Test method and criteria for evaluating the mechanical integrity of boom sprayers

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TABLE OF CONTENTS

SUMMARY

A. Context

A.1. Spray boom motions, a major cause of an irregular spray distribution

An exponentially growing world population and constantly increasing food quality requirements made chemical crop protection become one of the most important field operations. Field sprayers, equipped with large spray booms are used worldwide for the application of phytopharmaceutical products to agricultural crops. In the EC there are approximately 400.000 field sprayers in operation.

New tendencies towards the use of concentrated spraying agents (small volume spraying techniques), together with the increasing cost of chemicals and pollution pressure on the environment impose more severe technical requirements to spraying-machines in the near future. Spray deposit variations as they occur nowadays are intolerable for these applications for the sake of excessive residues and crop damage. The problem of an unequal distribution of pesticides is mainly situated on three levels:

- variations in the travel speed of the machine and defects in the hydraulic equipment (worn nozzles, technical defect of the pump and valves, leaking hoses, …)
- environmental factors as wind influencing the travel distance of the droplets;
- vibrations of the spray boom during field operations, mainly caused by an ineffective suspension or by mechanical defects in the boom construction (worn hinges, boom deformation, ...).

During field operation, tractor vibrations, mainly effected by soil unevenness, induce undesired spray boom motions creating local under- and overdoses of spray liquid. Resulting spray boom motions can be divided into two main groups: vertical and horizontal boom movements. Vertical vibrations, as rolling, give rise to local variations in spray deposit between 0 % and 1000 % and horizontal vibrations, as yawing, between 20 % and 600 %, (100 % is ideal) and by this belong to the major causes of an irregular spray deposition.

Vibrations of the spray boom during field operations are mainly caused by an ineffective suspension or by mechanical defects (boom deformations, improperly locked hinges causing backlash in the hinges, worn springs and dampers,…).

A.2. Inspection of field sprayers

The present hydraulic state of all sprayers in use is being inspected on regular basis in several European countries, including Belgium, Germany and the Netherlands, in a mandatory procedure. The mandatory inspection aims at checking hydraulic pressure variations along the boom, liquid distribution, nozzle wear and other defects, influencing the liquid distribution under static conditions. A CEN working group within CEN TC 144/WG3 is harmonising the today’s used evaluation criteria throughout Europe.

Although unwanted spray boom vibrations dramatically effect the spray distribution pattern, procedures to evaluate the mechanical integrity or structural condition of booms are not included yet in current sprayer inspections. ***Therefore, to keep spray boom vibrations within tolerable margins, boom constructions should be properly designed and well maintained which can only be guaranteed by inspecting on a regular basis the performance of the suspension and the quality of the hinges and hinge locks, springs and dampers built in the boom structure.***

Unfortunately, still no standards have been formulated to establish the mechanical condition of operational spray boom constructions and new makes by which no procedures have yet been included in current sprayer inspections to evaluate the mechanical condition of spraying-machines.

Consistent research about boom vibrations and related spray distribution patterns has been initiated within the shared cost action AIR3-CT94-1170 “European System for Field Sprayers

Inspection at the Farm Level (SPECS)", funded by the EC. In this project, six leading research groups in spraying techniques, co-ordinated by the K.U.Leuven, Laboratory of Agro-Machinery and –Processing, started developing a systematic procedure for testing the mechanical integrity (i.e. condition) of operational sprayers at the farm level. In a final stage of this research project, two prototype test systems were developed with a view to evaluate the feasibility of integrating a standardised inspection for the mechanical status of sprayers in use and new makes, in current sprayer inspections. However, both procedures still show important insufficiencies which must first be solved before they become applicable in routine tests.

A.3. Insufficiencies of the test procedures of the SPECS project

A.3.1. Input disturbances

Soil and road unevenness induces vibrations on a spraying-machine crossing the field or moving on the road during transport. In vibration engineering, these are called systems with base motion since the input disturbances are displacements under the tires. In the SPECS project, the ISO 5008 standard tracks have been used as input excitations. These tracks are however not very reliable as their power spectrum shows the absence of important frequencies in the frequency band of interest (i.e. mainly between 0 Hz and 5 Hz) indicating that not all dominant natural frequencies of the structure between 0 Hz and 5 Hz will be excited equally. Representative input excitations at the suspension of the spray boom have also been derived. It is clear that these excitation signals can only be used when the spray boom is uncoupled from the machine which is unfeasible in practice.

A.3.2. Experimental modal analysis

In the first procedure, the tested spraying-machine is excited on a mobile shaker. During the experiment, input excitations and response accelerations on appropriate locations of the machine are registered in the longitudinal and the vertical direction as well. From these input-output signals, experimental models are built which are used to simulate longitudinal and yawing spray boom motions as a response to certain standardised input disturbances. In their term, simulated boom vibrations are used to calculate the corresponding spray distribution pattern from which conclusions concerning mechanical integrity of the tested spraying-machine are drawn. The linear dynamic models of the sprayers are derived by experimental modal analysis (EMA) from measured output accelerations of certain locations on the structure as a response to force input excitations. Consequently, the derived dynamic models can only use forces as input signals. Because spraying-machines are directly excited by soil unevenness which are displacements and not forces, EMA in its current form was not the appropriate method for model building in this application. In addition, an EMA on mechanical structures should be performed by specially trained people and will therefore not be considered in this research proposal.

A.3.3. Inspection rig with camera

In the second procedure, the tested spraying machine is driven across a bump and the vertical and horizontal movements of one of the boom tips is registered by camera. However, this methodology could not fully be evaluated and compared to the modal analysis based method due to a lack of time. In addition, before starting the measurements with the camera, some data like geometrical features of the sprayer and the track had to be used to calibrate the measurements. If this was not done very carefully, the measurements became completely worthless and the measurements had to be repeated. At last, but not at least, it is clear that a bump is not a representative track and the motion of one of the boom tips is not a representative measure for vibrations on other parts of the boom (backlash in the hinges, flexible deformations, …).

A.3.4. Spray liquid simulation models

Within the SPECS project, mathematical models to simulate spray liquid distribution and which are function of the tractor speed and rolling and yawing of the boom, are developed. Experimental validations showed that under certain conditions, these models do not generate reliable output simulations mainly because important parameters which contribute significantly to the final spray deposition pattern as evaporation, drift induced by yawing of the boom,…, were introduced in the model.

B. Objectives

B.1. Overall objective of the research proposal

Research in this field has been initiated in the EC project “European System for Field Sprayer Inspection at the Farm Level” that still show some insufficiencies. The overall objective of the proposal therefore concerns

The improvement and extension of the methodology for testing the mechanical integrity of sprayers in use and new makes, developed in the EC research project AIR3-CT94-1170, such that the methodology becomes applicable in routine tests, can be used to define directives concerning tolerable boom movements, can easily be integrated in current (mandatory or voluntary) sprayer inspections, provides sufficient technology and know how to develop a standardised procedure for the evaluation of the mechanical status of sprayers.

B.2. Sub-objectives of the research proposal

- Development of a mathematical model of a self-propelled sprayer and a trailed sprayer to be used for the derivation of representative tracks and optimization of the optimal position of the sensors.
- Derivation of representative tracks that can be used as excitation sources for the sprayer tests. These tracks will have the same stochastic characteristics as the field unevenness sensed by the sprayer tyres.
- Determination of the type of sensors (accelerometers, optical sensors as camera, laser, infrared, ultrasonic) their number and their position on the sprayer by performing field tests combined with the mathematical models. The sensors will be used to measure the mechanical condition of the tested sprayers.
- Development of reliable spray deposit distribution models to simulate the spray distribution as a function of boom vibrations.
- Establishment of the maximum tolerances for variation in liquid distribution under a spray boom during operation (i.e. under dynamic conditions) based upon extensive field measurements.
- Development of a test rig (based upon a sequence of bumps tests) for rapid testing the mechanical status of sprayers. The inspection procedure will consist of four major parts: excitation of the tested sprayer by driving it across the track, simultaneous registration of boom movements, processing the measurements and simulation of the related spray distribution, formulation of a quality label for the tested machine.

C. Conclusions

C.1. Multibody model of a trailed and self propelled sprayer

A multibody model of a trailed sprayer from the company Beyne and the self propelled sprayer “EUROTRACK” from the company Delvano was built with the general purpose software ADAMS and DADS respectively.

The model of the trailed sprayer consisted of two parts: a detailed model of the boom with suspension and a model of the carrying frame with the tires. Boom roll and hop could be predicted accurately. Predictions of horizontal boom movements were not so reliable. Roll of

the frame could be well predicted contrary to yaw of which the model could not provide reliable results.
In the model of the EUROTRACK much attention was paid on a detailed model of the tractor. The model of the boom with suspension was conceived in less detail. Based on measurements of machine vibrations, unknown machine parameters were estimated through an optimisation procedure in OPTIMUS. To this end a mono poster mobile shaker was conceived. Tractor roll, tractor hop and boom roll could be predicted accurately. Prediction of tractor pitch and yaw gave unreliable results.

From the results it may be concluded that multibody models are an interesting tool for predicting the dynamic behaviour of machines. However, the accuracy of the prediction of the dynamic behaviour of both sprayers depends on the modes considered. Vibrations in the modes roll and hop can be well predicted, vibrations in the modes yaw and pitch are much more difficult to predict. The accuracy of the models could be improved by increasing the number of bodies in the multibody and the introduction of more precise parameter values (masses, centres of mass, moments of inertia for the different bodies, damping and stiffness coefficients of tires and suspensions, better tire models, …). This problem could be (partially) solved by setting up extensive experiments for a precise determination of these parameters.

The model of the self propelled sprayer was used for deriving excitation tracks in a formal way. The model of the trailed sprayer was used to determine the optimal position and number of sensors for measuring the mechanical integrity of the spray boom and suspension and for evaluating the derived tracks.

C.2. Derivation of representative tracks as excitation source of the tested sprayer

Currently, the ISO5008 track is available for testing the dynamic behaviour of mobile agricultural machinery. From a stochastic viewpoint this track was not rich enough such that not all the modes of interest on a spraying machine could be excited in a proper way.
Representative tracks were derived according to a unique procedure:

- Measurement of vertical (rolling) and horizontal (yawing) boom vibrations of different spraying machines under different field conditions. The newly designed tracks had to be able to reproduce similar (i.e. realistic) boom vibrations.
- Traditional derivation of excitation tracks is a tedious and extremely time consuming work. Fortunately, a formalised procedure for deriving representative tracks has been proposed called “service load simulation”. The procedure is has been developed in the road vehicle industry and was used for the first time on agricultural machinery in this project. Normally, a four poster electro-hydraulic shaker should be available for reproducing iteratively measured accelerations on the wheel axles. The vertical movement of each hydraulic cylinder under the tyres of the vehicle is a representation of a wheel track. For heavy vehicles, a powerful four poster had to be available. In this project, the real vehicle was replaced by a multibody model with which the measured vertical axle accelerations were reproduced by a virtual four poster placed under the tyres of the model. The vertical motion of each poster represented the wheel tracks. Although the accuracy of the EUROTRACK model was not complete, the axle accelerations could be reproduced very precisely by the introduction of four feedback control systems, increasing the robustness of the reproduction procedure against model uncertainties. This procedure, based on multibody models is unique
- Based on this information 16 short tracks with the shape of a multisine and a block profile were derived with a power spectrum as close as possible to that of the reproduced tracks. An important conclusion was that a simple block profile could reproduce a spectrum as rich as any other type of track (e.g. multisine) which is an important conclusion from a practical viewpoint (easy to construct, …).

- The two virtual tracks that could reproduce most accurately realistic boom vibrations were selected with the model of the trailed sprayer. Although the selected tracks were much richer than the ISO5008 track, they were unable to provide satisfactory results (i.e. reproduction of realistic boom vibrations) especially for boom roll. From this it seemed clear that representative tracks may not be derived based on one machine.
- Finally the block profile with a constant block height of 5 cm and a total length of 51.2 m with an adaptable distance between the blocks and lengths of the blocks.
- The designed track was finally tested. Measured boom movements of a trailed sprayer while crossing the track were higher than under field conditions, especially between 0.1 and 0.2 Hz. This problem could be solved by smoothen the edges of the blocks and/or by lowering the blocks (e.g. by filling up the space between the blocks).

C.3. Determination of the type of sensors to be used, their number and position on the spraying machine

- Radar sensor: rigidly fixed to the sprayer frame or to the tractor (trailed sprayer), measures tractor or sprayer forward speed.
- Gyroscope: rigidly fixed to the sprayer frame or a sprayer part rigidly fixed to the frame, measures yaw and roll.
- Ultrasonic distance sensors: placed symmetrically on the sprayer boom at a minimal distance of 45 cm from the boom centre, measure the relative displacement of the boom with respect to the vehicle
- Five accelerometers: placed on five different predefined locations on the spray boom, measure the absolute horizontal boom accelerations
- Two accelerometers: placed on two different predefined locations on the spray boom, measure the absolute vertical boom movements.
- Infrared sensor: placed on the suspension, measures the distance related to the relative inclination between the boom and the sprayer frame. In addition, a detailed procedure is given for describing the calibration of the infrared sensor.

It is the first time according to the most recent literature that such a detailed procedure for measuring boom movements has been described.

C.4. Development of reliable spray deposit distribution models to simulate the spray distribution as a function of boom vibrations

In a next stage, after registration of horizontal and vertical boom movements of the sprayer under consideration, these movements should be related to a so called dynamic spray deposition pattern. The latter is extremely difficult to obtain directly. Therefore, an indirect method was worked out consisting of four steps:

- Registration of the static spray distribution pattern of different nozzles. Based on a 2D-scanner, developed at the University of Uppsala, Sweden, in the framework of the SPECS project, a totally refreshed 2D- scanner was designed. The scanner consists of 24 liquid tubes that are filled with liquid from the nozzle during a predefined number of steps the scanner moves at constant time intervals under the nozzle during the experiment. With this scanner it is possible to measure the static spray distribution of any kind of nozzle at a certain liquid pressure and height of the nozzle by measuring the evolution of the liquid height in the tubes during the experiment. The time needed to register one static spray pattern is between 2 and 4 hours. Since it took quite a lot of time to upgrade the SPECS scanner, only about 20 static spray patterns of different nozzles could be registered yet.
- Preparation of the data for developing the dynamic spray distribution pattern. The data should be presented as a data matrix in excel (24 liquid tubes of the scanner x the number of steps the spray scanner has been executing).

- A mathematical relation between the static spray distribution model and the dynamic spray distribution model has been established by F. Lebeau whose model is an improvement of the model of H. Ramon.
- A methodology for the validation of the dynamic spray distribution model was executed. A laboratory set up intended for validation under more controlled conditions, was constructed but calibration and experiments could not be performed yet. The experiment makes use of differences in capacity between two steel plates depending of the amount of demineralised water between the plates. The principle is not new but the precision is increased significantly compared to the existing set ups owing to the use of smaller steel plates. In addition, a large surface of 5mx1.2m could be measured in one test instead of a small strip. Three field tests were examined. In the first test or mineral tracer test, the sprayer crossed wooden grids covered with special absorbing paper, sprayed with mineral water. By chemical analysis of the papers, on which the tracer was grafted, undesired boom movements during spraying could be quantified. Unfortunately, this is an expensive method that limited the number of experiments. In the second test water sensitive paper strips were fixed on wooden sticks and placed on regular distances in the field. After spraying, the strips were treated by image analysis techniques. A full 2D spray distribution pattern was obtained by interpolating the measured data. This method is cheap but gives only qualitative results. In the third method, a pesticide is used and meanwhile boom movements are recorded. Boom movements were induced by crossing wooden obstacles or small ditches with the sprayer. In this research a round up was used and its effect was successfully reproduced by the dynamic spray distribution model.

C.5. Establishment of the maximum tolerances for variation in liquid distribution under a spray boom during operation

Field experiment three was used to establish the relation between boom movements and efficiency of the pesticide. Only round up was used. In more extensive experiments the relation between boom movements and the efficiency of other pesticides should still be investigated. Conclusion from the project is that phytopathologists had to be involved in the project to derive the relation between tolerable boom movements and pesticide efficiency. Final directives and standards about tolerable boom movements is however an international matter in which the project results and developed methodologies can contribute significantly as it is the first project in succession of the SPECS project that provides a well established and systematic procedure for investigating tolerable boom movements.

C.6. Development of a test rig for rapid testing the mechanical status of sprayers.

As a final result of this project, a detailed description of a test procedure with necessary equipment, for evaluating the mechanical status of spraying-machines is established. The proposed test procedure is unique in the sense that it has been performed for the first time.
The procedure includes the following steps:

- Description and calibration of the sensors used together of the data acquisition apparatus and the power source.
- Description of the test track with proposed travel speed for excitation of the sprayer.
- Placement of the sensors and acquisition equipment on the machine.
- Description of the configuration of the boom and suspension during preparation and during the test.

D. Contribution of the project in a context of support to the process of standardisation and technical regulation

- First development of excitation tracks shaped as an easy to construct block profile, for off-road (agricultural) machines in a scientific way based on service road simulation by the aid multibody models of two types of sprayers.

- Extensive measurements of vertical and horizontal boom movements under different field conditions with different sensors.
- Determination of the type and number of sensors used and their position on the machine and boom to register in a reliable way boom movements.
- Refinement of existing laboratory equipment to register the static spray distribution pattern of a nozzle (i.e. the 2D spray scanner) and the dynamic spray distribution pattern, the latter based on capacity measurements.
- Dynamic spray distribution pattern model, developed by Lebeau, using the static spray distribution pattern of a nozzle.
- Refined laboratory set up based on capacity measurements, for validating the dynamic spray distribution pattern.
- Evaluation of three different field test for validating the dynamic spray distribution pattern model.
- Establishment of a methodology for the formulation of directives and standards for allowable boom movements derived from maximum acceptable unevenness in the spray deposition pattern.
- Establishment of a methodology for rapid testing the mechanical status of field sprayers.

E. Keywords

Trailed sprayer, self-propelled sprayer, field sprayer, spraying-machine, spray boom, sprayer frame, boom suspension, liquid tank, undesired horizontal (jolting, yawing) and vertical (roll, hop) spray boom movements, Multi body models, electro-hydraulic shaker (four poster, one poster), excitation track (multisine, block profile), 2D-scanner, static and dynamic spray distribution model, capacitor method, mechanical status of field sprayers, data acquisition, power spectrum of a signal, field trials, water sensitive paper, maximal acceptable tolerances in the spray distribution pattern (spray deposition pattern, spray pattern), sensors (accelerometer, ultrasonic sensor, infrared sensor, radar sensor, gyroscope)

SAMENVATTING

A. Context

A.1. Spuitboombewegingen, één van de belangrijkste oorzaken van een onregelmatige spuitvloeistofverdeling

Een exponentieel groeiende wereldpopulatie en een vraag van de consument naar steeds betere voedingsproducten maakte de chemische gewasbescherming tot een van de belangrijkste veldbewerkingen. Veldspuiten, uitgerust met lange spuitbomen worden wereldwijd ingezet voor het verspreiden van fytofarmaceutische producten over te behandelen landbouwgewassen. In de EU zijn momenteel ongeveer 400.000 veldspuitmachines in gebruik.
Een nieuwe tendens naar het gebruik van meer geconcentreerde agentia gecombineerd met een stijging van de kostprijs voor chemicaliën en een toenemende verontreinigingsdruk op het milieu vereist machines met steeds betere technische kwaliteiten. Variaties in de verdeling van de spuitvloeistof over het veld, zoals deze vandaag worden geregistreerd zijn niet meer aanvaardbaar. Om een bepaalde effectiviteit te behouden, dwingen zij de landbouwer tot het verspuiten van overdosissen die leiden tot gewasbeschadiging en overmatige hoeveelheden residu in het milieu en op landbouwproducten.
Het probleem van een onregelmatige pesticidenverdeling situeert zich hoofdzakelijk op drie niveau’s:

- Variaties in the rijsnelheid van de trekker en defecten in de hydraulische componenten (versleten doppen, technische defecten in de pomp, kleppen, lekken in de leidingen, …
- Omgevingsfactoren zoals de wind die de afstand van de druppels tot het gewas sterk kan beëinvloeden.
- Trillingen van de spuitboom tijdens veldbewerkingen, hoofdzakelijk veroorzaakt door slecht functionerende ophanging of door mechanische defecten in de boomconstructie (versleten koppelingen, vervormingen van de boom, …).

