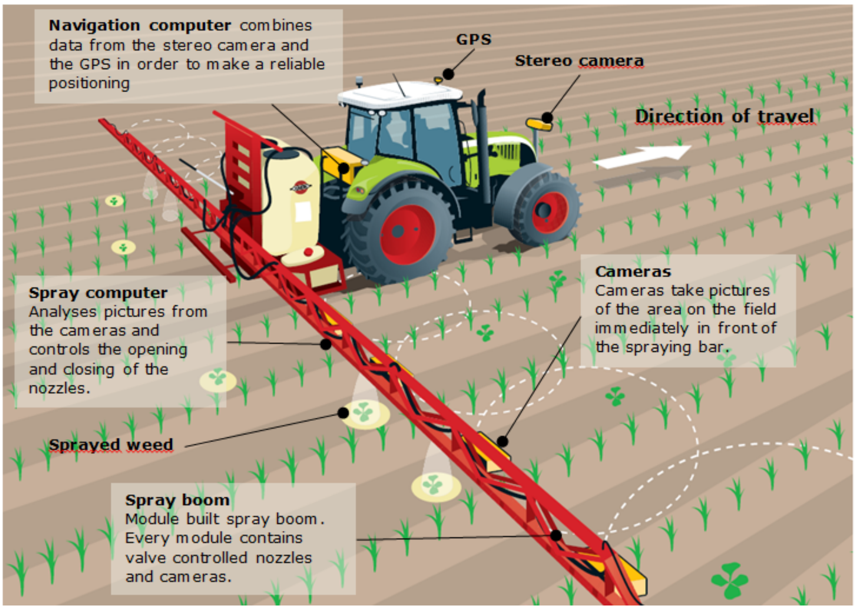

Figure 2: The principal design of the Intelligent Sprayer Boom.

The active damping system (Section 2) controls the displacement of the boom relative to the field. This is necessary when the boom is in the wrong attitude with respect to the ground surface when, for example, the boom tilts on its own suspension (Roll movement, see Figure 3) or the ground is sloping. The means to force the alteration produce a final boom position which is altered from the stabilised suspended position.

Control means to control the means to force the alteration in the said dimension provide a continuous correction of the displacement more slowly than the stabilisation action of the passive suspension of the whole boom and suspension. This control means include a distance sensor to measure the distance of the boom from the ground, means responsive to this measurement to determine the alteration in the dimension to correct the distance of the boom from the ground, and means responsive to this determination to alter the dimension to continuously correct the distance of the boom from the ground. One problem with this known device is that the fundamental frequency of the boom is low. The fundamental frequency of the spray boom in Figure 1 has been determined numerically, see Table 1.

Mode no.	f [Hz]	Modeshape	Mode no.	f [Hz]	Modeshape
1	0.1	1. Roll	7	1.8	6. Yaw
2	0.23	1. Yaw	8	3.7	7. Yaw
3	0.24	2. Yaw	9	3.8	8. Yaw
4	0.83	3. Yaw	10	4.3	9. Yaw
5	0.86	4. Yaw	11	5.1	2. Roll
6	1.7	5. Yaw	12	5.7	10. Yaw

Table 1: Natural frequencies of the spray boom, from 3D numerical calculations.

This means that it reacts very slowly to any attempt to change its inclination to the ground. This slow reaction makes it difficult for the driver of the tractor to estimate exactly how far the boom must be moved – for example changing direction when traversing a sloping field requires that the slope of the boom must be changed as the tractor turns the corner to traverse the slope in the reverse direction. To avoid over-or undershoot, the driver must wait for stabilisation after each adjustment of the boom.

Through the last decade the unsteady boom movement has been recognised as an influential factor on the spray distribution [3-8]. In the mentioned references [3-8] attempts for solving the problem mentioned above, mathematical models and simulation is established. Different suspension design is tested, but field condition test is lacking, still it is difficult to keep the spray boom parallel to the ground (and thus to the crops to be sprayed) at all times under field condition without rebuilding the boom and using special designed instrumentation.