Gedurende veldbewerkingen induceren tractortrillingen, hoofdzakelijk veroorzaakt door bodemoneffenheden, ongewenste spuitboombewegingen die op hun beurt het verantwoordelijk zijn voor locale over- en onderdosissen aan spuitvloeistof. Spuitboombewegingen kunnen worden onderverdeeld in twee groepen: verticale en horizontale trillingen. Verticale trillingen, zoals rollen, en horizontale trillingen, zoals gieren, geven variaties in de spuitvloeisofverdeling variërend tussen 0 % - 1000 %, resp. 20% - 600 % (100 % is ideaal). Spuitboomtrillingen worden hoofdzakelijk veroorzaakt door een inefficiënte ophanging of door mechanische defecten (vervormingen van de boom, slecht geblokkeerde scharnieren die speling veroorzaken, versleten veren, dempers, …).

A.2. Inspectie van veldspuitmachines

De toestand van de hydraulische uitrusting van alle operationele spuitmachines wordt op regelmatige basis reeds getest in verschillende landen van de EU, zoals België, Duitsland en Nederland in een verplichte procedure. De verplichte inspectie heeft als doel het evalueren van drukvariaties langs de boom, de spuitvloeistofverdeling, sleet op spuitdoppen en andere defecten die de spuitvloeistofverdeling onder statische condities kunnen beïnvloeden. Een CEN werkgroep in CEN TC 144/WG3 harmoniseert momenteel de evaluatiecriteria die vandaag gehanteerd worden in de EU.
Niettegenstaande ongewenste spuitboomtrillingen een dramatische invloed uitoefenen op de spuitvloeistofverdeling, werden procedures om de mechanische integriteit of de structuurconditie van spuitbomen nog niet opgenomen in de huidige inspecties.
Hieruit moet men zeker stellen dat om spuitboomtrillingen binnen aanvaardbare grenzen te houden, boomconstructies correct moeten worden ontworpen en goed onderhouden. Dit kan enkel worden gegarandeerd door het invoeren van een

regelmatige inspectie van de spuitboomophanging en de –constructie met haar veren, dempers, koppelingen en vergrendelingssystemen.
Helaas, werden nog steeds geen normen geformuleerd voor het vastleggen van de mechanische conditie van spuitmachines en spuitmachines in gebruik waardoor nog geen procedures ontwikkeld zijn voor de inspectie van de mechanische conditie van spuitmachines.
Consistent onderzoek op ongewenste spuitboomtrillingen en de hiermee gerelateerde spuitvloeistofverdelingspatronen werd voor het eerst uitgevoerd in het EU project AIR3-CT94-1170 “1170 “European System for Field Sprayers Inspection at the Farm Level (SPECS)”. In dit project startte een internationaal team van zes leidende onderzoeksgroepen in het domein van de spuittechnieken, onder leiding van het Labo voor Landbouwwerktuigkunde van de K.U.Leuven, met de ontwikkeling van een systematische procedure voor het testen van de mechanische integriteit van operationele spuitmachines. In een finaal stadium van het project werden twee prototype testsystemen ontwikkeld met als doel na te gaan of een dergelijke procedure zou kunnen worden geïntegreerd in de bestaande inspectie voor spuitmachines. Beide procedures vertonen echter een aantal gebreken die eerst moeten worden opgelost vooraleer zij kunnen worden toegepast.

A.3. Onvolkomenheden in de testprocedures van het SPECS project

A.3.1. Ingangsstoorsignalen

Bodem- en wegoneffenheden induceren via de banden trillingen op spuitmachines. In het SPECS project werden de ISO 5008 gestandaardiseerde tracks gebruikt. Deze zijn echter niet zeer betrouwbaar omdat heel wat frequenties ontbreken tussen 0 en 5 Hz in het vermogenspectrum waardoor sommige belangrijke eigenfrequenties van de machine niet zullen geëxciteerd worden. Representatieve ingangsexcitaties ter hoogte van de spuitboomophanging werden eveneens afgeleid. Deze kunnen echter enkel worden gebruikt wanneer de spuitboom losgekoppeld is van de machine wat niet resulteerbaar is in praktijktesten.

A.3.2. Experimentele modale analyse (EMA)

In de eerste testprocedure werd de te evalueren spuitmachine geëxciteerd op een mobiele schudstand. Gedurende het experiment werden de ingangsexcitaties en de verticale en longitudinale responsversnellingen op bepaalde posities van de spuitmachine geregistreerd. Uit deze ingangs- en uitgangssignalen, werden experimentele modale modellen ontwikkeld die op hun beurt werden gebruikt voor het simuleren van longitudinale en slingerende/zwiepende spuitboombewegingen en voor de hiermee geralateerde spuitvloeistofverdeling waaruit vervolgens conclusies werden geformuleerd i.v.m. de mechanische integriteit van de spuitmachine. De lineaire dynamische modellen werden afgeleid d.m.v. EMA van gemeten uitgangsversnellingen op bepaalde punten van de structuur als een respons op ingangsexcitaties. Daar spuitmachines worden geëxciteerd door bodemoneffenheden (lees verplaatsingen) en niet door krachten, is de EMA in zijn huidige vorm geen gepaste methode voor modelbouw in deze toepassing. Daarenboven is een EMA vrij complex en kan enkel worden uitgevoerd door speciaal opgeleide techniekers. Daarom zal ze in dit voorstel niet in beschouwing worden genomen.

A.3.3. Testprocedure met camera

In de tweede procedure wordt de te evalueren spuitmachine aan een zekere snelheid over een bump gestuurd terwijl de verticale en horizontale bewegingen van één van de spuitboomuiteinden wordt geregistreerd. Deze methode werd echter niet volledig geëvalueerd en vergeleken met de modale analysemethode door tijdsgebrek. Daarenboven moet voor iedere meting een zorgvuldige calibratie worden uitgevoerd, met geometrische gegevens van de spuitmachine en de tractor. Indien dit niet zorgvuldig gebeurt zijn de metingen waardeloos en dienen ze herhaald te worden. Daarenboven is het duidelijk dat een bump geen representatieve trade is en dat de bewegingen van één spuitboomuiteinde geen representatieve maatstaf zijn voor vibraties op andere delen van de boom (speling in de koppelingen, elastische vervormingen,…).

A.3.4. Simulatiemodellen voor de spuitvloeistofverdeling.

In het SPECS project werden wiskundige modellen ontwikkeld voor het simuleren van de spuitvloeistofverdeling i.f.v. de rijsnelheid van de tractor en van de rollende en zwiepende spuitboombewegingen. Experimentele validaties tonen aan dat onder specifieke condities, deze modellen geen betrouwbare uitgangssimulaties opleveren omdat sommige belangrijke parameters die de vloeistofverdeling beïnvloeden zoals evaporatie en drift veroorzaakt door het zwiepen van de spuitboom niet in de modellen zijn opgenomen.

B. Doelstellingen

B.1. Het algemeen objectief van het onderzoeksvoorstel

Onderzoek in dit domein werd opgestart in het EU project "European System for Field Sprayer Inspection at the Farm Level" dat nog steeds een aantal onvolkomenheden vertoont. Het algemeen objectief van het onderzoeksvoorstel omvat daarom
De verbetering en de uitbreiding van de methodologie voor het evalueren van de mechanische integriteit van spuitmachines in gebruik en nieuwe machines, ontwikkeld in het EU onderzoeksproject AIR3-CT94-1170, zodat de methodologie bruikbaar wordt in routinetesten, gebruikt kan worden voor het formuleren van richtlijnen over toelaatbare boombewegingen, kan eenvoudig worden geïntegreerd in de huidige (vrijwillige of verplichte) inspecties en voldoende technologie en kennis levert voor de ontwikkeling van een standaard procedure waarmee de mechanische conditie van spuitmachines kan worden getest.

B.2. Subobjectieven van het onderzoeksproject

- Bouw van een wiskundig model van een zelfrijdende en een getrokken spuitmachine, gebruikt voor de ontwikkeling van tracks en voor het bepalen van de optimale posities van de meetsensoren.
- Afleiden van representatieve tracks, gebruikt als excitatiebron voor de spuitmachinetesten. Deze tracks moeten dezelfde stochastische karakteristieken hebben als de veldoneffenheden zoals ze gevoeld worden door de banden.
- Bepaling van de type sensoren (versnellingsopnemers, optische sensoren zoals camera, infrarode en ultrasone sensoren), hun aantal en hun positie op de spuitmachine, door het uitvoeren van veldtesten gecombineerd met de wiskundige modellen. De sensoren worden gebruikt voor het registreren van de mechanische conditie van de te testen spuitmachines.
- Ontwikkeling van een wiskundig model voor de simulatie van het spuitvloeistofpatroon als functie van spuitboomtrillingen.
- Bepalen van de maximale tolerantiegrenzen voor variaties in het spuitvloeistofverdelingspatroon onder een spuitboom in werking (i.e. onder dynamische condities).
- Constructie van een systeem voor het evalueren van de mechanische toestand van spuitmachines. De inspectieprocedure wordt doorlopen in vier stappen: excitatie van de spuitmachine door het sturen van de machine over een track, simultaan worden de boombewegingen opgemeten, nabehandeling van de meetgegevens en simulatie van de spuitvloeistofverdeling veroorzaakt door de opgemeten spuitboombewegingen, formulering van een kwaliteitslabel voor de geteste machine.

C. Besluiten

C.1. Multibody model van een getrokken spuit en een zelfrijder

En multibody model van een getrokken spuit van de constructeur Beyne en de zelfrijder "EUROTRACK" van de constructeur Delvano werd ontwikkeld met behulp van de respectievelijke software ADAMS en DADS
Het model van de getrokken spuit bestaat uit twee delen: een gedetailleerd model van de boom met ophanging en een model van het dragend frame met de banden. Rollende en dansende boombewegingen konden vrij nauwkeurig worden voorspeld. Het voorspellen van horizontale boombewegingen was minder nauwkeurig. Het rollen van de boom kon goed worden voorspeld in tegenstelling tot het gieren van de boom
In het model van de EUROTRACK werd veel aandacht besteed aan een gedetailleerd model van de tractor. Het model van de boom met suspensie werd minder gedetailleerd ontworpen. Gebaseerd op metingen van machinetrillingen, werden de onbekende machineparameters geschat met behulp van de optimilaisatieprocedure in OPTIMUS. Hiervoor werd een mobiele éénposter schudstand ontwikkeld. Het rollen en het dansen van de tractor kon zeer nauwkeurig worden voorspeld terwijl voorspellingen van het stampen en gieren van de tractor aanleiding gaven tot onbetrouwbare resultaten.

Uit deze resultaten mag worden besloten dat multibody modellen een interessant instrument zijn voor het voorspellen van het het dynamisch gedrag van mechanismen. The precisie van de predictie van het dynamisch gedrag van beide spuitmachines hangt af van de beschouwde trillingsmodes. Trillingen in de mode rollen en dansen kan goed worden voorspeld. De betrouwbaarheid van de modellen zou kunnen worden verhoogd door het aantal lichamen in de multibody op te drijven door de introductie van meer nauwkeurige parameterwaarden (massa, zwaartepunten, traagheidmomenten en traagheidsproducten, dempingzwaarden en stijfheden van de banden, de ophangingen, betere bandenmodellen, …). Deze laatste zou kunnen worden opgelost door het opzetten van uitgebreide experimenten voor het nauwkeurig bepalen van deze parameters.

Het model van de zelfrijder was in de eerste plaats ontwikkeld als hulpmiddel voor het ontwerp van excitatie wegprofielen of tracks. De getrokken spuit werd voornamelijk gebruikt om de optimale positie en het aantal sensoren vast te leggen en dit voor het meten van de mechanische integriteit van spuitbomen en hun suspensie en voor het evalueren van de ontwikkelde tracks.

C.2. Afleiding van representatieve wegprofielen gebruikt als excitatiebron voor de te testen spuitmachine

Momenteel wordt de ISO5008 track gebruikt voor het testen van het dynamisch gedrag van mobiele spuitmachines. . Vanuit een stochastisch standpunt was deze track niet rijk genoeg zodat niet alle modes op en spuitmachine konden worden geëxciteerd op een correcte wijze.
Representatieve tracks werden ontwikkeld volgens een unieke procedure:

- Het meten van de verticale (rollen) en horizontale (gieren) boom trillingen van verschillende spuitmachines onder verschillende veldcondities. De nieuw ontwikkelde tracks moeten in staat zijn realistische boombewegingen t induceren.
- Het traditioneel afleiden van tracks is een zeer tijdrovend werk. Gelukkig werd een geformaliseerde procedure voor het afleiden van representatieve tracks voorgesteld, "Service load simulation" genoemd. De procedure werd ontwikkeld voor wegtransport en werd voor de eerste keer toegepast in dit project op landbouwmachines. Normalerwijze dient men te beschikken over een vierposter elektro-hydraulische schudstand voor het iteratief reproduceren van opgemeten versnellingen op de wielassen. De verticale beweging van iedere hydraulische cilinder onder de wielen van het voertuig De verticale beweging van iedere hydraulische cilinder vertegenwoordigt een wieltrack. Voor zware machines was er helaas geen schudstand voorhanden. In dit project, werd de machine

vervangen door het multibody model waarmee de opgemeten verticale versnellingen van de wielassen werden gereproduceerd door een virtuele vierposter geplaatst onder de wielen van het model. De verticale beweging van iedere poster vertegenwoordigde een wieltrack. Ondanks het feit dat het EUROTRACK model niet zo nauwkeurig was, versnellingen aan de wielassen konden zeer nauwkeurig worden gereproduceerd door de introductie van vier terugkoppelkringen waardoor de robuustheid van de reproductieprocedure tegen modelonzekerheden sterk toenam. De procedure, gebaseerd op multibody modellen is uniek.

- Uit de bekomen informatie werden 16 korte tracks gegenereerd met de vorm van een multisine en een blokprofiel waarvan het spectrum zo dicht mogelijk lag bij dat van de gereproduceerde. Als belangrijke conclusie kon men stellen dat eenvoudige blokprofielen een even rijk spectrum hebben als enig ander type track (vb. multisine). Dit is een belangrijke conclusie vanuit een praktisch standpunt (gemakkelijk te construeren, …).
- Twee virtuele tracks die op de meest performante wijze realistische boombewegingen konden reproduceren werden geselecteerd met de het model van de getrokken spuitmachine. Ondanks het feit dat de twee geselecteerde tracks een veel rijker spectrum hebben dan de ISO5008 track, waren zij niet in staat bevredigende resultaten af te leveren (i.e. de reproductie van realistische boombewegingen) in het bijzonder het rollen van de boom. Hieruit mogen we besluiten dat de ontwikkeling van representatieve tracks niet mag worden gebaseerd op één machine.
- Finaal werd een blokprofiel met een constante blokhoogte van 5 cm en een lengte van 51.2 m gebouwd met een aanpasbare afstand tussen en lengte van de blokken.
- De ontwikkelde track werd getest op het einde van het project. De opgemeten boombewegingen van een getrokken spuit tijdens rijden over de track, werden opgemeten. Deze opgemeten boombewegingen waren heftiger dan deze opgemeten onder veldcondities in het bijzonder de trillingen tussen 0.1 en 0.2 Hz. Dit probleem kan worden opgelost door het afronden van de hoeken van de blokkenen/of door het verlagen van de blokken (vb. het opvullen van de ruimte tussen de blokken, ..). .

C.3. Bepaling van het type te gebruiken sensoren, hun aantal en hun positie op de spuitmachine

- Radar sensor: vast verbonden met het frame van de spuitmachine of aan de tractor (getrokken spuit), meet de rijsnelheid van de machine.
- Gyroscoop: vast verbonden met het frame van de spuitmachine of met een vast gedeelte van de machine, meet het gieren en rollen.
- Ultrasone afstandssenoren: symmetrisch geplaatst op de spuitboom op een minimale afstand van 45 cm van het ophangcentrum van de boom, meten de relatieve verplaatsing van de boom t.o.v. de machine.
- Vijf versnellingsopnemers: geplaatst op vijf verschillende vooraf gedefinieerde locaties op de spuitboom, meten de absolute horizontale boomversnellingen.
- Twee versnellingsopnemers: geplaatst op twee vooraf gedefinieerde locaties op de spuitboom, meten de absolute verticale boombewegingen.
- Infrarood sensor: geplaatst op de suspensie, meet de afstand gerelateerd met de relatieve inclinatie tussen de boom en het frame van de spuitmachine. Een gedetailleerde procedure werd beschreven voor het calibreren van de infrarood sensor.

Volgens de meest recente literatuur is het de eerste maal dat een dergelijke gedetailleerde procedure voor het meten van boombewegingen werd beschreven.

C.4. Ontwikkeling van betrouwbare spuitdepositiemodellen voor het simuleren, van het spuitpatroon als functie van boomtrillingen

In een volgende fase, na het registreren van de horizontale en verticale boombewegingen van d beschouwde spuitmachine, moeten deze boomewegingen worden gerelateerd aan een zogenaamd dynamisch spuitpatroon. Het is uiterst moeilijk om deze laatste rechtstreeks te berekenen. Om dit te verhelpen werd een indirecte methode uitgewerkt in vier stappen:

- Registratie van een statisch spuitpatroon van verschillende spuitdoppen. Gebaseerd op een 2D-scanner, ontwikkeld aan de Universiteit van Uppsala in het kader van het SPECS project, werd een vernieuwde en verbeterde versie geconcipieerd. De scanner bestaat uit 24 vloeistofbuisjes die tijdens het spuitexperiment worden gevuld met vloeistof verspoten door de beschouwde spuitdop. Tijdens de meetsessie wordt de scanner een welbepaald aantal keer met regelmatige tijdsintervallen onder de spuitdop verplaatst. De scanner laat toe het statisch spuitverdeelpatroon te registreren van om het even welk type spuitdop aan een zekere vloeistofdruk en hoogte van de spuitdop door het registreren van de evolutie van de vloeistofhoogte in de buisjes. Het registreren van één statisch verdeelpatroon duurt tussen de 2 à 4 uur. Daar het verbeteren en verfijnen van de SPECS scanner vrij veel tijd in beslag nam werden enkel rond de 20 statische spuitpatronen opgemeten.
- Het voorbereiden van de data voor het afleiden van het dynamisch spuitverdeelpatroon. Deze data worden opgenomen in een data matrix in excel (de 24 buisjes van de scanner x het aantal stappen die de scanner heeft uitgevoerd).
- Een wiskundige relatie tussen het statisch en dynamisch spuitpatroonmodel werd afgeleid door F. Lebeau wiens model een verbetering is van het model van H. Ramon.
- Een methodologie voor de validatie van het dynamisch spuitpatroonmodel werd uitgewerkt. Een laboratorium proefstand, met als doel de validatie onder meer gecontroleerde omstandigheden uit te voeren, werd geconstrueerd. De calibratie van de stand en de hierop volgende experimenten konden nog niet worden uitgevoerd. Het experiment maakt gebruik van het verschil in capaciteit tussen twee staalplaten afhankelijk van de hoeveelheid gedemineraliseerd water dat zich tussen de platen bevindt. Het principe is niet nieuw maar de precisie werd significant verhoogd in vergelijking met de reeds bestaande teststanden door het gebruik van kleinere staalplaten. Daarenboven kan een grote oppervlakte van 5x1.2m worden opgemeten in één test in plaats van een smalle strip. Drie vedtesten werden onderzocht. In de eerste test of de mineraal tracer test, rijdt de spuitmachine over een houten geraamte bedekt met speciaal waterabsorberend papier, dat wordt bespoten met mineraalwater. Door een chemische analyse van het papier, waarop de tracer werd geënt, worden de ongewenste boombewegingen tijdens het spuiten gekwantificeerd. Het aantal experimenten werd echter beperkt door de hoge kostprijs van de mineraal tracer. In de tweede test werden watergevoelige papierstroken bevestigd op houten latten op regelmatige afstanden in het veld. Na het spuiten werden de stroken geanalyseerd met behulp van beeldverwerkingstechnieken. Een volledig 2D spuitverdeelpatroon werd afgeleid door interpolatie van de opgemeten data. Deze methode is goedkoop maar levert enkel kwalitatieve resultaten op. In de derde methode werd een pesticide gespoten terwijl de boombewegingen werden opgemeten. Deze laatste werden geïnduceerd door het rijden van de spuitmachine tijdens de test over houten obstakels en door smalle grachten. In dit onderzoek werd een round-up gebruikt waarvan het effect met succes kon worden gereproduceerd door het dynamisch spuitverdeelmodel.

C.5. Vastleggen van de maximale toleranties voor de variatie in het spuitvloeistofverdeelpatroon onder een spuitboom

Veldexperiment drie bleek bruikbaar voor het determineren van de relatie tussen boom bewegingen en de efficiëntie van het gebruikte pesticide. In dit project werd enkel round-up gebruikt. In meer uitgebreide experimenten dient de relatie tussen boombewegingen en de efficiëntie van andere pesticiden meer in detail te worden onderzocht. Uit dit onderzoek moeten we echter concluderen dat beter een aantal fytopathologen werden betrokken in het project om de relatie tussen toelaatbare boombewegingen en de efficiëntie van de gebruikte pesticides af te leiden. Finale richtlijnen met betrekking tot toelaatbare boombewegingen is echter een internationale aangelegenheid waarbij de projectresultaten en ontwikkelde methodologieën een significante bijdrage kunnen leveren daar het, in opvolging van het

SPECS project, een goed uitgewerkte en systematische procedure heeft ontwikkeld voor het vastleggen van toelaatbare boombewegingen.

C.6. Ontwikkeling van een teststand voor een snelle registratie van de mechanische status van spuitmachines

Het finaal resultaat van het project omvat een gedetailleerde beschrijving van een testprocedure met de noodzakelijke uitrusting voor het evalueren van de mechanische status van spuitmachines. De voorgestelde procedure is uniek in de zin dat zij voor de eerste keer praktisch uitvoerbaar werd. De procedure zelf omvat de volgende stappen:

- Beschrijving en calibratie van de gebruikte sensoren samen met de data acquisitie apparatuur en de kracht bron.
- Beschrijving van een test track met rijsnelheid voor de excitatie van de spuitmachine.
- Plaatsing van de sensoren en data acquisitieapparatuur op de machine.
- Beschrijving van de configuratie van de boom en de ophanging tijdens de voorbereidingen en de uitvoering van de test.

D. Bijdrage van het project in een context van ondersteuning aan het proces inzake normalisatie en technische regelgeving

- Eerste wetenschappelijk gebaseerde ontwikkeling van excitatietracks bestaande uit een eenvoudig blokprofiel, voor terreinvoertuigen, gebaseerd op “service road simulation”, met behulp van multibody modellen van twee spuitmachines.
- Uitgebreide metingen van verticale en horizontale boombewegingen onder diverse veldomstandigheden met verschillende sensoren.
- Bepaling van het type en aantal gebruikte sensoren samen met hun locatie op de machine en de boom om op een betrouwbare wijze boombewegingen te registreren.
- Verfijning van bestaande laboratoriumuitrusting voor het registreren van het statisch spuitpatroon van spuitdoppen (i.e. de 2D scanner) en het dynamisch spuitpatroon, deze laatste gebaseerd capaciteitsmetingen.
- Een dynamisch spuitpatroon model, ontwikkeld door Lebeau, gebaseerd op het statisch spuitpatroon van een spuitdop.
- Evaluatie van drie veldtesten voor de validatie van het dynamisch spuitpatroon model.
- Beschrijving van een methodologie voor het formuleren van richtlijnen en standaarden voor toelaatbare boombewegingen, afgeleid van de maximaal aanvaardbare ongelijkmatigheden in het verdeelpatroon van de spuitvloeistof.
- Beschrijving van een methodologie voor een snelle test van de mechanische status van veldspuitmachines.

E. Trefwoorden

Getrokken spuitmachine, zelfrijdende spuitmachine, veldspuitmachine, spuitboom, frame van de spuitmachine, boomsuspensie (ophanging), vloeistoftank, ongewenste horizontale (stoten, gieren), en verticale (rollen, dansen) spuitboombewegingen, multibody modellen, elektro-hydraulische schudstand (vierposter, éénposter), excitatie track (multisinus, blok profiel), 2D scanner, statisch en dynamisch spuitvloeistofdistributiemodel, capaciteitsmethode, mechanische status van een spuitmachine, data acquisitie, vermogenspectrum van een signaal, veldexperimenten, watergevoelig papier, maximaal toelaatbare toleranties in het spuitpatroon, sensoren (versnellingsopnemer, ultrasone sensor, infrarood sensor, radar, gyroscoop).

RESUME

A. Contexte

A.1. Les mouvements de rampes de pulvérisation, une cause majeure de répartition non homogène des produits pulvérisés

Suite à la croissance exponentielle de la population mondiale et aux exigences de plus en plus poussées en matière de qualité des produits alimentaires, les techniques de traitement chimique des cultures sont aujourd'hui l'une des principales opérations culturales. On compte environ 400 000 pulvérisateurs agricoles dans l'UE pour l'application des produits phytopharmaceutiques. Ils sont équipés de rampes de pulvérisation de plus en plus larges. L'utilisation d'agents actifs concentrés (techniques de pulvérisation à volume réduit), l'augmentation du coût des matières actives et l'impact environnemental de ces produits seront vraisemblablement à la base de spécifications techniques plus contraignantes pour les pulvérisateurs, dans un futur proche.

Il est nécessaire de réduire les variations de répartition au sol du produit pulvérisé pour limiter les résidus sur les cultures. Les principales causes de répartition non homogène des pesticides sont les suivantes:

- les variations de vitesse d'avancement et les défectuosités des organes hydrauliques (buses usées, défauts techniques de la pompe et des valves, fuites au niveau des tuyaux,...);
- les facteurs environnementaux, comme le vent qui modifie la trajectoire des gouttelettes;
- les vibrations de la rampe de pulvérisation en cours de travail, causées principalement par l'inefficacité de la suspension ou des défauts mécaniques (charnières usées, rampe déformée...).

Lors de la recherche, l'accent a été mis sur ce dernier aspect. En effet, en cours de travail, les vibrations du tracteur, provoquées principalement par les inégalités du terrain, induisent des mouvements indésirables de la rampe et causent localement des surdosages et des sous-dosages du produit pulvérisé. Les mouvements de rampe peuvent être subdivisés en mouvements verticaux et horizontaux. Les mouvements verticaux, comme *le roulis*, provoquent des variations locales de répartition comprises entre 0 et 1000 % et les mouvements horizontaux, comme *le lacet*, donnent lieu à des variations locales se situant entre 20% et 600% (100% étant la dose de consigne). Ces mouvements résultent essentiellement de l'inefficacité de la suspension ou de défauts mécaniques (segments de la rampe déformés de façon permanente, charnières bloquées dans une mauvaise position ou jeu excessif, ressorts et amortisseurs usés,...).

A.2. Contrôle technique des pulvérisateurs agricoles

L'état des organes hydrauliques de tous les pulvérisateurs en service est régulièrement contrôlé dans plusieurs pays européens, dont la Belgique, l'Allemagne et les Pays-Bas, selon une procédure obligatoire. Celle-ci a pour objet de détecter les variations de pression le long de la rampe, la distribution du produit pulvérisé, l'usure des buses et d'autres défauts qui influencent la répartition dans des **conditions statiques**.

Bien que les mouvements de rampe indésirables affectent considérablement la répartition du produit, les procédures d'évaluation de la stabilité mécanique ou de l'état structurel des rampes ne sont pas encore incluses dans les procédures de contrôle actuelles. Pour limiter les mouvements des rampes de pulvérisation dans des limites acceptables, les rampes doivent être correctement conçues. Elles doivent aussi être bien entretenues, ce qui ne peut être garanti que par une inspection régulière des performances de la suspension, par la vérification de l'état des charnières, des systèmes de verrouillage, des ressorts et des amortisseurs. Un groupe de travail au sein du CEN TC 144/WG3 travaille actuellement à l'harmonisation des critères de test à travers l'Europe.

Des recherches ciblées sur les mouvements de rampes et les variations consécutives de la répartition ont été entamées au sein du projet AIR3-CT94-1170 "European System for Field Sprayers Inspection at the Farm Level (SPECS)" financé par l'UE. Dans ce projet coordonné par le Laboratorium of Agro-Machinery and –Processing de la K.U.Leuven, six groupes de recherches leaders dans l'étude des techniques de pulvérisation ont démarré le développement d'une procédure systématique de test de la stabilité mécanique des pulvérisateurs en service à la ferme. Au stade final de la recherche, deux procédures de test ont été développées dans l'optique d'évaluer la faisabilité de l'intégration d'une inspection standardisée de l'état mécanique de pulvérisateurs neufs et usagés, dans les inspections actuelles. Néanmoins, les deux procédures montrent des insuffisances qui doivent être comblées avant d'être applicables dans les tests de routine.

A.3. Insuffisances des procédures de test du projet SPECS

A.3.1. Sollicitations d'entrée

Lors du déplacement d'un pulvérisateur, les inégalités du terrain induisent des vibrations au niveau des pneumatiques qui sont amplifiées par la rampe. Dans le projet SPECS, la piste normalisée ISO 5008 a été utilisée comme sollicitation d'entrée. Néanmoins, cette piste n'est pas adaptée car sa densité de puissance spectrale montre l'absence de fréquences importantes dans la bande de fréquence d'intérêt. Ceci implique que les fréquences propres du pulvérisateur, prépondérantes entre 0 Hz et 5 Hz, ne sont pas excitées correctement. Les signaux d'entrée appliqués à la suspension de la rampe de pulvérisation ont également été évalués. Cependant, il est clair que ces sollicitations ne peuvent être utilisées que lorsque la rampe de pulvérisation n'est pas couplée avec la machine, ce qui s'avère inutilisable en pratique.

A.3.2. Analyse modale expérimentale

Dans la première procédure du projet SPECS, le pulvérisateur testé est excité par un shaker mobile. Les sollicitations d'entrée (forces) et les réponses (accélérations) sont mesurées à des emplacements appropriés dans les directions longitudinale et verticale. A partir de ces signaux d'entrée-sortie, des modèles expérimentaux sont construits et utilisés pour simuler les mouvements horizontaux de moutonnement et de lacet. Ensuite, les vibrations de la rampe simulées sont utilisées pour calculer la répartition du produit pulvérisé à partir de laquelle les conclusions concernant la stabilité mécanique du pulvérisateur sont tirées. Des modèles linéaires dynamiques de pulvérisateurs sont déduits par analyse modale expérimentale (AME). En réalité, les pulvérisateurs sont sollicités directement par les inégalités du terrain qui sont des déplacements et non des forces et, par conséquent, l'AME n'est pas la méthode la plus appropriée pour construire un modèle reproduisant le comportement dynamique d'un pulvérisateur.

A.3.3. Circuit d'inspection par caméra

La deuxième procédure du projet SPECS consiste à faire rouler le pulvérisateur sur un obstacle en enregistrant les mouvements horizontaux et verticaux des extrémités de la rampe à l'aide d'une caméra. Néanmoins, les résultats de cette méthodologie n'ont pas pu être entièrement évalués et comparés à la méthode basée sur l'analyse modale par manque de temps. De plus, l'étalonnage du système de mesure des mouvements s'avère délicat. Finalement, il est clair qu'un obstacle n'est pas une piste représentative et que le mouvement d'une extrémité de rampe ne permet pas de déduire les vibrations des autres segments de la rampe (jeu et mouvements des articulations, déformation des segments, ...).

A.3.4. Modèles de répartition du produit pulvérisé

Dans le projet SPECS, des modèles mathématiques ont été développés pour simuler la répartition du produit en fonction de la vitesse du tracteur et des mouvements de roulis et de lacet de la rampe. Des validations expérimentales ont montré que, sous certaines conditions, ces modèles ne génèrent pas de signaux de sortie valables, essentiellement parce que des paramètres importants qui contribuent de façon significative à la répartition du produit n'ont pas été introduits dans le modèle.

B. Objectifs

B.1. Objectif global de la proposition de recherche

L'objectif global de la proposition concerne l'amélioration et l'extension de la méthodologie développée dans le projet susmentionné AIR3-CT94-1170 pour évaluer la stabilité mécanique des pulvérisateurs agricoles neufs et en service. Plus précisément, il est souhaitable que la procédure devienne applicable dans les tests de routine, puisse être utilisée pour définir les mouvements acceptables des rampes de la rampe et offre la possibilité d'être intégrée dans les inspections actuelles (obligatoires ou volontaires) des pulvérisateurs.

B.2. Sous-objectifs de la proposition de recherche

- Développement de modèles mathématiques multi-corps d'un pulvérisateur automoteur et d'un pulvérisateur traîné qui seront utilisés pour définir une piste représentative et optimiser la position des capteurs mesurant les mouvements de la rampe.
- Design d'une piste représentative qui puisse être utilisée comme source d'excitation pour les tests de pulvérisateurs. Cette piste aura les mêmes caractéristiques stochastiques que les irrégularités de terrain sur lesquelles se déplacent les pulvérisateurs.
- Détermination des types de capteurs nécessaires pour mesurer les mouvements de rampe (accéléromètres, capteurs optiques tels que caméra, distance mètres laser, infrarouge, ultrasonique), de leur nombre et leur position sur le pulvérisateur en effectuant des tests de terrain combinés avec les modèles mathématiques. Les capteurs seront utilisés pour caractériser la stabilité des pulvérisateurs testés.
- Développement de modèles fiables de répartition du produit pulvérisé pour simuler la répartition en fonction des vibrations de la rampe.
- Définition des tolérances maximales pour les variations de la répartition sous une rampe de pulvérisation en fonctionnement, c'est-à-dire en conditions dynamiques, basées sur des mesures de terrains effectuées dans des conditions variées.
- Développement d'une méthodologie de test rapide de la stabilité des pulvérisateurs. Cette méthodologie comportera quatre étapes majeures: l'excitation du pulvérisateur qui parcourt une piste pourvue d'obstacles, l'enregistrement des mouvements de la rampe, le traitement des données, la simulation de la répartition résultante et la formulation d'un label de qualité pour la machine testée.

C. Conclusions

C.1. Modèles multicorps d'un pulvérisateur traîné et d'un pulvérisateur automoteur

Des modèles multicorps d'un pulvérisateur traîné de la société Beyne et d'un pulvérisateur automoteur "EUROTRAC" de la compagnie Delvano ont été construits respectivement avec les logiciels ADAMS (Mechanical Dynamics) et DADS.

Le modèle du pulvérisateur traîné comprend deux parties: un modèle détaillé de la rampe et de la suspension, dans lequel tous les paramètres de masse, de frottement,… sont évalués par voie expérimentale, et un modèle global du châssis du tracteur et du pulvérisateur, incluant les pneumatiques. Dans la première partie, le roulis de la rampe et des autres mouvements verticaux sont évalués avec précision, mais la prédiction des mouvements horizontaux n'est pas aussi fiable. Le roulis du châssis est estimé correctement mais le modèle n'a pas pu donner de résultat précis pour le lacet.

Dans le modèle de l'EUROTRAC, la partie tracteur a été modélisée avec beaucoup d'attention et de détail. Le modèle de la rampe et de la suspension était moins détaillé. Les paramètres inconnus ont été estimés grâce à une procédure d'optimisation dans OPTIMUS, à partir de mesures de vibrations effectuées sur la machine. Un shaker monoposte a été conçu à cette fin. Le roulis du tracteur, le pompage du tracteur, et le roulis de la rampe ont pu être prédits avec précision. La prédiction du moutonnement et du lacet du tracteur n'a pas donné de résultats fiables.

A partir des résultats, on peut conclure que les modèles multicorps sont un outil intéressant pour la prédiction du comportement dynamique des pulvérisateurs. Néanmoins, la précision du comportement dynamique des deux pulvérisateurs dépend des modes considérés. Si les vibrations de roulis et de pompage ont pu être correctement prédites, celles de lacet et de moutonnement sont beaucoup plus difficiles à estimer. La précision des modèles pourrait être améliorée en augmentant le nombre de degrés de liberté pris en compte et en utilisant des valeurs plus précises pour les paramètres (masses, centres de masse, moments d'inertie des différents corps, coefficients d'amortissement et raideurs des pneus et des suspensions, meilleurs modèles de pneumatiques, ...). Ce problème pourrait être (en partie) résolu par la mise en place de tests étendus pour la détermination précise de ces paramètres.

Le modèle du pulvérisateur automoteur a été utilisé pour définir les caractéristiques de la piste d'excitation d'un point de vue conceptuel. Le modèle du pulvérisateur traîné a été utilisé pour déterminer la position optimale des capteurs pour mesurer la stabilité mécanique de la rampe de pulvérisation et de sa suspension, ainsi que pour évaluer la piste de test.

C.2. Design d'une piste représentative comme source d'excitation de pulvérisateur

Actuellement, la piste ISO5008 est utilisée pour tester le comportement dynamique des véhicules agricoles. D'un point de vue stochastique, cette piste ne présente pas une gamme d'excitation suffisamment large pour que les tous les modes principaux d'un pulvérisateur agricole soient excités de façon satisfaisante.
La piste représentative a été conçue en mettant en œuvre la procédure originale suivante :

- Mesure des vibrations verticales (roulis) et horizontales (lacet) de différents pulvérisateurs agricoles dans différentes conditions expérimentales. La piste développée doit être capable de reproduire des vibrations similaires (réalistes).
- Le calcul traditionnel d’une piste d'excitation est un travail pénible et extrêmement long. Une procédure pré-établie appelée "service load simulation", utilisée en industrie automobile, a été utilisée pour la première fois pour des véhicules agricoles dans ce projet. En principe, un shaker électro-hydraulique à 4 postes devrait être disponible pour reproduire de façon itérative les accélérations mesurées au niveau des essieux. Le mouvement vertical de chaque vérin sous les pneus du véhicule est une représentation de la piste sous la roue. Pour les véhicules lourds, un shaker à 4 postes puissant est nécessaire. Dans ce projet, le véhicule réel a été remplacé par son modèle multicorps. Les accélérations aux essieux ont été obtenues en plaçant un shaker à 4 postes virtuel sous les pneumatiques dans le modèle. Le mouvement vertical de chaque poste était une représentation de la piste sous la roue. Bien que le modèle Eurotrack ne soit pas très précis, les accélérations au niveau des essieux ont pu être reproduites très

précisément par l'introduction de quatre systèmes de contrôle avec asservissement, augmentant la robustesse de la procédure de reproduction et palliant aux imprécisions du modèle. Cette procédure, basée sur l'utilisation d'un modèle multicorps, est originale.

- Sur la base de ces informations, 16 pistes courtes conçues sur le modèle multisinusoïdal ou munies d'obstacles ont été déduites, avec une densité de puissance spectrale aussi proche que possible de celle des pistes reproduites. Une conclusion importante est qu' une piste munie d'obstacles simples peut reproduire un spectre aussi riche que n'importe quel autre type de piste (ex. multisinusoïdal), ce qui est intéressant d'un point de vue pratique (facilité de construction, ...).
- Les deux pistes virtuelles qui reproduisaient le plus précisément les mouvements réels d'une rampe de pulvérisation ont été sélectionnées et ont servi d'entrée au modèle de pulvérisateur traîné. Bien que le contenu fréquentiel des pistes sélectionnées soit plus riche que celui de la piste ISO 5008, les résultats n'ont pas été satisfaisants, en particulier pour le roulis de la rampe.
- Finalement, une piste à obstacles d'une hauteur constante de 5 cm et d'une longueur de 51.2 m a été construite. La distance entre les blocs et leur longueur sont modulables.
- La piste conçue a été testée. Les mouvements de la rampe d'un pulvérisateur traîné ont été mesurés lorsque celui-ci parcourait la piste. Ces mouvements étaient plus élevés sur la piste que sur le terrain, particulièrement entre 0.1 et 0.2 Hz. Ce problème pourrait être résolu en adoucissant les arêtes des obstacles et en réduisant leur hauteur (ex. en remplissant les espaces entre les blocs).