The boom can oscillate, under the influence of variations in the transverse slope and external forces such as, for example, the wind. This tends to cause its ends to strike the ground and, in any case, disrupts the regularity of spraying. For the intelligent sprayer boom the roll movement (Figure 3) of the boom is the main issue in order for the cameras to get good focus quality.

Figure 3: Spray Boom Movement.

Spray booms do also oscillate horizontally even when the ground is even. Such movement is highly undesired. It is an object of the invention described in Section 2, to provide a system that actively damps any undesired horizontal movement of a spray boom. In this respect it is also an object to provide an automatic height control system, which can automatically and independently control and adjust the working heights of a pair of boom assemblies, especially relatively wide-span boom assemblies, pivotably attached to a tractor or another vehicle.

2 ACTIVE DAMPING SYSTEM

A patent for an active damping system of the sprayer boom has been obtained at the University of Southern Denmark (SDU). The invention in the patent is mainly described with reference to agricultural spray booms.

The stabilising device is configured as a block movable on a track along the length of the boom assembly (see Figure 4 and 5) and due to the mass of the block it compensates for any undesired horizontal movement, said activating means capable of moving the device along the boom assembly, said computer controlling means receiving information from the means for measuring the position of the boom assemblies on the horizontal movement of the pair of boom assemblies, whereby the computer controlling means controls the horizontal position of the stabilising device through the activating means in response to the received information.

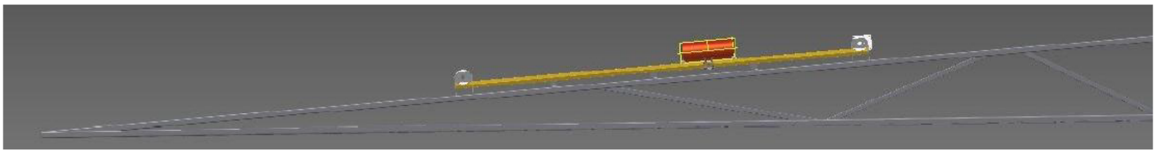

Figure 4: Counterweight placement on the spray boom.

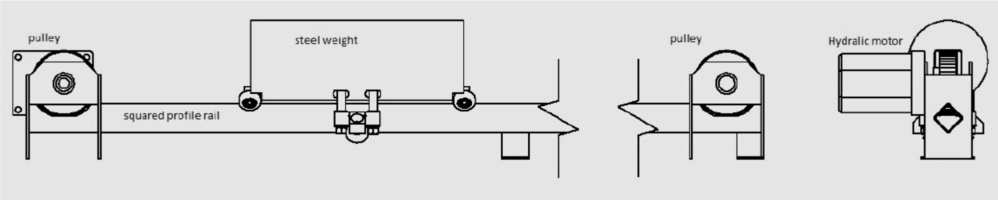

Figure 5: Schematic drawing of the stabilizing device

The block has a mass of at least 12 kg and is moved along the length of the boom by hydraulic pistons. The block moves along a timing belt with nearly the same width as the boom section. When working in the field, the horizontal vibration of the boom is measured by accelerometers, see Figure 6. To achieve very precise measurements the accelerometers for measuring the position of the boom assemblies are placed on the outer sections of the boom assemblies. The stabilising device is mounted just before the outer boom section on left and right side on the top frame of the boom, see Figure 4.

Figure 6: The accelerometer mounted on the spray boom.

3 EXPERIMENTAL WORK

The active damping system (Section 2) is currently being tested experimentally. The experimental work encompasses a stationary test of the hydraulic system and a field test of the active damping system on the spray boom. Since the experimental field tests are on-going, preliminary results are presented here.