C.3. Détermination des types de capteurs à utiliser, leur nombre et leur position sur le pulvérisateur

Une chaîne complète de mesure a été mise au point pour mesurer les mouvements des rampes en conditions dynamiques. Elle comporte les capteurs suivants, dont les signaux sont traités par *fusion de capteurs* :

- Un capteur radar rigidement fixé au châssis du pulvérisateur ou au tracteur (porté et traîné) mesure la vitesse d'avancement du véhicule.
- Un gyroscope électronique, rigidement fixé au châssis du pulvérisateur ou à un organe rigidement fixé au châssis, mesure le roulis et le lacet.
- Des capteurs de distance à ultrasons sont placés symétriquement sur la rampe de pulvérisation de part et d'autre du centre, à une distance minimale de 45 cm, ils mesurent la distance relative entre la rampe et le châssis du véhicule.
- Cinq accéléromètres: placés à cinq emplacements prédéfinis sur la rampe de pulvérisation, ils mesurent les accélérations absolues horizontales.
- Deux accéléromètres placés à deux emplacement prédéfinis sur la rampe de pulvérisation mesurent les accélérations absolues verticales.
- Un capteur de distance infrarouge placé au niveau de la suspension mesure l'inclinaison relative entre la rampe et le châssis du pulvérisateur par l'intermédiaire d'une courbe d'étalonnage.

Par rapport à la littérature la plus récente, c'est la première fois qu'une procédure aussi précise est mise au point pour la mesure des mouvements d'une rampe de pulvérisation.

C.4. Développement de modèles de répartition dynamique pour simuler la répartition du produit pulvérisé en fonction des mouvements de la rampe

Une fois enregistrés, les mouvements horizontaux et verticaux du pulvérisateur doivent être mis en correspondance avec un modèle de répartition dynamique. Ce dernier est extrêmement difficile à obtenir directement. Par conséquent, le choix d'une méthode indirecte a été favorisé. Elle comprend 4 étapes:

- La mesure et l'enregistrement de la distribution statique de différentes buses. Sur la base d'un scanner 2D développé à l'Université d'Uppsala en Suède dans le cadre du projet SPECS, un scanner 2D entièrement retravaillé a été conçu. Il consiste en 24 tubes qui sont remplis de liquide par la buse de pulvérisation. Le scanner se déplace sous la buse avec un nombre de pas prédéterminé durant l'expérimentation. Il permet de mesurer la répartition statique de n'importe quel type de buse à une pression et une hauteur déterminées en enregistrant l'évolution de la hauteur de liquide dans les tubes au cours du temps. Le temps nécessaire pour enregistrer la distribution statique varie de 2 à 4 heures. Comme l'amélioration du scanner 2D a pris beaucoup de temps, seulement 20 répartitions statiques de buses différentes ont pu être mesurées jusqu'à ce jour.

- La préparation des données pour le développement du schéma de distribution dynamique de la buse. Les données devraient être présentées sous forme d'une matrice dans Excel (24 hauteurs de liquides du scanner x le nombre de pas d'avancement du scanner).
- Un modèle mathématique établissant une relation entre la distribution de la buse et la répartition dynamique a été établi par F. Lebeau. Il s’agit d’une amélioration du modèle de H. Ramon.
- Une méthodologie pour la validation de la distribution dynamique a été définie. Un dispositif de laboratoire destiné à la validation dans des conditions sévèrement contrôlées a été construit mais l'étalonnage et les essais n'ont pas encore pu être réalisés. Le dispositif fait usage de la différence de capacité entre deux plaques d'acier qui dépend de la quantité d'eau déminéralisée présente entre les deux plaques. Le principe n'est pas nouveau mais la précision est améliorée significativement en comparaison avec les dispositifs existants qui utilisent des plaques d'acier plus petites. De plus, une surface de 5 x 1.2 m peut être mesurée en un seul test au lieu d'une bande réduite. Trois types d'essais en champ ont été examinés. Lors du premier test, ou test par traceur minéral, la rampe du pulvérisateur passe au-dessus de châssis en bois couverts de papiers qui servent de récepteur à l'additif chimique ajouté dans la cuve. Par l'analyse chimique des papiers, les mouvements indésirables de la rampe pendant la pulvérisation ont pu être identifiés. Malheureusement, c'est une méthode coûteuse, ce qui limite le nombre d'expériences. Lors du deuxième test, des bandelettes de papier hydrosensible sont fixées à des châssis en bois et disposées à intervalles réguliers dans le champ. Après la pulvérisation, les bandelettes sont observées avec des techniques d'analyse d'images. Un schéma complet de distribution 2D a été obtenu par interpolation à partir des emplacements de mesures. Cette méthode est peu coûteuse mais ne donne que des résultats qualitatifs. La troisième méthode utilise un pesticide qui est appliqué tandis que les mouvements de rampe sont mesurés simultanément. Les mouvements de rampe ont été induits par le franchissement d'obstacles en bois ou de petites ornières. Pour cette recherche, le produit Round Up a été utilisé et son effet a été reproduit avec succès par le modèle de répartition dynamique.

C.5. Etablissement des tolérances maximales pour les variations au sein de la répartition du produit sous une rampe de pulvérisation pendant le traitement

Trois expériences de terrain ont été utilisées pour établir la relation entre les mouvements de rampe et l'efficacité du pesticide. Seul le Round Up a été utilisé. La relation entre les mouvements de rampe et l'efficacité d'autres pesticides doit être recherchée avec des tests plus poussés. Il serait souhaitable que des phytopathologistes soient inclus dans ce genre de projet pour établir la relation entre les mouvements acceptables des rampes de pulvérisation et l'efficacité du pesticide.
Les directives finales concernant les mouvements de rampe acceptables ont néanmoins un caractère international, dans la mesure où les résultats du projet et les méthodologies développées apportent une contribution significative.

C.6. Développement d'un circuit de test pour le test rapide de l'état mécanique des pulvérisateurs

Le résultat final du projet comprend une description détaillée de la procédure de test avec l'équipement nécessaire (les capteurs) pour évaluer la stabilité mécanique des pulvérisateurs. Notons qu'il s'agit de la première fois qu'une procédure systématique et complète d'évaluation de la stabilité mécanique des rampes en mouvement est mise en œuvre. Cette procédure comporte les étapes suivantes:

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- Description et étalonnage des capteurs utilisés pour l'acquisition des données servant à la mesure des mouvements de rampe, ainsi que des équipements annexes.
- Description de la piste de test avec la vitesse d'avancement proposée pour solliciter le pulvérisateur.
- Placement des capteurs et du matériel d'acquisition sur la machine.
- Mesure de la configuration de la rampe et de la suspension (simultanément avec le placement des capteurs)

D. Contribution du projet dans un contexte de support au processus de normalisation et de contrôle technique

- Premier développement scientifique de pistes d'excitation à obstacles modulaires pour véhicules tout-terrain (agricoles) sur la base de simulation à l'aide de modèles multicorps de deux types de pulvérisateurs.
- Mesure des mouvements verticaux et horizontaux de rampes de pulvérisation dans une très large gamme de conditions de terrains avec plusieurs types de capteurs.
- Sélection du type, du nombre de capteurs utilisés, de leur disposition sur le pulvérisateur pour mesurer de façon fiable les mouvements de rampe ; mise au point de méthodes de traitement des signaux efficiente.
- Amélioration de matériel de laboratoire existant pour la mesure du schéma de distribution statique (c.à.d. le scanner à jet 2D) et du schéma de distribution dynamique du liquide pulvérisé.
- Modèle de distribution dynamique basé sur une méthodologie développée par F. Lebeau.
- Amélioration et modification du dispositif de laboratoire basé sur la mesure de capacité pour la mesure du schéma de distribution dynamique.
- Evaluation de trois techniques de terrain différentes pour l'évaluation du schéma de distribution dynamique en champ.
- Etablissement d'une méthodologie pour obtenir les directives et/ou une norme concernant les tolérances acceptables sur les mouvements de la rampe de pulvérisation à partir des inégalités maximales acceptables dans la répartition du produit pulvérisé.
- Etablissement d'une méthodologie pour le test rapide de l'état mécanique des pulvérisateurs agricoles.

E. Mots-Clés

Pulvérisateur traîné, pulvérisateur automoteur, pulvérisateur agricole, pulvérisateur, rampe de pulvérisation, châssis du pulvérisateur, suspension de rampe, cuve de pulvérisation, mouvements (indésirables) de la rampe, lacet, roulis, pompage, moutonnement, modèle multicorps, shaker électro-hydraulique (à un et quatre postes), piste d'excitation, piste à obstacles, piste multisinusoïdale, scanner 2D, modèle de répartition statique, modèle de répartition dynamique, distribution statique, distribution dynamique, méthode capacitive, stabilité mécanique des pulvérisateurs, état mécanique des pulvérisateurs, acquisition de données, mesure de mouvements de rampe, densité de puissance spectrale, tests en champ, papier hydrosensible, tolérances maximales pour les variations de la répartition dynamique, capteurs, accéléromètre, capteur de distance à ultrasons, capteur de distance à infrarouge, radar, gyroscope, fusion de capteurs.

1 INTRODUCTION

1.1 SPRAY BOOM MOTIONS, A MAJOR CAUSE OF AN IRREGULAR SPRAY DISTRIBUTION

An exponentially growing world population and constantly increasing food quality requirements made chemical crop protection become one of the most important field operations. Field sprayers, equipped with large spray booms are used worldwide for the application of phytopharmaceutical products to agricultural crops. In the EC there are approximately 400.000 field sprayers in operation.

New tendencies towards the use of concentrated spraying agents (small volume spraying techniques), together with the increasing cost of chemicals and pollution pressure on the environment impose more severe technical requirements to spraying-machines in the near future. Spray deposit variations as they occur nowadays are intolerable for these applications for the sake of excessive residues and crop damage. The problem of an unequal distribution of pesticides is mainly situated on three levels:

- variations in the travel speed of the machine and defects in the hydraulic equipment (worn nozzles, technical defect of the pump and valves, leaking hoses, …)
- environmental factors as wind influencing the travel distance of the droplets;
- vibrations of the spray boom during field operations, mainly caused by an ineffective suspension or by mechanical defects in the boom construction (worn hinges, boom deformation, ...).

During field operation, tractor vibrations, mainly effected by soil unevenness, induce undesired spray boom motions creating local under- and overdoses of spray liquid. Resulting spray boom motions can be divided into two main groups: vertical and horizontal boom movements. Vertical vibrations, as rolling, give rise to local variations in spray deposit between 0 % and 1000 % and horizontal vibrations, as yawing, between 20 % and 600 %, (100 % is ideal) and by this belong to the major causes of an irregular spray deposition.

Vibrations of the spray boom during field operations are mainly caused by an ineffective suspension or by mechanical defects (boom deformations, improperly locked hinges causing backlash in the hinges, worn springs and dampers,…).

1.2 INSPECTION OF FIELD SPRAYERS

The present hydraulic state of all sprayers in use is being inspected on regular basis in several European countries, including Belgium, Germany and the Netherlands, in a mandatory procedure. The mandatory inspection aims at checking hydraulic pressure variations along the boom, liquid distribution, nozzle wear and other defects, influencing the liquid distribution under static conditions. A CEN working group within CEN TC 144/WG3 is harmonising the today's used evaluation criteria throughout Europe.

Although unwanted spray boom vibrations dramatically effect the spray distribution pattern, procedures to evaluate the mechanical integrity or structural condition of booms are not included yet in current sprayer inspections. ***Therefore, to keep spray boom vibrations within tolerable margins, boom constructions should be properly designed and well maintained which can only be guaranteed by inspecting on a regular basis the performance of the suspension and the quality of the hinges and hinge locks, springs and dampers built in the boom structure.***

Unfortunately, still no standards have been formulated to establish the mechanical condition of operational spray boom constructions and new makes by which no procedures have yet been included in current sprayer inspections to evaluate the mechanical condition of spraying-machines.

Consistent research about boom vibrations and related spray distribution patterns has been initiated within the shared cost action AIR3-CT94-1170 "European System for Field Sprayers Inspection at the Farm Level (SPECS)", funded by the EC. In this project, six leading research groups in spraying techniques, co-ordinated by the K.U.Leuven, Laboratory of

Agro-Machinery and –Processing, started developing a systematic procedure for testing the mechanical integrity (i.e. condition) of operational sprayers at the farm level. In a final stage of this research project, two prototype test systems were developed with a view to evaluate the feasibility of integrating a standardised inspection for the mechanical status of sprayers in use and new makes, in current sprayer inspections. However, both procedures still show important insufficiencies which must first be solved before they become applicable in routine tests.

1.3 INSUFFICIENCIES OF THE TEST PROCEDURES OF THE SPECS PROJECT

1.3.1 Input disturbances

Soil and road unevenness induces vibrations on a spraying-machine crossing the field or moving on the road during transport. In vibration engineering, these are called systems with base motion since the input disturbances are displacements under the tires. In the SPECS project, the ISO 5008 standard tracks have been used as input excitations. These tracks are however not very reliable as their power spectrum shows the absence of important frequencies in the frequency band of interest (i.e. mainly between 0 Hz and 5 Hz) indicating that not all dominant natural frequencies of the structure between 0 Hz and 5 Hz will be excited equally. Representative input excitations at the suspension of the spray boom have also been derived. It is clear that these excitation signals can only be used when the spray boom is uncoupled from the machine which is unfeasible in practice.

1.3.2 Experimental modal analysis

In the first procedure, the tested spraying-machine is excited on a mobile shaker. During the experiment, input excitations and response accelerations on appropriate locations of the machine are registered in the longitudinal and the vertical direction as well. From these input-output signals, experimental models are built which are used to simulate longitudinal and yawing spray boom motions as a response to certain standardised input disturbances. In their term, simulated boom vibrations are used to calculate the corresponding spray distribution pattern from which conclusions concerning mechanical integrity of the tested spraying-machine are drawn. The linear dynamic models of the sprayers are derived by experimental modal analysis (EMA) from measured output accelerations of certain locations on the structure as a response to force input excitations. Consequently, the derived dynamic models can only use forces as input signals. Because spraying-machines are directly excited by soil unevenness which are displacements and not forces, EMA in its current form was not the appropriate method for model building in this application. In addition, an EMA on mechanical structures should be performed by specially trained people and will therefore not be considered in this research proposal.

1.3.3 Inspection rig with camera

In the second procedure, the tested spraying machine is driven across a bump and the vertical and horizontal movements of one of the boom tips is registered by camera. However, this methodology could not fully be evaluated and compared to the modal analysis based method due to a lack of time. In addition, before starting the measurements with the camera, some data like geometrical features of the sprayer and the track had to be used to calibrate the measurements. If this was not done very carefully, the measurements became completely worthless and the measurements had to be repeated. At last, but not at least, it is clear that a bump is not a representative track and the motion of one of the boom tips is not a representative measure for vibrations on other parts of the boom (backlash in the hinges, flexible deformations, …).

1.3.4 Spray liquid simulation models

Within the SPECS project, mathematical models to simulate spray liquid distribution and which are function of the tractor speed and rolling and yawing of the boom, are developed. Experimental validations showed that under certain conditions, these models do not generate reliable output simulations mainly because important parameters which contribute significantly to the final spray deposition pattern as evaporation, drift induced by yawing of the boom,…, were introduced in the model.

1.4 OVERALL OBJECTIVE OF THE RESEARCH PROPOSAL

Research in this field has been initiated in the EC project "European System for Field Sprayer Inspection at the Farm Level" that still show some insufficiencies. The overall objective of the proposal therefore concerns
The improvement and extension of the methodology for testing the mechanical integrity of sprayers in use and new makes, developed in the EC research project AIR3-CT94-1170, such that the methodology becomes applicable in routine tests, can be used to define directives concerning tolerable boom movements, can easily be integrated in current (mandatory or voluntary) sprayer inspections, provides sufficient technology and know how to develop a standardised procedure for the evaluation of the mechanical status of sprayers.

1.5 SUB-OBJECTIVES OF THE RESEARCH PROPOSAL

- Development of a mathematical model of a self-propelled sprayer and a trailed sprayer to be used for the derivation of representative tracks and optimization of the optimal position of the sensors.
- Derivation of representative tracks that can be used as excitation sources for the sprayer tests. These tracks will have the same stochastic characterisics as the field unevenness sensed by the sprayer tyres.
- Determination of the type of sensors (accelerometers, optical sensors as camera, laser, infrared, ultrasonic) their number and their position on the sprayer by performing field tests combined with the mathematical models. The sensors will be used to measure the mechanical condition of the tested sprayers.
- Development of reliable spray deposit distribution models to simulate the spray distribution as a function of boom vibrations.
- Establishment of the maximum tolerances for variation in liquid distribution under a spray boom during operation (i.e. under dynamic conditions) based upon extensive field measurements.
- Development of a test rig (based upon a sequence of bumps tests) for rapid testing the mechanical status of sprayers. The inspection procedure will consist of four major parts: excitation of the tested sprayer by driving it across the track, simultaneous registration of boom movements, processing the measurements and simulation of the related spray distribution, formulation of a quality label for the tested machine.

2 METHODOLOGY

2.1 WP-1. DEVELOPMENT OF A MATHEMATICAL MODEL OF A TRAILED SPRAYER AND SELF PROPELLED SPRAYER

The mechanical status of spraying machines can be evaluated most reliably and accurately by the analysis of their response to input excitations entering the mechanism through its tires as it happens during field operation. Mathematical modelling of sprayers is a suitable tool to learn more about the relation between the structural characteristics and the dynamic behaviour of the sprayer.
Chemical plant protection is ever more performed by contractors. As a consequence, self-propelled and trailed sprayers become more successful at the expense of mounted sprayers

whose sale is still decreasing. Logically, this research was focussed upon the application of self-propelled and trailed sprayers. As the developed methodology is general, it can directly be applied to mounted sprayers.

2.1.1 Task 1.1. Development of a multibody model of a trailed and self-propelled sprayer

Nowadays, virtual study of the dynamics of complex mechanisms by multibody dynamics codes has become common practice in many applications of computer aided engineering in car, aeroplane, train, … manufacturing. In multibody dynamics, the mechanism is considered as built from several single bodies which can be rigid or elastic. These bodies are connected with each other by single or composite joints which determine the number of degrees of freedom between the bodies.
In this task, a multibody model of a trailed and a self-propelled sprayer was developed. These two models were used for the derivation of representative excitation tracks and to determine the optimal placement of the measurement devices.

1. TRAILED SPRAYER

The development of a multibody model of a trailed sprayer (Beyne traîné 24 m 2700 l) was carried out using ADAMS 10-12 (Mechanical Dynamics) in two steps :

- the first step was the design of a general model of a sprayer boom and its suspension, allowing the prediction of the boom motion using the frame movements as solicitation. The model is applicable to most existing machines (model I, figures 1 and 2). The masses and inertia of each boom section were estimated by drawing the pieces with their real dimensions and locations within the software;
- the second step was the construction of a model including the whole trailed sprayer and the tractor and allowing the prediction of the sprayer frame's movements while running on rigid tracks (model II, figures 1, 2, and 3).

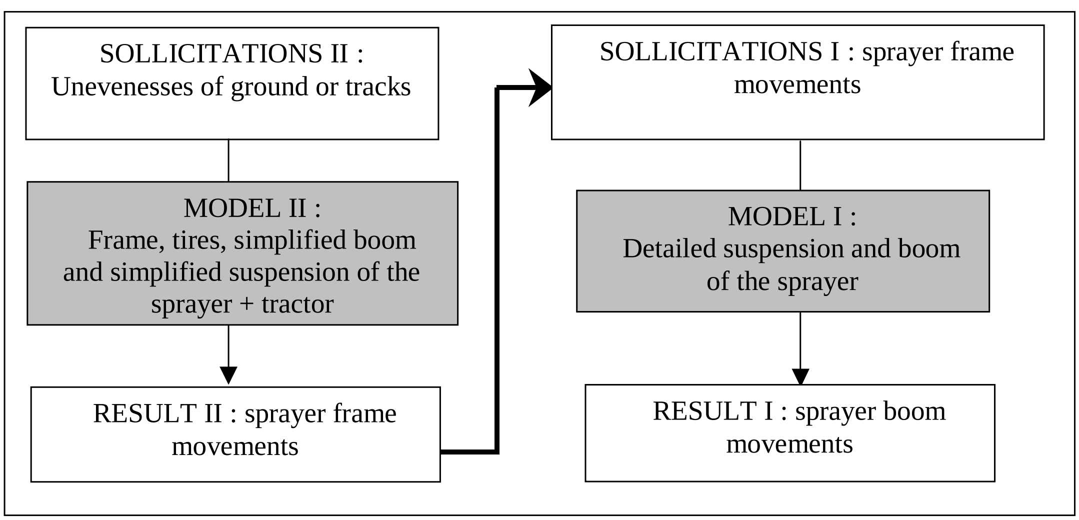


Figure 1. General structure of the trailed sprayer model

In model I, most of the parameters were adjustable with the aim to represent easily several types of machines. Particularly, the model was provided with an especially designed interface giving the possibility to introduce any kind of suspensions. The adjustable parameters were : the dimensions of the boom parts, the geometry of the boom suspension, the mass and inertia of the boom parts, the disposition of the friction supports, the coefficient(s) of friction of the friction support, the damping and stiffness of the suspension, the stiffness and damping coefficients of the vertical hinges of the boom.