3.1 Stationary Test

The active damping system described in Section 2, is based on hydraulic actuation combined with software-based regulation and calculation of the boom position as well as the regulation of the position of the counterweights on the boom, see Figure 7.

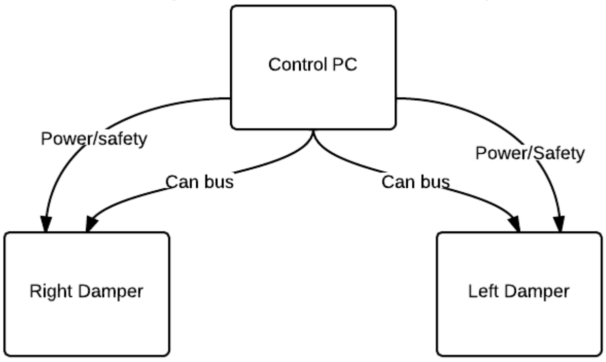

Figure 7: The Schematic drawing of the active control system.

The system consists of a central control computer which through a communication bus communicates with two valve-control boxes. Valve-control boxes are positioned on the boom and are individually equipped with accelerometers to estimate the external influence of the boom. Furthermore the valve control boxes are connected to a proportional valve which controls the flow of oil to the hydraulic engine that moves the counterweights back and forth. An absolute encoder is placed on the hydraulic motor in order to determine the position of the boom.

A stationary test was carried out at the company Hydac (a company for hydraulic accessories) December 2012 in order to preliminary test the hydraulics and control software in the active damping. The purpose of the trials at Hydac was to investigate whether the performance of the selected hydraulics and control software lived up to a demand of a forced velocity of 3 m/s of the counterweights, when moving from one end to the other of the system, see yellow line of Figure 4. The velocity demand of 3 m/s of the counterweight is an estimate based on the maximum possible length of the timing belt being 2.8 m, due to the length of the boom section.

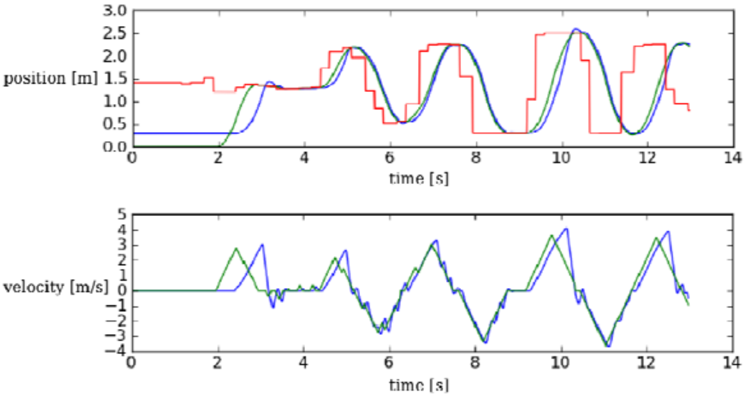

Figure 8: The position (top), velocity (bottom) as a function of time in the stationary test 2.

Figure 8 shows the results from stationary test where the counterweight where controlled using input from accelerometers. Figure 8 (top) shows the position of a counterweight as a function of time and Figure 8 (bottom) shows the velocity of the counterweight. In both figures the green curve is the theoretically desired and the blue curve is the measured. The red shows the desired position calculated from the input from the accelerometer.

The stationary test proved it possible to obtain a velocity of more than 3 m/s of the counterweights when moving from one end to the other. As can be seen from the figure, there is a delay in the position of the counterweight. The delay time is about 200-300ms and depends on how much the counterweight must be moved. This delay affects the performance of the system when this is mounted on the boom, and that is why it is important to compensate for this in the control system in the full scale field test, of the counterweights mounted on the boom.

3.2 Field Test

Two preliminary field test has been performed, one where the spray boom is manually excited and one where controlled movement of the counterweights excites the spray boom. Figure 9 shows the movement of the spray boom when manually excited. The blue curve shows the vibration behaviour of the spray boom without active damping and the green curve is when the active damping system is used. Since the spray boom is manually excited (not controlled or measured) the two curves are not directly comparable, but the trend of how the active damping system influences the vibration may be seen.

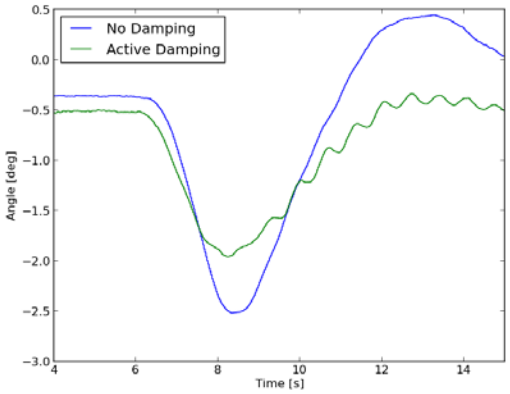

Figure 9: The measured roll angle of the spray boom, green curve with active damping and blue curve without.

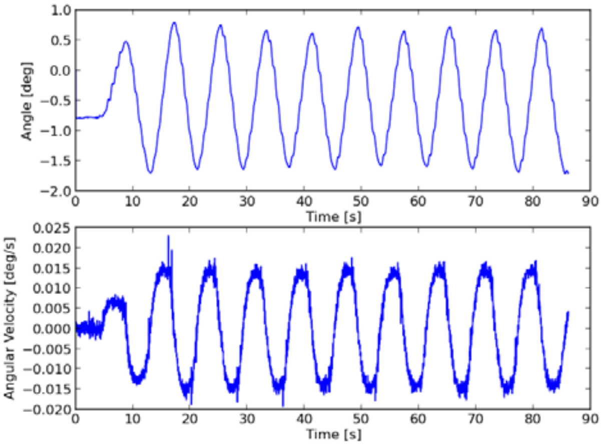

Figure 10: The measured roll angle (top) and angular velocity (bottom) of the spray boom.

In the second preliminary field test the boom vibrations are measured when the active damping system is used to initiate vibrations of the spray boom. The counterweights are controlled to move from one end to the other for every 4 seconds.

Figure 10 shows that the counterweights are able to initiate roll vibrations of substantial amount, even though the weight of the counterweights are relatively small (12.5 kg) compared to the total weight of the spray boom (711 kg). The angular velocity of the spray boom is very small, as may be seen from Figure 10 (bottom).

The on-going field tests are challenged by the fact that a lot of noise appears in the measurement this is being minimized by using a gyroscope at the boom centre, instead of accelerometers as seen in Figure 6.

4 MULTIBODY DYNAMICS MODEL

The spray boom is mounted at the rear of a frame and can be adjusted up and down to the height of the crop via hydraulic pistons. The spray boom is constructed as a truss structure, see Figure 1. The boom is divided into nine sections that can be folded during transportation. On the bottom of the sprayer boom there are mounted nozzles to distribute the liquid evenly over the crop. The spray boom is mounted on a trailer by a pendulum connection as shown in

Figure 11 (left). This connection allows for both roll and yaw movement of the sprayer boom through a ball joint.