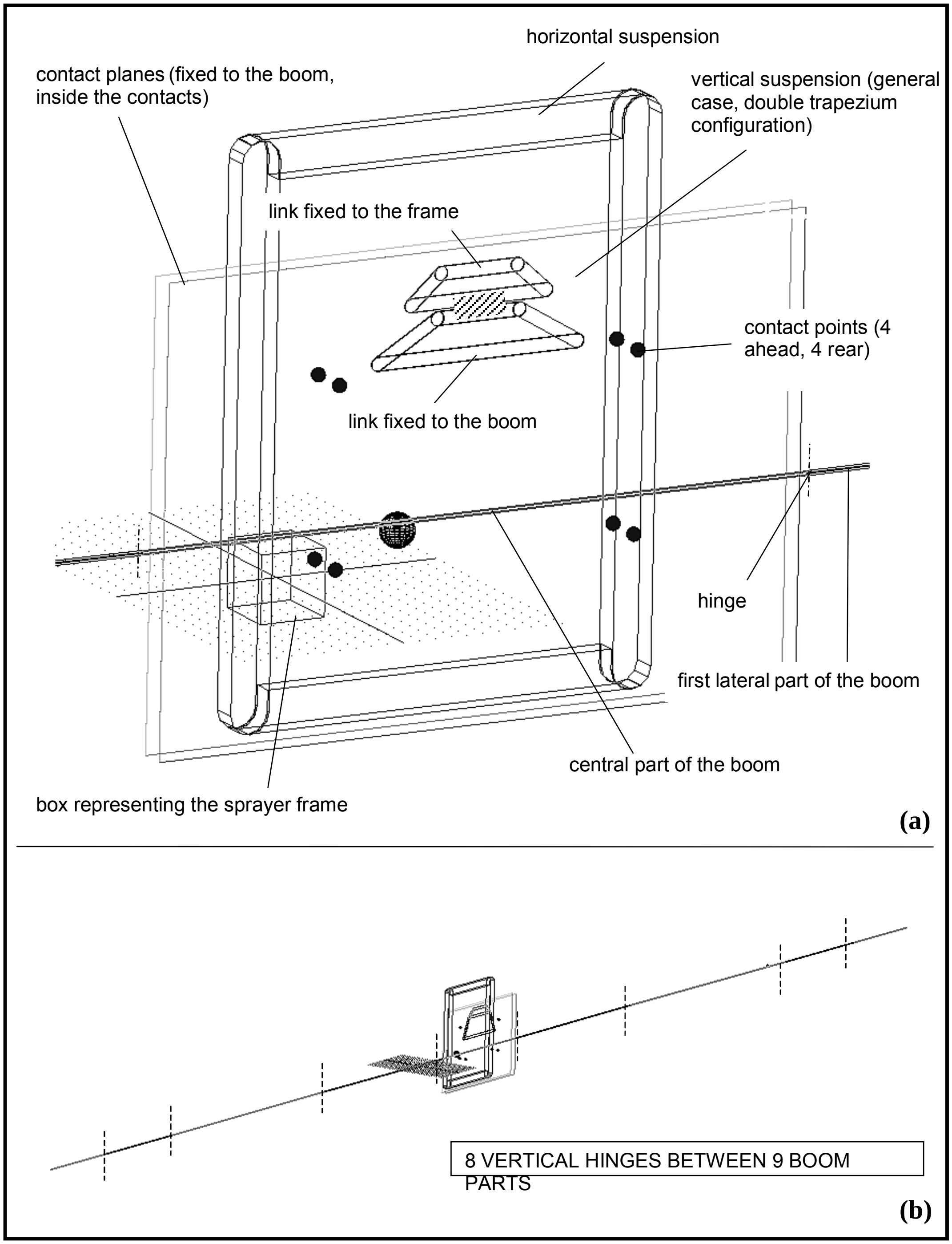


Figure 2. Trailed sprayer, Structure of the model I **(a)** suspension; **(b)** whole body model

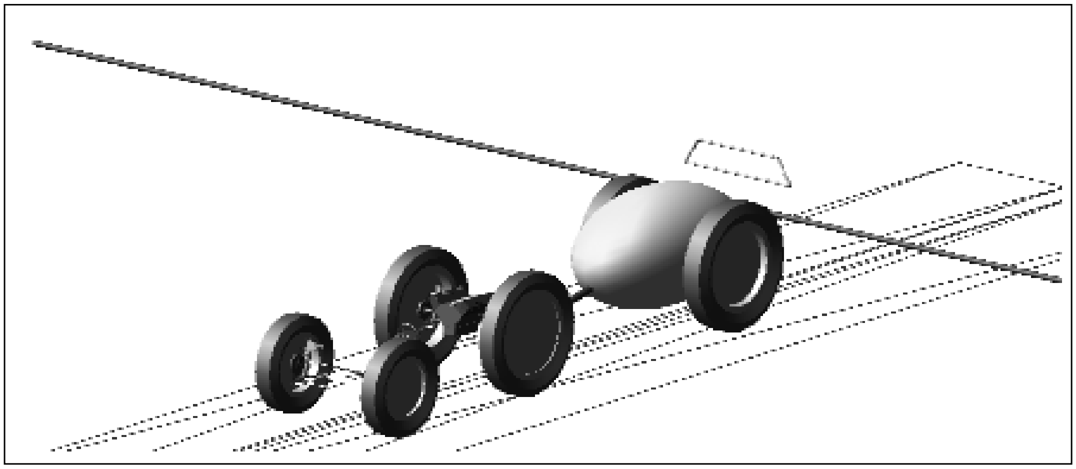


Figure 3. Trailed sprayer. Model II. Whole sprayer

Some parameters such as friction coefficients, stiffness of the boom hinges and suspension damping were estimated in the laboratory with appropriate tests. Other parameters were adjusted (section 2.1.2).

For model II, a Fiala tire model (Mechanical Dynamics) was chosen. The main parameters were the radial stiffness, the radial damping, the dimensions of the tire and the rolling resistance. The other main parameters affecting the frame movements were the inertia of the sprayer frame, the masses and inertia of the boom (taken from model I) and the damping of the boom suspension. The latter was modelled on a more simple way than in the previous model.

2. SELF-PROPELLED SPRAYER

A multibody model of the Delvano self propelled sprayer EUROTRACK (figure 4) was developed in several steps. DADS general purpose software was used to perform dynamic simulations with the multibody model. For each body in the multibody the following mechanical parameters had to be known: mass, centre of gravity, inertia tensor. Other parameters that had to be determined were stiffness and damping coefficients of springs, dampers and tires and friction in the hinges.

- For the carrying frame of the tractor or chassis of the EUROTRACK of which 3-D AutoCAD CAD drawing were available, mass distribution and moments of inertia were calculated. These parameter values were directly introduced into the DADS software.
- For different other bodies of the machine, as the spray liquid tank, the motor, the cabin, … the mechanical parameters were calculated on the basis of their geometry.
- From the spray boom structure and suspension, only drawings on paper were available. Based on these drawings and additional measurements, a detailed CAD drawing was introduced directly in DADS. From the DADS drawings mass distribution, centres of gravity and inertia tensors were derived for the boom structure and its suspension.

For the model the following issues had to be considered:

- The Parameter estimation in DADS was less accurate as those obtained from the AutoCAD drawings which led to inaccuracies in some parts of the multibody model.
- On the other hand, since the EUROTRACK is a complex multibody, some model simplification had to be introduced to avoid overloading the simulation.

Figure 4. Picture of the EUROTRACK

- For very specific parts as the tires and the suspension, simple linear systems were used since the nonlinearities in these systems were extremely difficult to determine. Former measurements had demonstrated that in the frequency band of interest (i.e. below 5Hz) these parts behave approximately linear.
- The wheelbase and track width have a dramatic effect on the dynamic behaviour of the machine and by this had to measured very precisely.

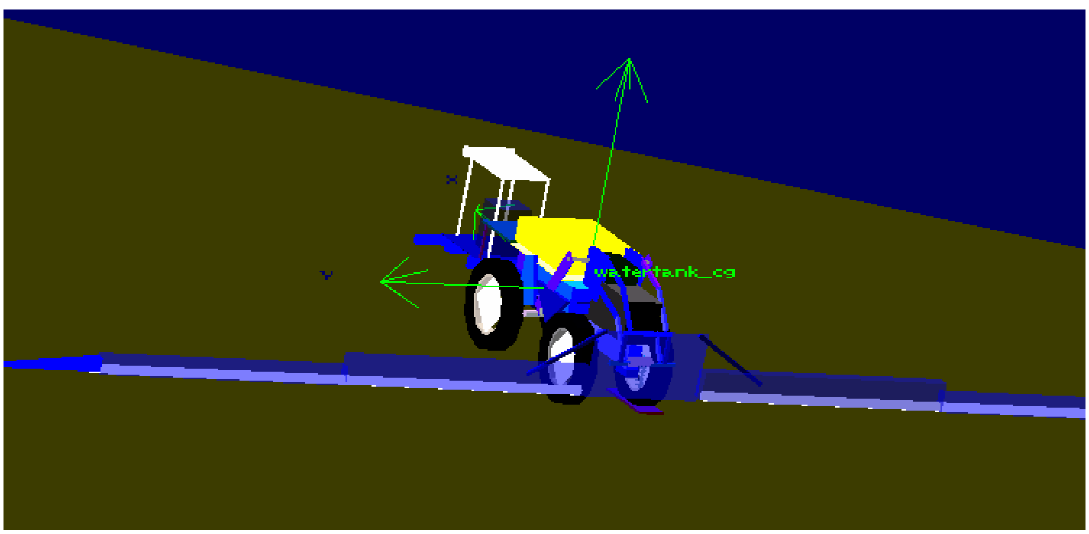


Figure 5. DADS Model of the EUROTRACK

2.1.2 Task 1.2. Optimisation of the mechanical parameters of the two models

The reliability of the multibody models is often questionable due to the inaccuracy of the applied parameter values. This problem was solved by upgrading the numerical values of the different mechanical parameters in an iterative optimisation procedure.

1. TRAILED SPRAYER

In model I, the stiffness and damping of the boom hinges were adjusted in order that the simulated boom movements match the movements measured in the field. Since the first estimation of the parameters was satisfactory (see results), no further optimisation was necessary for the parameters affecting the vertical movements. The friction coefficients were adjusted to match with the observed damping of the boom suspension.

In model II, the parameters that mostly affected the frame movements were the masses and inertia of the boom (already known with sufficient precision), the damping of the boom suspension, the stiffness of the tires, the inertia of the sprayer frame and the tire damping. To validate this model, tests were made on rigid tracks with two bump obstacles to compare the behaviour of the real sprayer with that of the model. The stiffness of the tires, the inertia of the sprayer frame and the tire damping were adjusted to match with the real machine.

2. SELF-PROPELLED SPRAYER

In case of the self-propelled sprayer, optimisation of different mechanical parameters of the multibody model was performed in the following steps:

- **Construction of a one poster electro-hydraulic shaking platform** (figure 6). The platform consists of a steel construction in which a vertical hydraulic actuator is built. An air spring in the shaker compensates the weight of the machine in static equilibrium. The platform is able support to one wheel of the tested machine. Vertical motions of the platform induce vibrations on the machine. The actuator can move the platform vertically at frequencies between 0.4 Hz and 20 Hz. An LVDT displacement sensor measures the platform motions such that the excitation signals are exactly known.

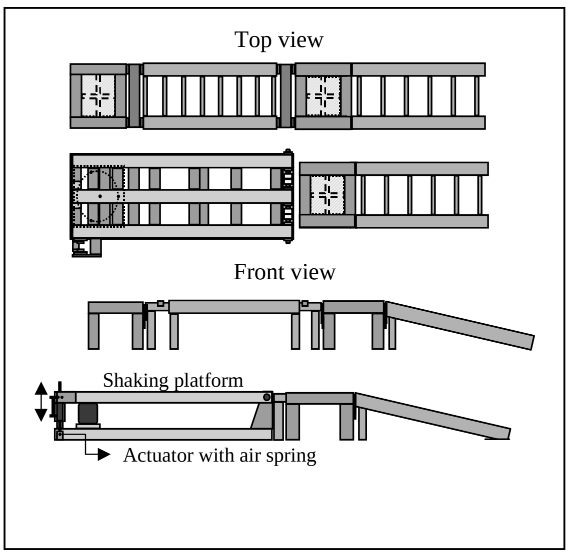


Figure 6. Schematic drawing of the one poster shaker

- **Positioning of the machine on the shaker.** The three remaining tires of the sprayer were placed on steel supports to bring the machine in its horizontal position. During excitation, the sprayer was put in its operational condition, i.e. with unfolded boom and the nozzles at a distance of about 50 cm above the soil.
- **Excitation of the machine and measurement of machine vibrations (i.e. rigid body motions).** The machine was excited by a swept sine with a frequency band ranging between 0.4 Hz and 20 Hz and a maximum amplitude of 4 cm. To register the appropriate machine vibrations, several three axial accelerometers were placed on crucial locations of the machine depending on the direction of the dominant machine

motions. To avoid contamination of the measurement signals by unmodelled elastic deformations of some machine parts, one had to take care that the accelerometers were fixed on rigid locations of the sprayer. Spray boom motions could not be measured by the accelerometers due to the very low eigenfrequencies of the boom laying below 0.085 Hz. The latter were determined visually by counting the number of periods of boom rolling and boom yawing in a certain time interval.

- **Determination of the natural frequencies of the sprayer.** From the measurements, the most important natural frequencies of the sprayer were determined as those which mainly contribute to the dynamic behaviour of the sprayer. The most important natural frequencies were machine roll at 0.85 Hz (i.e. rotation around the x-axis according to figure 5), machine pitch at 1.2 Hz (i.e. rotation around the y-axis according to figure 5), machine yaw at 0.95 Hz (i.e. rotation around the z-axis according to figure 5), machine hop at 2.4 Hz (i.e. translation along z-axis according to figure 5), pendulum motion of the boom at 0.085 Hz (i.e. rotation around the x-axis according to figure 5).
- **Optimisation of the mechanical parameters of the EUROTRACK.** For the parameter optimisation, the optimisation software OPTIMUS was used in combination with DADS. Since the natural frequencies of the machine are fully determined by the masses and inertias of the different bodies of the sprayer, the stiffness and damping coefficients of tires and suspension, it is straightforward to perform the optimisation in the frequency domain. Only parameters with uncertain values were introduced as variables in the optimisation while the exactly known parameters were kept fixed. In the optimisation procedure, mainly masses and inertias of different bodies in the multibody were selected as variables to be optimised. The cost function or objective function to be minimised, was the difference between the measured natural frequencies of the above mentioned machine motions and the corresponding simulated ones with DADS for different values of the selected variables (i.e. machine parameters). The natural frequencies were represented as the peak values in a Fast Fourier Transform of the measured and simulated time signals. The cost function was minimized by adapting the selected machine parameters according to a least squares approach.

2.2 WP-2. DEVELOPMENT OF REPRESENTATIVE DISTURBANCE INPUTS, I.E. TRACKS, FOR THE TEST RIG.

Soil and road unevenness induce vibrations on a spraying-machine crossing the field or moving on the road during transport. In vibration engineering, these are called systems with base motion since the input disturbances are displacements under the tires. Reliable tracks that can reproduce machine movements as these occur under field conditions, form an essential part of the test procedure. The ISO 5008 standard track is not rich enough to be used as excitation source as its power spectrum shows the absence of important frequencies in the frequency band of interest (i.e. mainly between 0 Hz and 5 Hz) indicating that not all dominant natural frequencies of the structure between 0 Hz and 5 Hz will be excited equally. The development of a representative track was divided into two major parts: registration of actual solicitations of sprayers (machine and boom) during operation under field condition and derivation of representative tracks that could reproduce the measured sprayer vibrations.

2.2.1 Task 2.1. Evaluation of responses of sprayers to actual solicitations under operating conditions in the field

The measurement of boom movements was carried out using several sensors. The measurement chain was composed of five accelerometers, five distance sensors (one short-range infrared sensor, two medium-range infrared sensors and two medium-range ultrasonic sensors), a two-axis gyroscope within a DMU (Dynamic Measurement Unit, Crossbow) and a radar sensor. The frequency response of each sensor was established to assure that they were suitable in their allocated frequency range. The accelerometers were used to measure movements above 0.2 Hz and other sensors to measure movements at very low frequency (Ooms *et al.*, 2002). After pre-processing, sensor fusion was applied to obtain the horizontal speed of the boom at five different points, the yaw motion, the deformations, the jolting motion, the roll motion and hop (vertical motion) of the boom (figures 7 and 8).

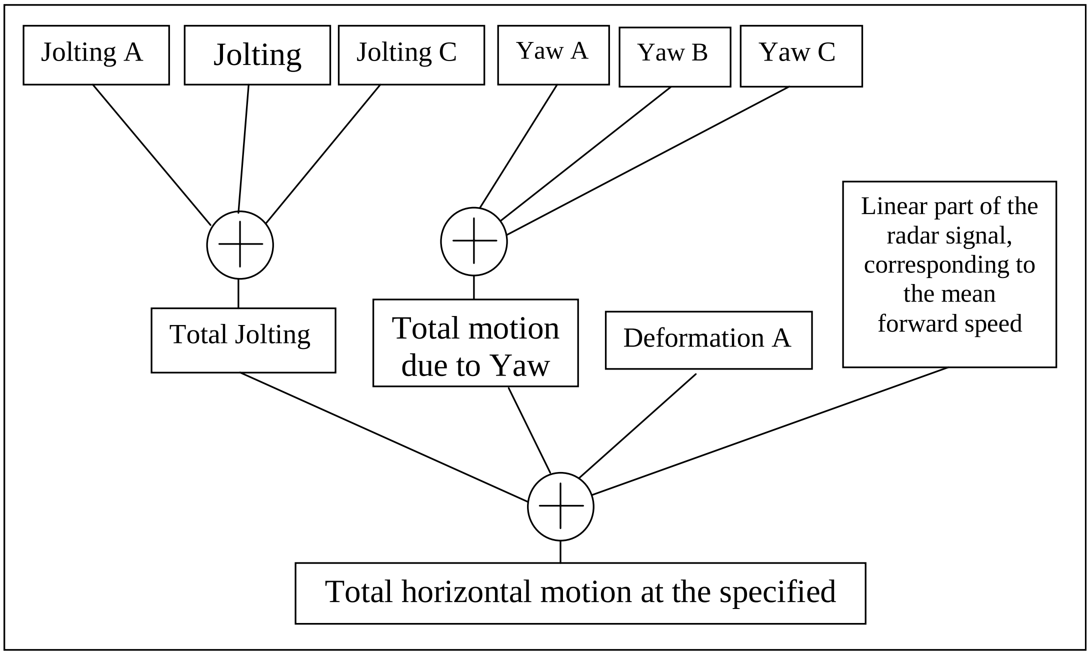


Figure 7. Sensor fusion for evaluating the horizontal boom speed.