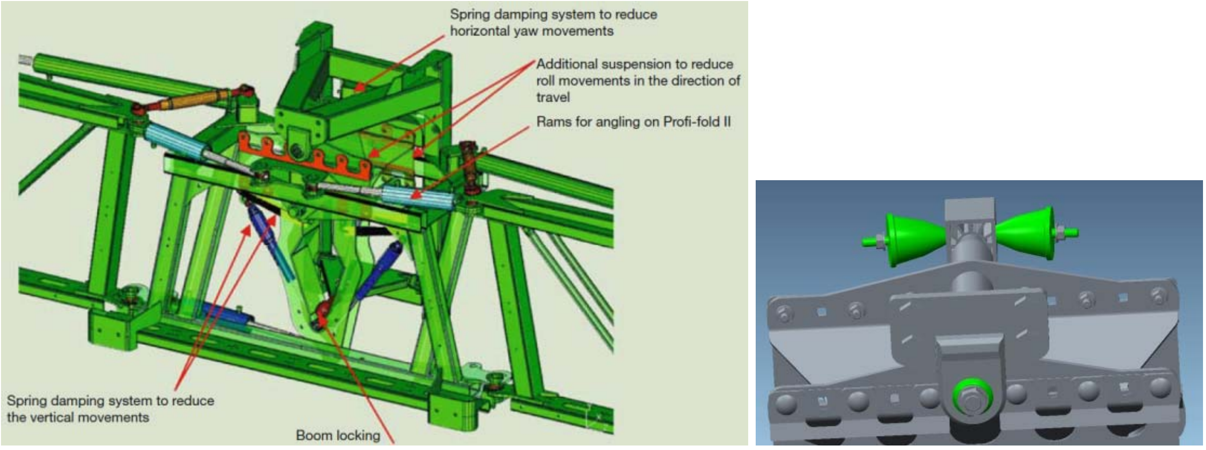

Figure 11: The pendulum connection between trailer and spray boom (left) [9] and ball joint and cone buffers (right).

To reduce the vertical roll movements four springs and two dampers are mounted on the connection. To reduce horizontal yaw movement two cone buffers are also mounted on the connection, shown as green parts in Figure 11 (right).

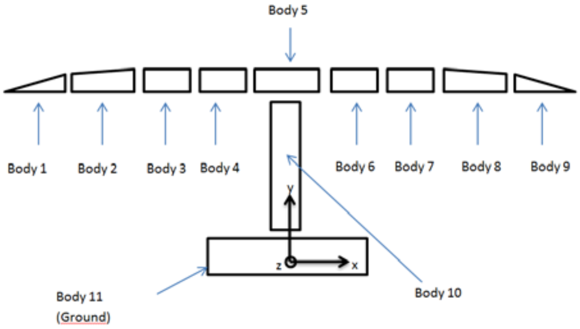

Figure 12: Model of the spray boom.

Body	x	y	z	Ix[kgm^2]	Iy [kgm^2]	Iz [kgm^2]	m [kg]
1	-13.32	0.82	0.17	0.359	30.29	30.51	28.69
2	-9.52	1.07	0.17	2.475	125.33	127.56	50.36
3	-5.55	1.24	0.17	6.749	93.03	99.22	68.68
4	-2.19	1.24	0.17	14.188	125.58	137.23	114.41
5	0.00	1.41	0.00	21.01	24.16	34.88	186.601
6	2.19	1.24	0.17	14.188	125.58	137.23	114.41
7	5.55	1.24	0.17	6.749	93.03	99.22	68.68
8	9.52	1.07	0.17	2.475	125.33	127.56	50.36
9	13.32	0.82	0.17	0.359	30.29	30.51	28.69
10	0.00	0.94	0.00				
11	0.00	0.00	0.00				

Table 2: Center of gravity location for the 11 bodies and Mass moment of inertia and mass of the 9 bodies.

A Multibody Dynamics model of the sprayer boom shown in Figure 1 is analysed. The spray boom is modelled as sections and the model consist of 11 bodies. Figure 12 shows the model and Table 2 the model data used. The model data is taken from a full CAD model (by courtesy of Amazone) of the spray boom. The model is formulated in Cartesian coordinates and the local coordinate systems are placed at the centre of gravity for each section.

The cone buffer is modelled as a non-linear spring; the spring force $f(x)$ is shown in Figure 13 and is in the model approximated by:

$$f(x) = 60000x^3 - 190000x^2 + 4300x \tag{1}$$

where x is the spring elongation.

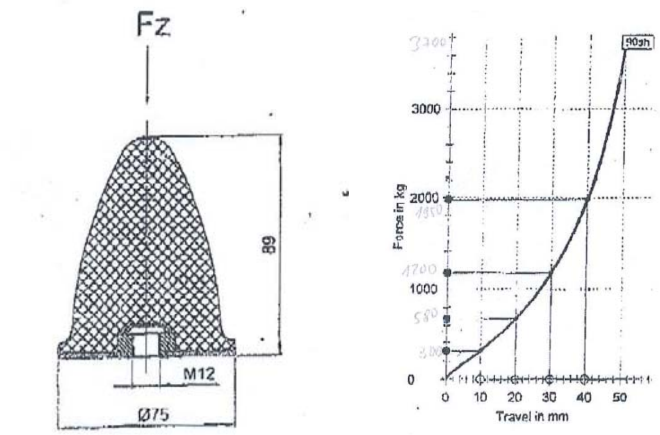

Figure 13: Cone buffer (Gummi-Technik Civak GmbH, Parabel 75x89 M12, Ref. No. 100.000.2753).

To take into account that the sprayer boom is not a rigid structure and it is divided into sections, rotational spring about the y-axis and z-axis (Figure 12) is mounted between each section. Using a FEM model of the spray boom created with Matlab the spring stiffness for the rotational springs is calculated.

The spring stiffness of the rotational springs is estimated, based on the deflection of the individual girder structure of each boom section. The used estimated spring stiffness's are shown in Table 3. Since the spray boom is symmetric about the trailer 4 sections are analysed and the sections are numbered starting from the centre and out. It is assumed that the structural damping is 2%, which yields the damping coefficient given in Table 3.

Section	k [kNm/rad]	c [Nms/rad]
1	16330	7958
2	18010	7152
3	5531	4411
4	403	611

Table 3: Rotational spring stiffness *k* and viscous damping coefficient *c* for the 4 boom section.

The total set of equations of motion for the system is given by [2]:

$$\begin{bmatrix} M & \Phi_q^T \\ \Phi_q & 0 \end{bmatrix} \begin{Bmatrix} \ddot{q} \\ \lambda \end{Bmatrix} = \begin{Bmatrix} g \\ \gamma \end{Bmatrix} \tag{2}$$

where M is the mass matrix, Φ_q is the jacobian matrix, $\ddot{q}$ is the accelerations, λ is the Lagrange Multipliers, g is the general forces and γ is the right hand side of the constraint acceleration equation. The model is set up in Matlab and solved using the ordinary differential equations solver ODE113.

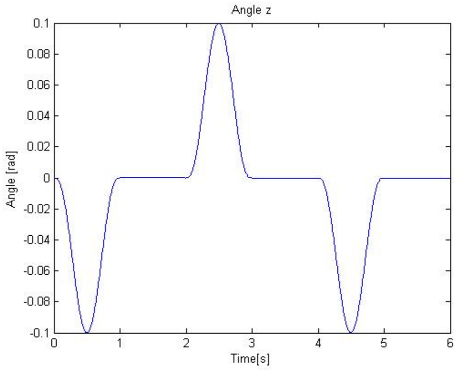

Figure 14: The driver function for the angle as a function of time.

In the field the spray boom is continuously affected by bumps. To model the uneven field the system is given input in the form of a driver which is applied in the rotational joint between the ground body and body 10. The driver is controlled by a 5th order polynomial as shown in Figure 14. The constants of the polynomial are adjusted in order to control the size and length of the bump. Furthermore it is possible to turn the driver off for a period of time and then apply the driver again in opposite direction.

4.1 Results from the Multibody Dynamics model

Simulation for the tractor driving on an uneven field has been performed using driver functions as shown in Figure 14. The driver function illustrates the driven roll angle of the spray boom, as a result of driving over a bump with the left wheel and afterwards with the right wheel. In Figure 14 the bumps are modelled as present every 2 seconds. The vertical movement of the tractor is not included in the present simulation. Figure 15 and 17 shows the results from using a driver function with bumps for every 5 seconds and every 10 seconds, respectively.