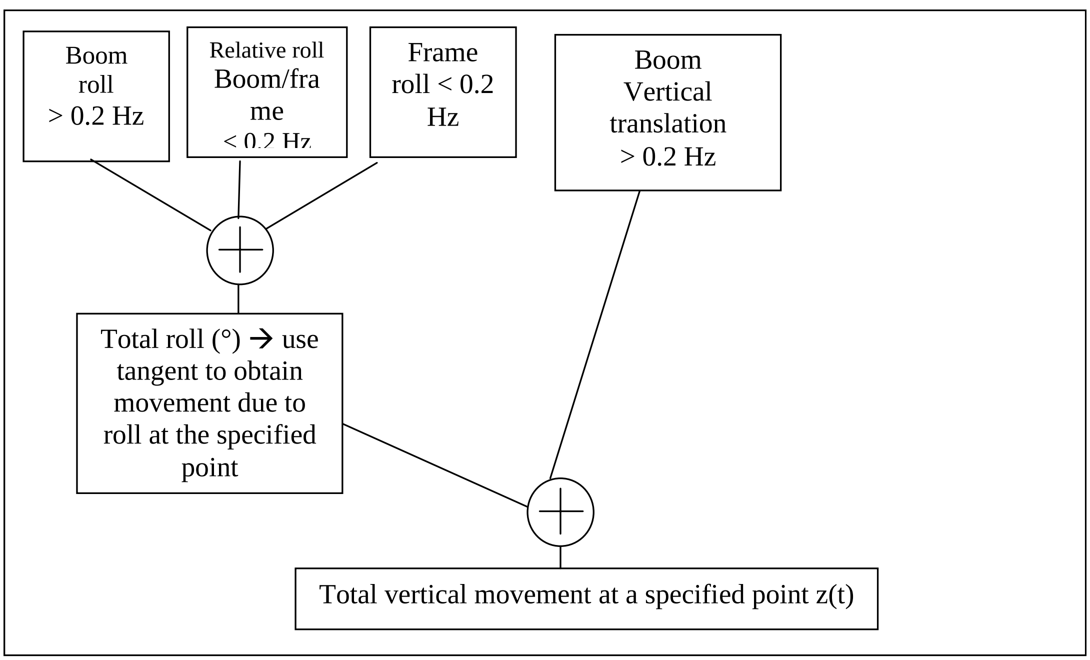


Figure 8. Sensor fusion for evaluating the vertical movement of any point on the boom.

2.2.2 Task 2.2. Development of representative drive files for the two sprayers

Direct measurement of field unevenness (e.g. by laser) for the construction of representative tracks is a very time-consuming activity. To obtain the correct stochastic characteristics of fields, numerous field tracks of sufficient length must be measured. In addition, the disturbance signals sensed by the tires of the spraying machines do not match the real soil unevenness as the soil is deformed, partially elastic, partially plastic, during crossing and the tires have a smoothing effect owing to the contact area soil-tire.

Input disturbance signals can be obtained by an interesting methodology, developed by the American company MTS and recently improved by LMS (De Cuyper et al, 1999) coping with the previously mentioned problems. This theory, called service road simulation, starts from a few test drives, in this case drives of the spraying-machines across different fields during which the target signals are measured, in order to be reproduced afterwards on a multi-axial electro-hydraulic shaker (e.g. four poster). Target signals can be three dimensional accelerations on the axles. The inputs to the hydraulic cylinders of the shaker can be considered as the sensed soil unevenness.

Sprayers are however heavy machines needing very powerful shakers that were not available, to reproduce the measured target signals. To circumvent this difficulty, the test rig was replaced by the optimized simulation model of the EUROTRACK, which was now used to reproduce the target signals.

The representative drive files were derived according to the following procedure:

- **Selection of representative field**. Rough field surface: lightly frozen corn stubble field; smooth field surface: rape seed stubble field, flax stubble field.
- **Registration of machine vibrations during field crossing of the machine.** For the derivation of the drive files, it is expected that vibrations on the axles of the machine are measured in the three directions. Simulations with the EUROTRACK model showed that only the vertical direction provided sufficient information for the drive files. By this a vertical accelerometer was placed on each wheel axle.

2.2.3 Task 2.3. Development of a sequence of representative tracks

The measured vertical vibrations on the four wheel axles were reproduced iteratively by the multibody model of the EUROTRACK. In the simulation, each tire of the machine model was placed on a virtual platform (figure 9).

Figure 9. Virtual shaker with four platforms for the EUROTRACK model

The four platforms replaced the function of a four poster shaker. The platforms were moved in the vertical direction in order to reproduce in an iterative scheme, the measured vertical axle vibrations of the four wheels. To speed up and improve the process, each of the four iteration schemes was embedded in a feedback control system provided with a PID controller. The input to each controller was the difference between the desired position of the wheel axle (i.e. the measured vertical vibration of the axle) and the simulated position of the wheel axle. The iterative procedure was repeated until the difference between measured and simulated axles motions became small enough. In that case, the corresponding motions of the four platforms represented the simulated tracks under each tire as sensed by the machine.

The simulated tracks had to transformed into real physical tracks with similar properties: similar frequency content and intensity based on the power spectral density of the tracks.

The tracks (one for the left and one for the right wheels) were designed in the following steps:

- Selection of the general shape of the tracks. Two types have been proposed: a multisine track based on a multisine signal (figure10) or a block profile based on a sequence of blocks of equal height but of different length and variable space between each block (figure 8).
- Sixteen different tracks were designed with different length and frequency content based on the properties of the reproduced tracks. As a first validation, the sixteen tracks were used as input excitation signals for the EUROTRACK model and the vertical movements of the four axles were simulated. The power spectrum of the simulated axle movements was compared with the power spectrum of the measured vertical axle motions.
- The model II of the trailed sprayer was used to validate the proposed tracks. These spectra were compared with the spectra measured in the field. Especially the roll and yaw motions of the frame measured in the field were compared with those simulated. The results are given in section 3.2.3. The best corresponding virtual track was selected, in this case a block profile.

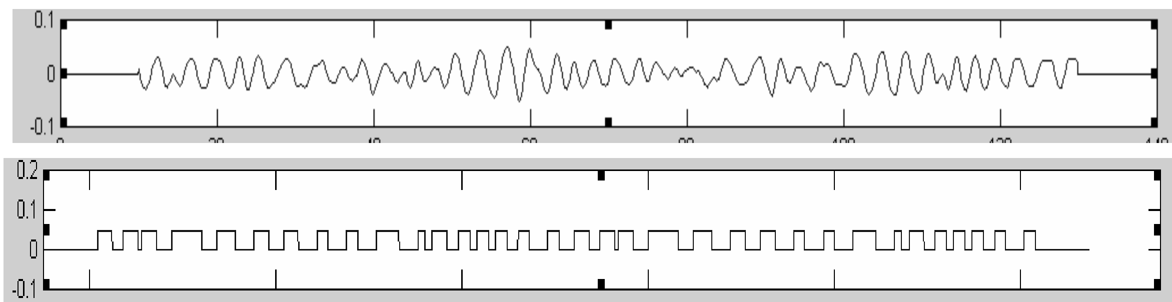


Figure 10. Multisine and block profile

2.2.4 Task 2.4. Construction of an experimental validation of the tracks

This block profile track was processed and the result was a real physical track consisting of building elements with the same height. The track is 51.2 m long and constructed of hard wooden blocks from 100x50x650 mm. The total height (frame and block) of the obstacles on this track is about 55 mm. figure 11 shows a picture of the test track.

The construction of the most interesting sequence of bumps was carried out in tropical hard wood. The construction was labour intensive due to the very hard wood. The intention was also to make the test track as versatile as possible what means that the track is adjustable in function of measured data and processed unevenness.

Due to some delays the construction could only start a few months before the finishing date of the project. Because of this delay the validation could only take place once by means of one sprayer. The track is very stable and durable.

The measurement of boom movements was carried out while a trailed sprayer (Hardi, boom length = 24 m) was running on the test tracks at 6 km/h and 7.2 km/h. The boom movements were compared with the movements observed in field conditions with the same sprayer and similar sprayers (see results).

Figure11. Test track of 51.2 m

2.3 WP-3 DEVELOPMENT OF A METHODOLOGY FOR QUANTIFYING THE EFFECT OF UNDESIRED SPRAY BOOM MOTIONS ON THE SPRAY DISTRIBUTION

2.3.1 Task 3.1. Development of a test set-up for automatic measurement of the static spray distribution pattern of different nozzles

An important part of the project was the development of a semi-automatic test set-up to measure the static spray distribution of different nozzle types. Existing spray pattern measuring equipment as described in the SPECS Project (AIR3-CT94-1170) was replaced by another concept. The previous equipment used a load cell to register the spray pattern. The load cell was static and the nozzle was moving over the load cell. Experience showed that the load cell was sensitive to vibrations.

The new equipment, the original 2D-scanner, developed in Sweden, consists of a 1x24 matrix with 5x5 cm squares in which the spray liquid rate from a nozzle is collected and measured. This matrix of squares is placed orthogonal to the direction of the spray boom. The scanner measures all sections together and thereafter moves in 5 cm steps on a special ladder so the area necessary for the measurement is scanned (figure 12). After the test, the static spray distribution pattern of the investigated nozzle is obtained.

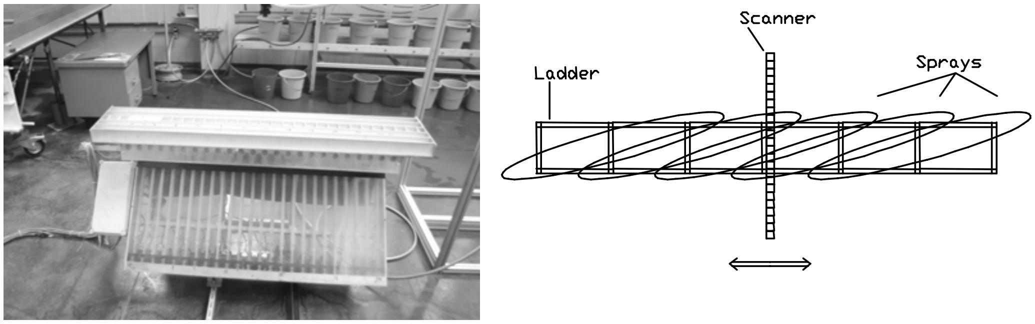


Figure 12. The 2D-scanner and the scanning principle

In comparison with the original 2D-scanner a lot of improvements were introduced. The original scanner was fitted with valves driven by two electromagnetic coils. This shut-off system didn't work well and was replaced by an electromagnetic valve for each tube. These valves were fed individually so that they could open and close separately. The open-close signal is sent from the process print. Each valve opens when the individual measurement is done. In addition, the complete process print was renewed. The new process print is able to measure without a computer. At the end, the computer just reads the measured data from the process print. In this way there are no losses of data in case of a communication disturbance between the computer and the process print during measuring. The positioning of the scanner is semi-automatic by handling a simple switch.

The measurements were performed according to the principle described in Enfält (1993). The instrument offers the possibility to measure the electrical resistance of the spray liquid but this was not used. In figure 13 the measuring part for one 5x5 cm element is shown.
The spray liquid is collected by the funnel (G) and led into a tube (J) passing through the block (F) with the electromagnetic valve (E). When the valve is closed it continues up in the second tube (H) where the flow rate measurements are performed. The flow rate is measured by two of the three electrode pairs, B to D. These electrodes measure the difference in resistance for water and air. The large difference in resistance between the two mediums is used to sense the passage of the liquid surface. Knowing the time for the liquid surface to pass between two electrode pairs and the volume between them, by means of a calibration, the flow rate can be calculated. When the liquid passes the electrode and changes the resistance a timer starts and the time needed to reach a following electrode pair is recorded. For common nozzles with a normal volume rate pair C and D are used to start and stop the timer. Pair B and D are used if the volume rate of the nozzle is too high. The selection of the measuring pairs can easily be done manually by changing the plugs.

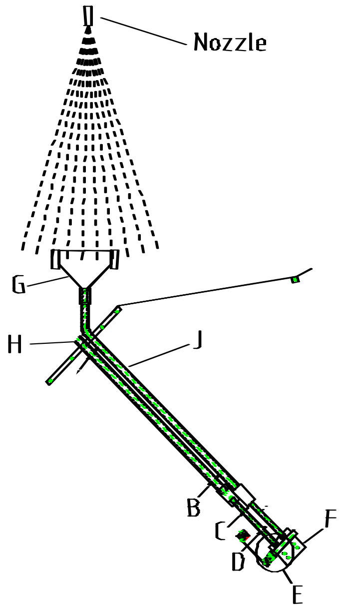


Figure 13. Measuring tube for the 2D-scanner

The measuring procedure is controlled by a program in a stationary computer that communicates via an RS-232 interface with three process prints connected to the 2D scanner. The program only reads the measured data from the process prints and sends the start and stop signal. The calibration values are stored in the computer. The Small Talk program shows an overview of the 24 tubes and their liquid level state during the measurement. After the measurement the program shows the recorded time for each tube and also the corresponding volume rate if the calibration values were entered in the program. The results can be saved as an Excel file.

The valves automatically close when the measurement starts and open when the measurement is done. This movement is controlled by the process prints. Figure 14 shows the users interface from the measuring software.

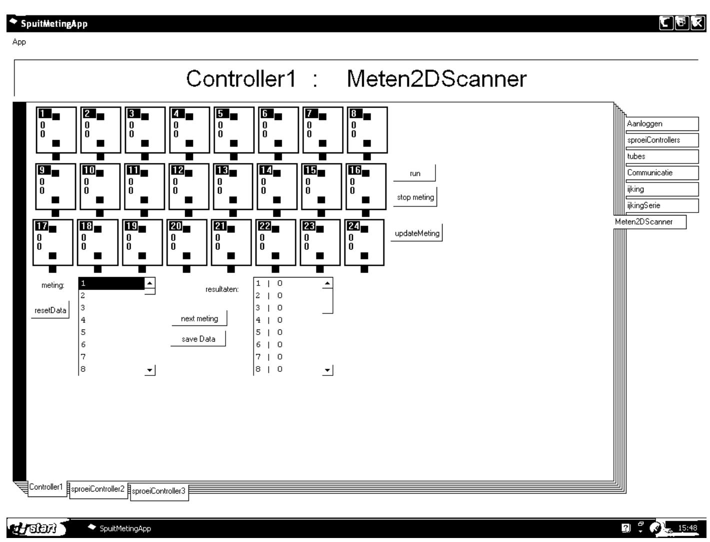


Figure 14. Users interface measuring software

All sensors have to be calibrated before using the equipment. Calibrations were carried out to find the volume between the different electrode pairs in each tube. The procedure for the calibration of the scanner is described hereafter.

To find the volume between the different electrode pairs a constant flow rate is necessary. This constant flow was created with a set-up as shown in figure 15. Liquid was pumped from the reservoir (A) up to a small tank (B) about 5 m above the ground. A pipette (D) attached to a tube coming from the tank (B) settles the level of flow rate and leads the liquid to the scanner tube (F) to be calibrated. To obtain a constant flow through the pipette a liquid surface with a constant height was created. The difference in flow between the pump and the liquid taken out is drained through a tube (C) to the reservoir giving a constant level liquid surface in the smaller tank.

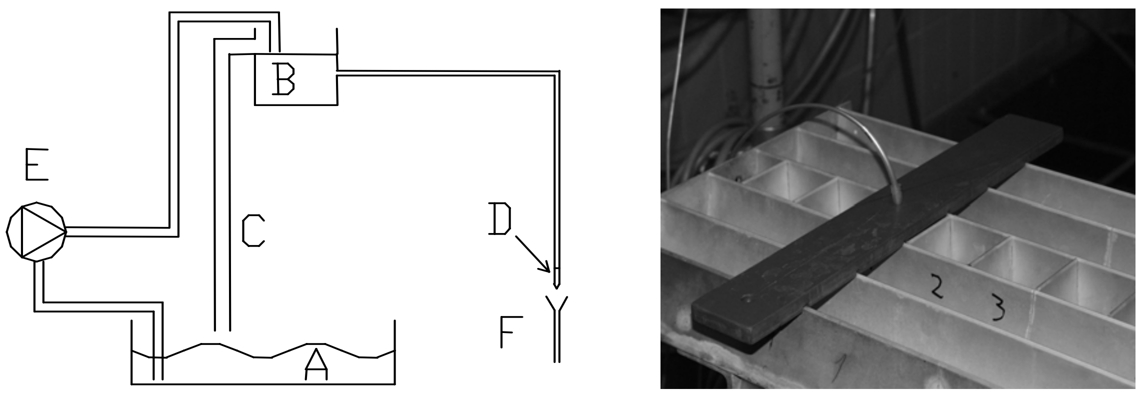


Figure 15: The set-up for calibrating the flow measuring system in the 2D scanner.

For the calibration different pipettes and valves were used giving flow rates from 0.051 – 0.243 l/min. The flow rate was measured after the calibration of each tube. In this way small changes in flow rate were incorporated. Each tube in the scanner was calibrated using six different flow rates. Every flow rate was measured five times in each tube to obtain a good calibration. A linear relation was found between the measurements of the different flow rates for each tube with an R^2 between 0.9975 and 0.9995.

2.3.2 Task 3.2. Measurement and derivation of parameterised static spray distribution models of different nozzles

A first step in this part was the search for the most common used nozzles. The results were based on the data of the mandatory inspection of sprayers in Belgium. Every three year the mounted nozzles on the inspected sprayers are registered during the inspection.

The 2D-scanner has the opportunity to measure immediate the 2D spray pattern of a nozzle. The results of these measurements are 2D grids of 50 mm wide square cells. For the model, developed by Lebeau et al. (2002), these 2D grids are needed at 3 different heights: 30, 50 and 70 cm at the same pressure.

2.3.3 Task 3.3. Development of a mechanistic model for the dynamic spray distribution pattern

The basis of the mechanistic model was developed by Ramon and De Baeremaeker (1997). This model was validated using a theoretical distribution in one dimension, and a good agreement was found at very low boom speeds. Unfortunately the model was not tested using realistic boom movements. The coupling of the static nozzle model and the more developed mechanistic model resulted in a dynamic repartition model by Lebeau et al.(2002).

To validate dynamic models, a movable spray boom was constructed. The trolley that supports the spray boom is mounted on two 15 m long rails. The boom height is manually adjustable between 40 – 130 cm above the ground. The mounted spray boom has 6 nozzles with a nozzle distance of 50 cm. The trolley is driven by an electric motor with controller. Horizontal spray boom movements can be simulated by programming the motor controller. The maximum speed is about 6 m/s. Figure 16 shows the movable spray boom.

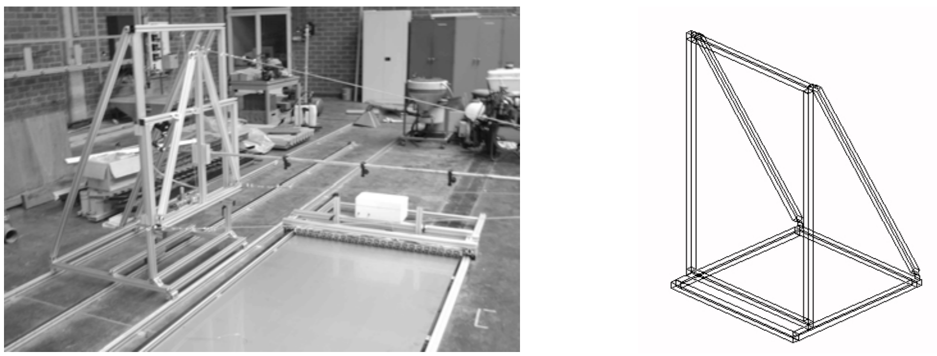


Figure 16. Picture and drawing of the movable spray boom and trolley

Different techniques can be used to register the dynamic spray pattern of a spray boom. Chemical tracer techniques are very useful in these studies (Langenakens et al., 2000) The spraying is performed on absorbing papers which are analysed in a lab. These techniques are sometimes too expensive to carry out a high number of tests. Also graphical techniques can be used (Sinfort et al.,1997; Enfält et al.,1997). Spraying with black dye on wall paper shows directly the spray pattern. Afterwards the wall paper can be scanned and the pattern can be reconstructed by image analysis. All these techniques are very labour intensive and time consuming. To get quantitative results, an analysis or image processing is necessary. Herbst and Wolf (2001) described a novel method to measure the dynamic spray pattern based on capacity measurements. This measuring principle was used to develop new spray pattern registering equipment. Figure 17 shows the equipment develop by CLO-DVL that consists of 24 small stainless steel plates forming 24 parallel plate capacitors with a large stainless steel plate.

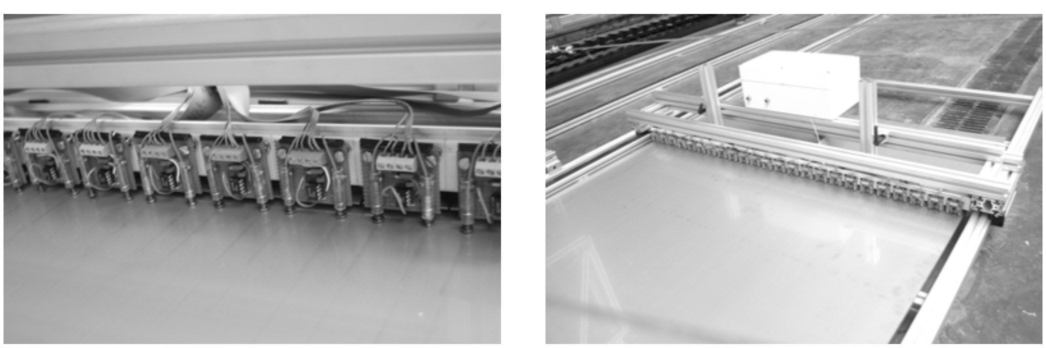


Figure 17. Capacitors to measure the spray pattern

The capacity C of a parallel plate capacitor is defined by following formula:

$$C = \varepsilon \frac{A}{d}$$

A is the surface of the plates, d is the distance between the plates and ε is the dielectric constant. When A and d are constant only ε will have an influence on the capacity of the capacitor. This dielectric constant is a property of the material. The dielectric constant of air is 1 and that of water 80. The larger the amount of water between the capacitor plates, the higher will be the measured capacity.

The dimensions of the individual small plates are 50 by 50 mm. The 24 plates are isolated fixed to a horizontal beam. This beam is mounted at the tips on a frame. The beam moves at a height of 0.1 m over the surface of a large stainless steel plate from 5 m by 1.2 m. The spray boom moves over this plate and a spray pattern is formed. Each capacitor has a separate measuring unit nearby. These measuring units are connected to a process print which processes the measured capacities. The output signal of this process print is a voltage that is translated after data acquisition into a certain volume per ha. The movement of the beam is caused by a rubber band fixed at one of the tips driven by an electric motor. The motor is controlled by a programmable controller unit. The beam can move in steps of 5 cm or continuously. To get a reference it’s necessary to perform a measurement without spraying. This measuring device has to be calibrated to find the relation between a certain amount of water and a increasing of the capacity.

To validate the dynamic spray distribution model in field conditions some field tests were carried out. To compare a simulated spray distribution with a real spraying under field conditions, a reliable registration method for the field spray pattern was needed. Three different methods were used to obtain a quantitative or at least a qualitative indication of the spray pattern. In two of the registration methods the same grid was used. This wooden grid consisted of 5 wooden sticks (2.5 m long) fixed on small metal beams (1 m long). In this way the dimensions of the grid were 1 by 2.5 m (figure 18). To measure in field conditions the grids were placed on the ground parallel and perpendicular to the driving direction.

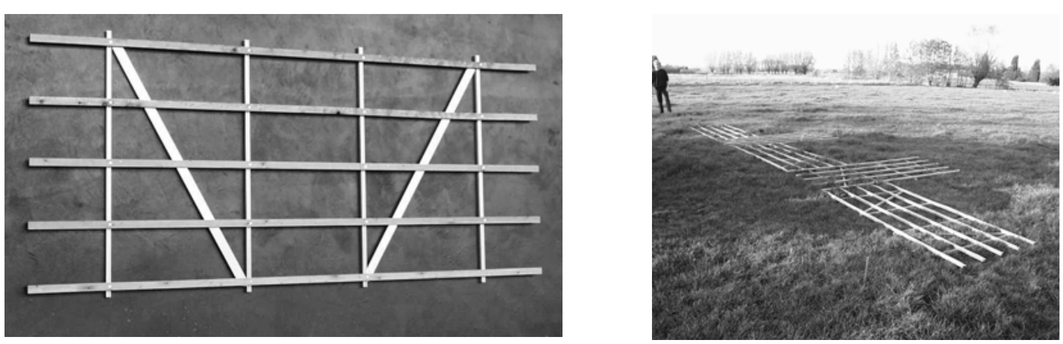


Figure 18. Grid and a possible positioning of the grids to do field measurements

A first quantitative way of registration was by means of absorbing filter papers and mineral tracers. The mineral tracer technique was improved and evaluated by CLO (De Moor et al., 2002). During the experiments a certain test protocol was followed (for loading, mixing, spraying, cleaning, … of the sprayer). A small amount of mineral chelate was mixed in the tank and sprayed across the field. Filter papers were fixed on the wooden sticks. These papers absorbed the sprayed liquid (water + chelate). The filter papers were extracted in the lab with nitric acid. After extraction, an ICP-analyser analysed the solution to quantify the concentration of minerals. This registration method was very exact but expensive. The great advantage is the durability and the chemical composition of the tracer. These tracer elements have a pesticide behaviour and are common used in the horticulture as a leaf nutrient.

For the second more qualitative way of registering the spray pattern, water sensitive strips were used. These water sensitive strips were yellow coloured. When a water droplet made contact with the yellow surface the contact area became blue. The blue dotted strips gave an impression of the amount, the size and the distribution of droplets. The paper strips were scanned by a camera. Image analysis provided for every 6 cm² the number of droplets and the average droplet diameter. These two parameters were necessary to calculate the coverage. This coverage was an indicator of the spray pattern. A possible problem with this kind of pattern registering was the high sensitivity of the strips to water. A high relative humidity or wet crops could cause a blue shadow on the strips. This shadow caused problems when the strips were scanned by the camera. It was very difficult to adjust the threshold to get a clear difference between the blue spots and the blue-yellow background. Also the sprayed volume per hectare was limited to 300 l/ha.

The third qualitative way was a destructive method and only useful when large spray boom movements could be observed by eye. In this experiment, the spray tank was filled with water and the herbicide Glyphosate, a systemic herbicide that works slowly. In this way it was easy to follow the evolution of the treated grassland. Places were the amount was too low to kill the grass will remain green. After some time green grass lines will appear. The dimensions of these lines can be measured and compared with the results of the simulation with the model.

The first and the second registration method made it possible to interpolate in between the wooden sticks to get a spray pattern of 2.5 m². This spray pattern be compared with the simulated pattern from the model.

The spray boom movements were recorded during all field experiments. To validate the dynamic spray pattern model the measured boom movements were used as an input in the simulation model. The model simulated the dynamic spray pattern. The simulated spray distribution pattern was then be compared with spray patterns resulting out of the field experiments.

2.3.4 Task 3.4. Defining the maximal acceptable tolerances for unevenness in the spray distribution

An easy way to define the maximal acceptable tolerances for the unevenness in the spray distribution is by using herbicides. Spraying a herbicide on an homogenous grassland results in surviving green grass lines if the spraying efficacy at this places was to low. The dimensions and the placing in the experimental plot of this green grass lines can be measured (figure 19).

Horizontal en vertical spray boom movements were recorded during the experiment. Also the speed of the vehicle was measured and registered. It was possible with this data to find out the exact position of the spray boom at a certain place in the experimental plot. If the bad spray pattern was especially caused by vertical spray boom movements, the critical height of the nozzles could be calculated.

It was more difficult to perform equal experiments with insecticides and fungicides. Evaluating the maximum acceptable tolerance for unevenness for these plant protection products was very difficult and requires a homogenous pest.

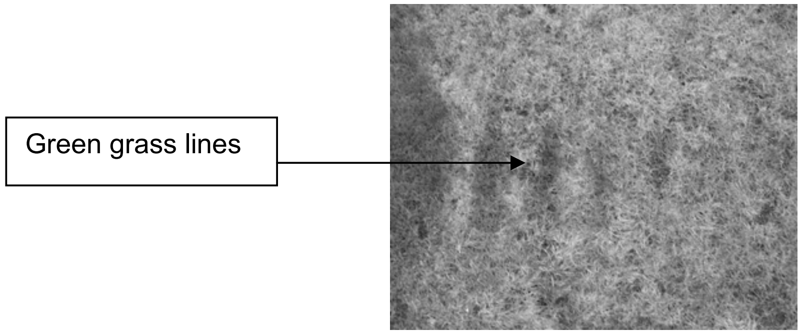


Figure 19. Green grass lines after spraying with Glyphosate

2.4 WP-4 DEVELOPMENT OF A TEST SYSTEM FOR EVALUATING THE MECHANICAL STATUS OF FIELD SPRAYERS

2.4.1 Task 4.1. Development of the test system

The development of the test system consists of the integration of all developments from the previous work packages in one test system: the excitation source consisting of a test track useful in routine tests, measurement of the spray boom movements by means of handy and cheap sensors, software to calculate the horizontal and vertical movements of all the nozzles and software to simulate the spray pattern in function of the undesired spray boom movements.
This integration could only take place when all the different parts were finished. This is one of the reasons why the construction of the test track started only a few months before the finishing date of the project.

2.4.2 Task 4.2. Evaluation of the test system

Two questions had to be answered before selecting the final configuration of the test system.

The selection of the test track. Registering the unevenness during driving on different soils and crops and processing this data into virtual test tracks results in a number of possible real test tracks. Selecting the best corresponding track is based on comparing the simulations of the movements frequency spectrum of a lot of field tests with the simulated movements frequency spectrum of the virtual test track and this for the two models (self-driven and trailed sprayer). Together with this simulation the driving speed on the test track and the content of the tank was chosen.
The final selection is the one of the sensors to measure the spray boom movements. In addition the number of sensors and their position on the sprayer have to be chosen.

Some practical problems appeared while organising these tests. The main problem was to find a place to perform this tests. A flat and carrying soil was required to place the physical test track. The best solution was an asphalt or concrete underground. This area had to be large enough because of the width of the spray booms. To exclude weather influences (rain, wind, …) a covered place was suggested.
During the evaluation the necessary time to mount and to remove the sensors and to carry out the tests was recorded.

2.4.3 Task 4.3. Formulation of directives about the test procedures

From the previous tests and developments, it is the aim to get a thorough description of the test procedure for establishing allowable horizontal and vertical boom movements related to acceptable tolerances in variations in spray deposition pattern. To be able to prepare and formulate Belgian or European directives and standards a lot of measurements will still be required.

3 RESULTS

3.1 WP-1. MATHEMATICAL MODEL OF A TRAILED SPRAYER AND SELF-PROPELLED SPRAYER

3.1.1 Multibody model of trailed and self-propelled sprayer

1. TRAILED SPRAYER

The cross validation of the model I was carried out using the field tests made with a Beyne sprayer (see section 2.1.1). The measured roll of the boom was compared to the simulated motion. The model gave a correct prediction (figure 20), with an slight overestimation of the roll movements around 0.75 Hz (figure 21). The horizontal movements were also compared. The model was not so reliable as for vertical movements, but gave an acceptable estimation of the horizontal speed of the boom.

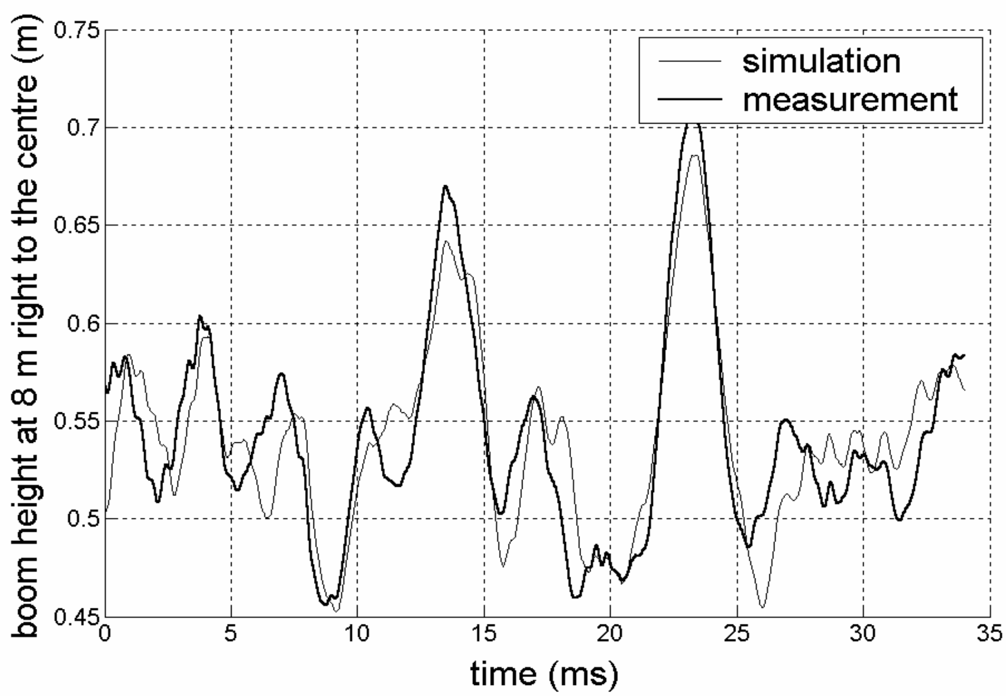


Figure 20. Trailed sprayer, model I : vertical movement of a single point located at 8.5 m from the centre of the boom ; comparison of simulation and measurement in the field (meadow at 6 km/h)

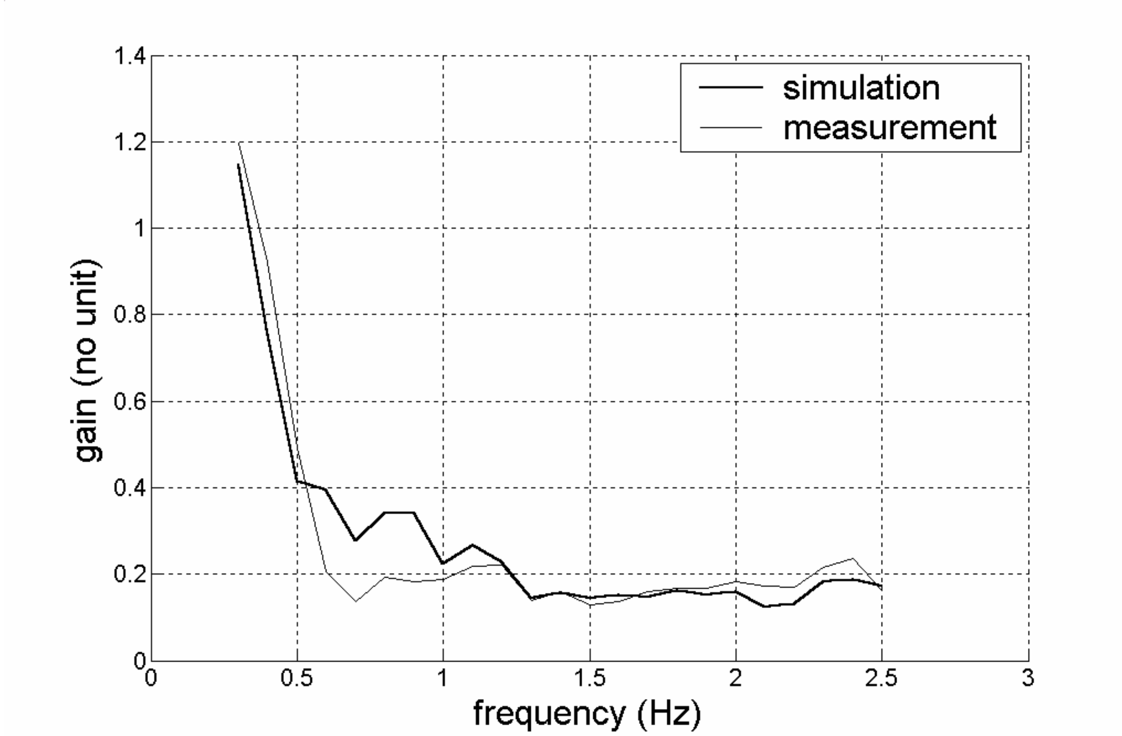
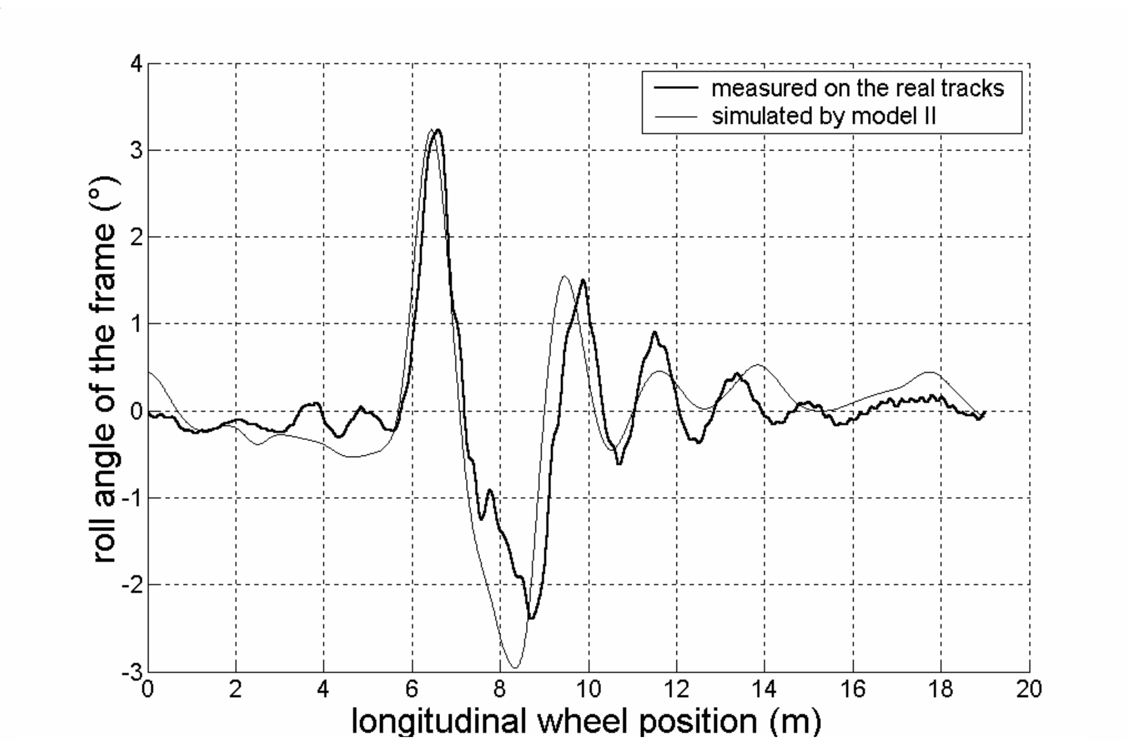


Figure 21. Trailed sprayer, model I. Frequency response, vertical movements.



The model II was intended to be used on rigid bump tracks. The validation was made on a straight road equipped with two bumps, reproducing similar conditions. The model gave good results in predicting the roll of the frame (figure 22), but poor result for yaw. Three repetitions were made, providing similar results.

2. SELF PROPELLED SPRAYER

Initially, the natural frequencies of the model were compared with the measured natural frequencies of the EUROTRACK for the nominal values of the mechanical parameters. The model showed a very good approximation for the modes tractor roll and tractor hop. Tractor pitch and yaw were approximated less accurately. For the spray boom, hop and pendulum motion of the boom had to be optimised.

3.1.2 Mechanical parameters of the two models

1. TRAILED SPRAYER

Model I : Concerning horizontal movements, it was observed that the behaviour of the model was different than that of the real machine whatever the values of the parameters. The amplitude of the horizontal movements under field solicitations could be slightly increased by adding clearance within the boom articulations. The validation showed that the values of the parameters influencing the vertical boom movements were correct, and that there was no other parameter affecting significantly these movements.

Model II : A variance analysis was made to determine the main parameters influencing the amplitude of the roll of the sprayer frame. It was obvious that the damping of the boom suspension influenced mostly this movement, five times more than the damping of the tires and thirty times more than their stiffness. A modification of the frame inertia did not influence the roll motion at all.

2. SELF-PROPELLED SPRAYER

After optimisation, the following natural frequencies of the different modes were obtained:

Table I. Measured and optimised natural frequencies of the tractor

	Measured (Hz)	Simulated (Hz)
Tractor roll	0.85	0.88
Tractor pitch	1.2	0.7
Tractor hop	2.4	2.4
Tractor yaw	0.95	-
Boom roll	0.085	0.085

Tractor roll and hop were easily optimised by adapting the stiffness and damping of the tires. Tractor pitch could only be improved by adapting the moments of inertia of the tractor. Unfortunately, the optimisation could not find a reasonable solution for the moments of inertia such that tractor pitch was not considered in the optimisation. Tractor yaw was not expressed significantly in the DADS model. Spray boom motions could be simulated quite accurately. Since the model was used for deriving representative tracks, boom vibrations were less important as their contribution to the total movements of the tractor part of the sprayer are marginal.
Some results are shown in the figures below (figures 23, 24 and 25).