When the bumps are applied every 5 seconds (0.2 Hz) we see from Figure 15-16 that the first natural frequency in roll mode is excited. The driver impulses are seen as vertical lines in Figure 15 (left) (likewise in Figure 17 (left)). This corresponds well with the fact the bump on the same wheel is introduced with a frequency of 0.1 Hz. In the yaw direction the simulation shows a response including more frequencies than in the roll direction. This corresponds well with the 1st natural frequencies in the roll direction, see Table 1.

When the bumps are applied every 10 seconds (0.1 Hz) we see from Figure 17-18 that the frequency response corresponds with the fact the bump on the same wheel is introduced with a frequency of 0.05 Hz. Figure 17 (right) shows that at this driver frequency the response seems to show the phenomenon of beats. This could corresponds with the 1st and 2nd natural frequency in yaw direction, see Table 1 being close to the excitation frequency of 0.2 Hz (when the same tractor wheel is excited). The simulation shows that the yaw direction is more sensitive to the excitation frequency than the roll. This direction however is not the problem with respect to the camera focus, but it is of interest in the prediction of the boom movement. The simulation time however with the current model is too long in order to use it for active prediction in the field.

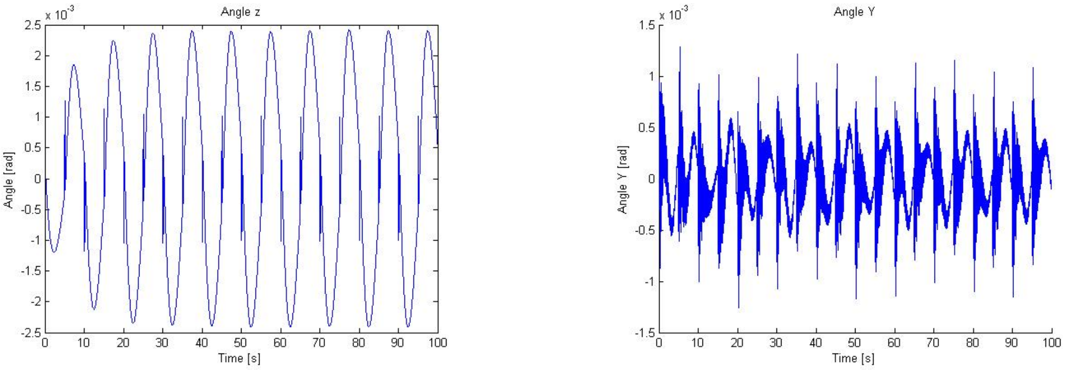

Figure 15: The roll angle (left) and yaw angle (right), for bumps every 5 seconds.

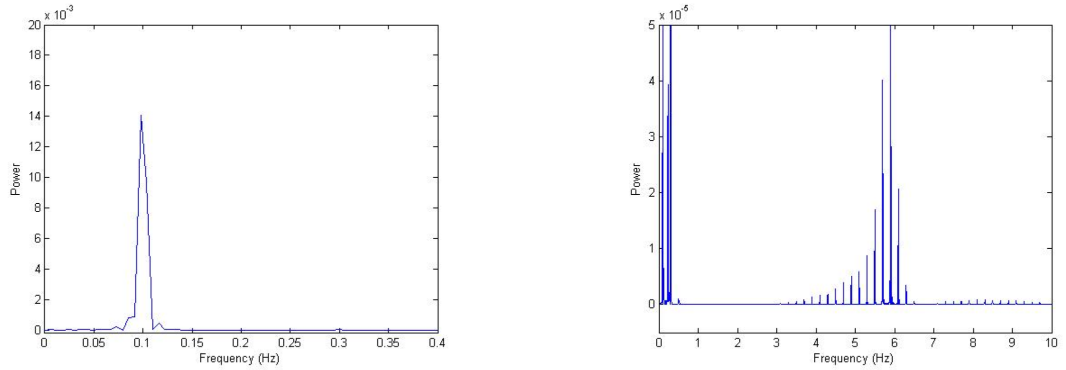

Figure 16: FFT of the roll angle (left) and yaw angle (right), for bumps every 5 seconds.

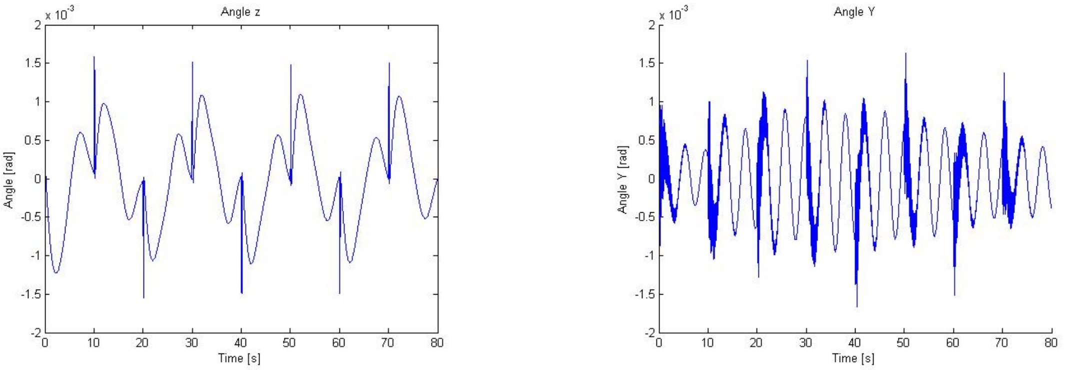

Figure 17: The roll angle (left) and yaw angle (right), for bumps every 10 seconds

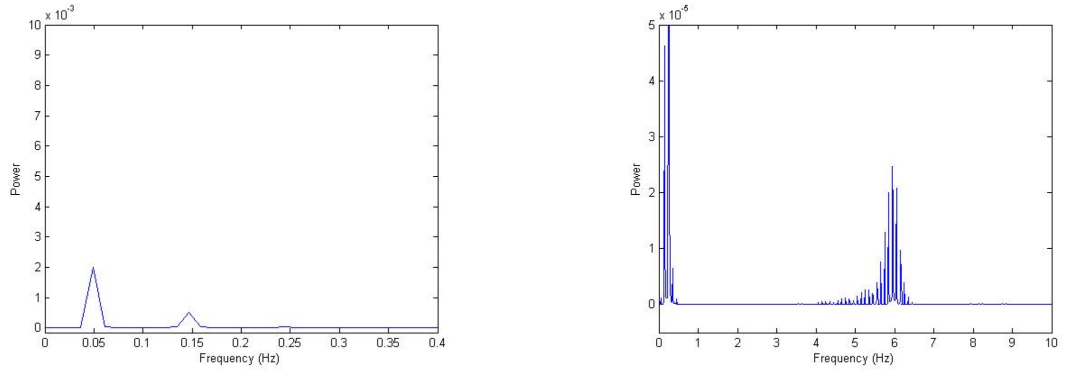

Figure 18: FFT of the roll angle (left) and yaw angle (right), for bumps every 10 seconds

5 CONCLUSIONS

- The work presented here is work still in progress.
- The future work for the Matlab Multibody Dynamics model is to include the active damping system in the model. This will be done in Matlab Simulink, with the pre-incorporated active control elements.
- The experiments with the patented active damping system are also on-going and the final tests are expected to be done during 2013.
- The stationary test of the hydraulic system show, that it is possible to active drive the counterweight system using hydraulics.
- The experimental field showed that even though the weight of the counterweights is relatively small, they are able to be used in the active damping system.

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