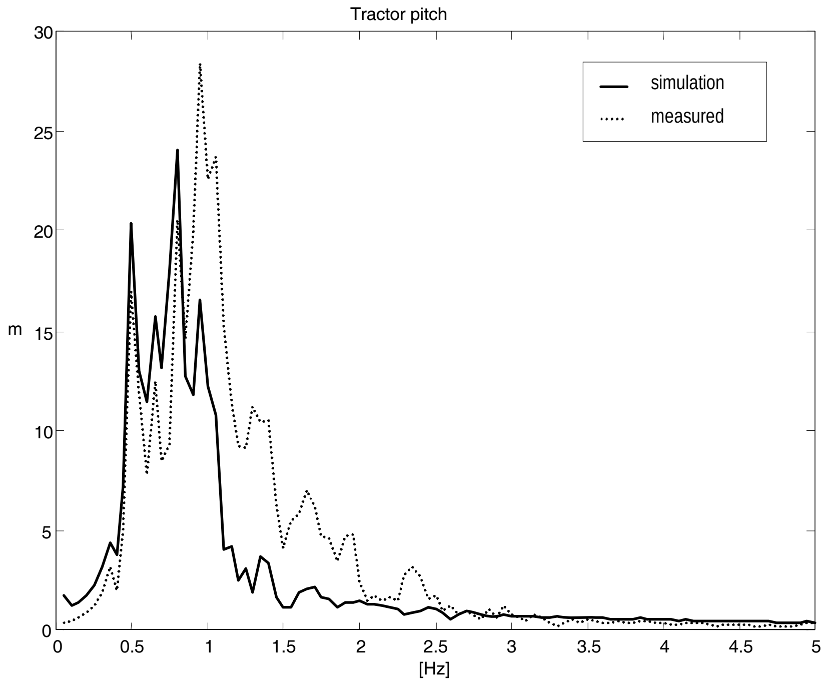


Figure 23. Power spectrum of tractor pitch (▬ : simulation, ····· : measured)

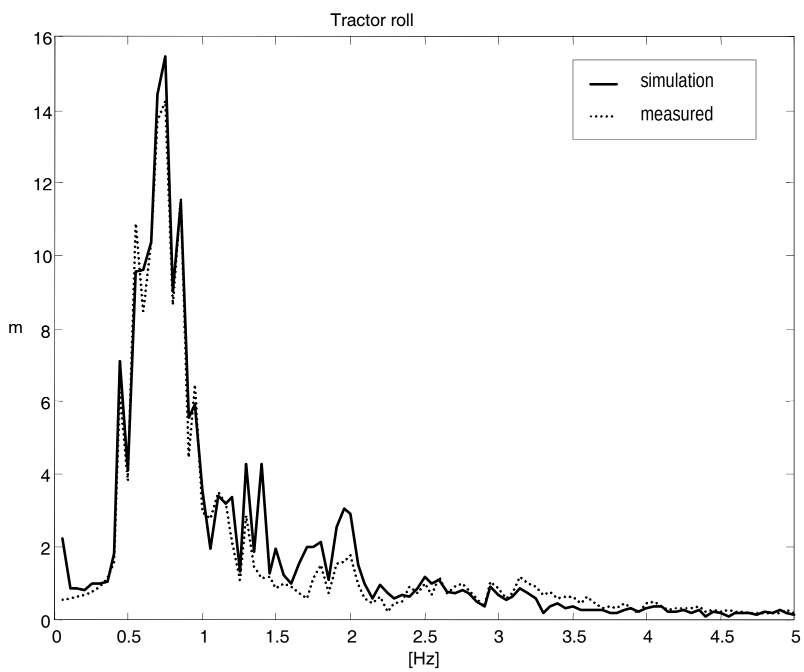


Figure 24. Power spectrum of tractor roll (▬ : simulation, ····· : measured)

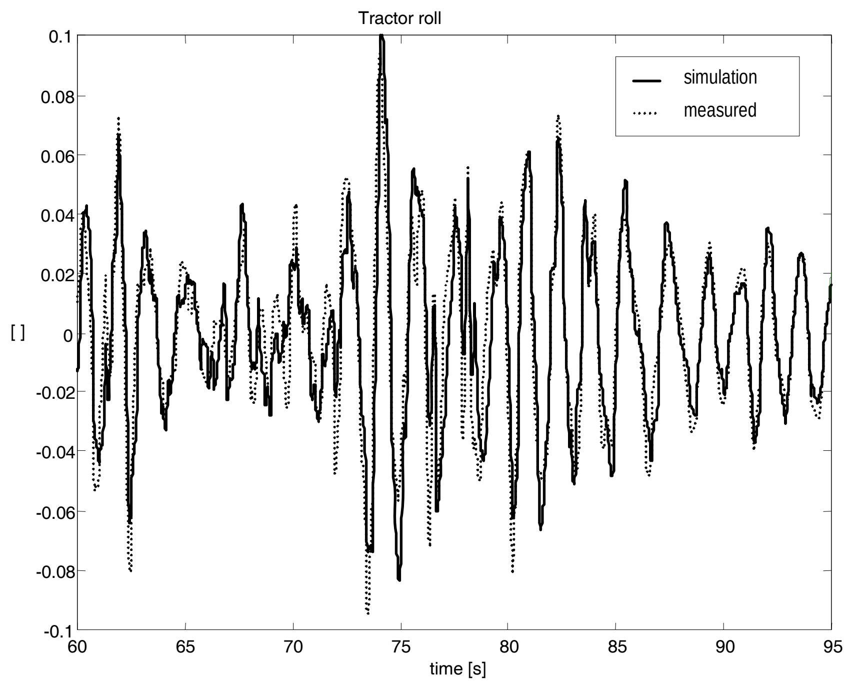


Figure 25. Time signal of tractor roll (── : simulation, ····· : measured)

3.2 WP-2. REPRESENTATIVE DISTURBANCE INPUTS, I.E. TRACKS, FOR THE TEST RIG

3.2.1 Responses of sprayers to actual solicitations under operating conditions in the field

Tests were performed in the fields on long distances to evaluate common movements of the boom in real situations. The fields used were composed of meadows, potatoes, chicory, wheat and bare fields located in Gembloux, Harelbeke and Moerzeke (Merelbeke). Several types of sprayers were used, including one mounted, four trailed and two self-propelled ones. The boom lengths were comprised between 18 m and 33 m. The trials were performed at four different speeds : 6, 8, 9 and 12 km/h. The trials are summarised in Table II.

The coefficient of variation of the horizontal speed of the whole boom was used to represent the overall horizontal speed variations. It was comprised between 2 % and 14 %, with a global mean of 6 %. The variations of the longitudinal spray distribution resulting of the horizontal boom movements should not be higher than these values (Ooms *et al.*, 2003). Taking the example of a trailed sprayer with a 24 m boom length, we could see that the increasing of the running speed did not increase the impact of horizontal boom movements on the ground distribution. With the mounted sprayer (18 m boom length), the same conclusion was drawn, and notable differences were proved between different fields (different soil humidity rate and crop). The movements were much greater on a dry meadow than on wet chicory field. The movements measured on a dry wheat field had a moderate amplitude.

Table II. Summary of field trials (Ooms *et al*., (2003)

Date	place[1]	sprayer[2]	speed	tank	crop[3]	horizontal boom speed CV	repetitions
15/06/00	Gembloux	S-P, 33 m, T	8 km/h	empty	wheat	7.7%	5
15/06/00	Gembloux	S-P, 33 m, T	5 km/h	empty	wheat	6.5%	2
18/07/00	Gembloux	Tr, 22 m, T	8 km/h	1/2 full	wheat	3.5%	2
19/07/00	Gembloux	Tr, 22 m, T	12 km/h	1/2 full	wheat	3.5%	2
19/07/00	Gembloux	Tr, 22 m, T	12 km/h	empty	wheat	3.5%	4
19/07/00	Gembloux	Tr, 22 m, T	8 km/h	empty	wheat	2.7%	2
12/10/00	Merelbeke	Tr, 24 m, T	6 km/h	1/10 full	meadow	4.3%	6
12/10/00	Merelbeke	Tr, 24 m, T	8 km/h	1/10 full	meadow	4.0%	2
12/10/00	Merelbeke	Tr, 24 m, T	12 km/h	1/10 full	meadow	5.6%	1
28/06/01	Gembloux	M, 18 m, T	6 km/h	empty	wheat	12.0%	3
28/06/01	Gembloux	M, 18 m, T	9 km/h	empty	wheat	9.1%	2
28/06/01	Gembloux	M, 18 m, T	12 km/h	empty	wheat	7.9%	3
28/06/01	Gembloux	M, 18 m, T	6 km/h	empty	chicory	4.3%	3
28/06/01	Gembloux	M, 18 m, T	9 km/h	empty	chicory	2.9%	5
28/06/01	Gembloux	M, 18 m, T	12 km/h	empty	chicory	4.7%	3
29/06/01	Gembloux	M, 18 m, T	6 km/h	empty	meadow	11.6%	2
29/06/01	Gembloux	M, 18 m, T	9 km/h	empty	meadow	7.5%	2
06/07/01	Gembloux	S-P, 33 m, T	6 km/h	empty	meadow	9.3%	5
06/07/01	Gembloux	S-P, 33 m, T	9 km/h	empty	meadow	6.7%	3
06/07/01	Gembloux	S-P, 33 m, T	12 km/h	empty	meadow	7.1%	2
06/07/01	Gembloux	S-P, 33 m, T	6 km/h	empty	wheat	7.5%	2
06/07/01	Gembloux	S-P, 33 m, T	9 km/h	empty	wheat	6.1%	2
06/07/01	Gembloux	S-P, 33 m, T	12 km/h	empty	wheat	6.3%	3
06/07/01	Gembloux	S-P, 33 m, T	6 km/h	empty	chicory	3.9%	3
06/07/01	Gembloux	S-P, 33 m, T	9 km/h	empty	chicory	2.6%	4
06/07/01	Gembloux	S-P, 33 m, T	12 km/h	empty	chicory	2.2%	2
31/08/01	Harelbeke	S-P, 33 m, P	6 km/h	empty	bare field #1	5.6%	4
31/08/01	Harelbeke	S-P, 33 m, P	12 km/h	empty	bare field #1	4.8%	4
31/08/01	Harelbeke	S-P, 33 m, P	9 km/h	empty	bare field #1	5.2%	1
31/08/01	Harelbeke	S-P, 33 m, P	6 km/h	empty	bare field #2	6.1%	4
31/08/01	Harelbeke	S-P, 33 m, P	12 km/h	empty	bare field #2	4.1%	4

1: all places are in Belgium
2: S-P=self-propelled, Tr=trailed, M=mounted; boom length; T=trapezoïdal suspension, P=pendulum
3: bare field #2 was more uneven than bare field #1.
CV does not take into account the low-frequency vehicle speed variations

3.2.2 Representative drive files for the two sprayers

The reproduction of the measured vertical axle vibrations of the EUROTRACK with the multibody model could be performed very accurately despite the model inaccuracies. This can be explained by the application of feedback loops with PID controllers. These feedback systems render the procedure robust against structured (parameter uncertainties) and unstructured (unmodelled high frequency dynamics as flexible properties of the structure) model uncertainties. A time signal (figures 26 and 27) shows the approximation between the measured and reproduced vertical vibration of the left rear axle. The only disadvantage of the procedure was the dramatic computation time due to the iteration procedure.

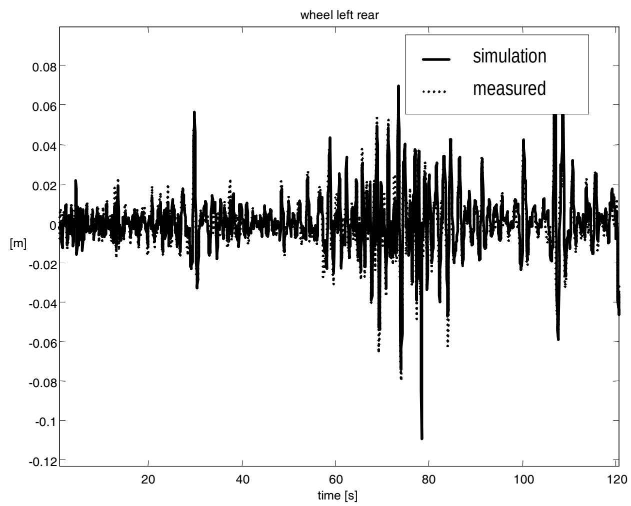


Figure 26. Time signal of the vertical vibration of the left rear axle of the EUROTRACK (····· : measured, ━━ : reproduced with the multibody model)

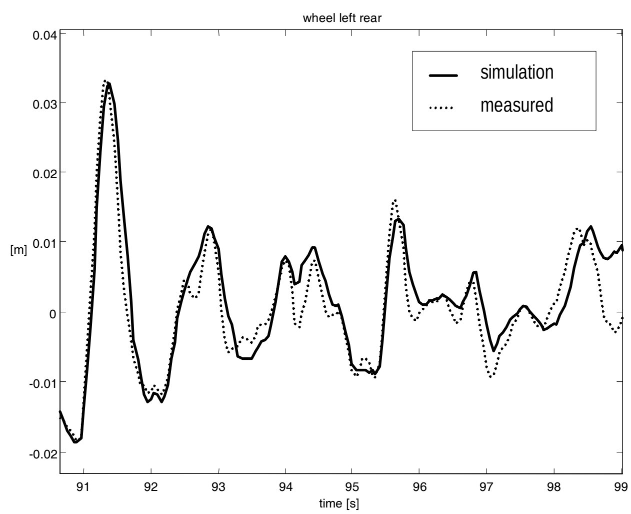


Figure 27. Detail of the time signal of Figure 26.

3.2.3 Sequence of a representative track

Two final tracks were selected based on their power spectrum. The multisine track and the block profile show similar qualities. Since the block profile is more simple to reproduce, it was chosen as final representative track. The height of the blocks was 5 cm, the smallest distance between the tracks and the smallest width of each block was 40 cm. The total length of the block profile is 51.2 m. In figure 28, the power spectrum of the block profile is shown and compared with the power spectrum of the existing ISO 5008 track (figure 29). Driving speed is 7.2 km/hr. Figure 28 shows that due to the limited length of the block profile, the high frequencies could not be reproduced entirely. Figures 28 and 29 show clearly that the proposed block profile is much richer than the ISO 5008 track although it is about half of the 100 m length of the ISO track.

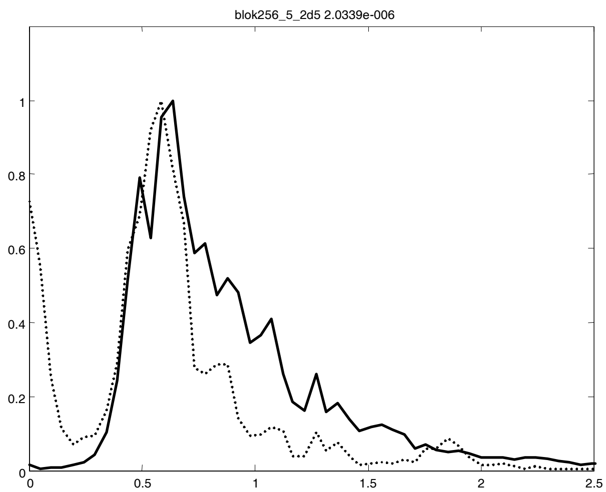


Figure 28. Power spectrum of the proposed block profile (·····) compared with the power spectrum for the tracks obtained from model (▬)

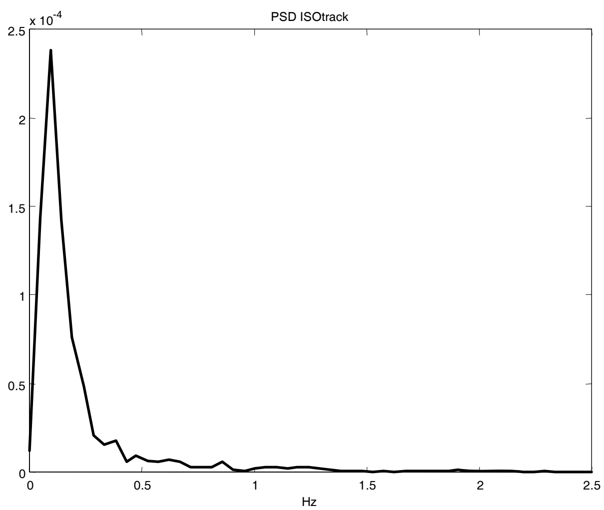


Figure 29. Power spectrum of the ISO 5008 track

The proposed tracks were also tested on the trailed sprayer Unfortunately, they could not reproduce the frame movements measured in the field on trailed sprayers. Results are presented in figure 30 for the best tracks. The model was not able to predict the yaw movement of the sprayer frame and no comparison could be made.

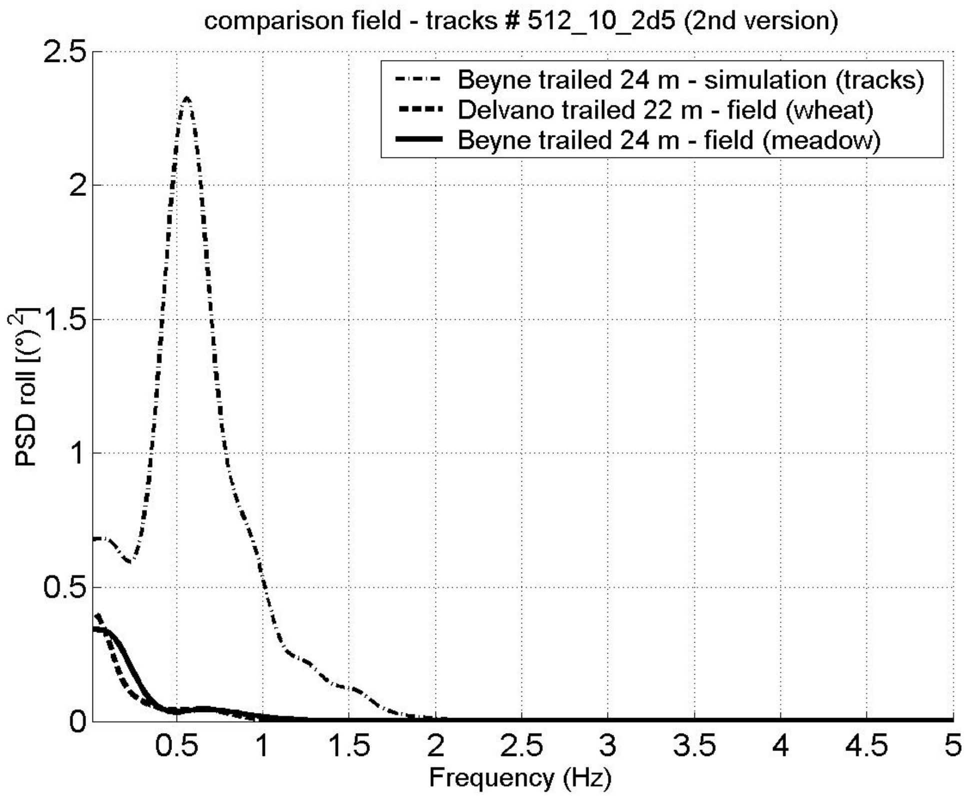


Figure 30. PSD of the roll movement of the sprayer frame. Comparison between the movements measured on the tracks and in fields (6 km/h).

3.2.4 Validation results for the track

The horizontal speeds of a boom (Hardi sprayer, 27 m length) were compared on the test track and on a field of potatoes (figure 31). They were measured at 11.5 m from the centre of the boom. Some movements measured in the field on other sprayer booms are also indicated. The comparison made at 5.5 m from the boom centre gave similar results. The amplitudes of the movements were higher on the track than in the field.

The roll movements of the same boom are presented in figure 32. The amplitudes of the movements were higher on the track than in the field, especially between 0.1 and 0.2 Hz.

A validation test was carried out with a trailed sprayer Hardi Commander Twin. Due to the lack of time the validation was only executed with one machine. Further validation with more different machines is of course recommended.

The usage of rectangular obstacles with a height of 50 mm induces horizontal spray boom movements which are 3 to 10 times more important then the ones registered during field measurements. For some frequencies the rolling movements are an average of 0.5 to 7 time higher than the movements measured on equal machines in field conditions. The amplitude corresponds with conditions which are more severe than the real field conditions. The frequency spectrum of the movements corresponds very well with the one observed in field conditions for the same machine.
All considered is this test track a more suitable test track then the ISO 8005. This track corresponds better the field conditions (even worst case) then the ISO track.

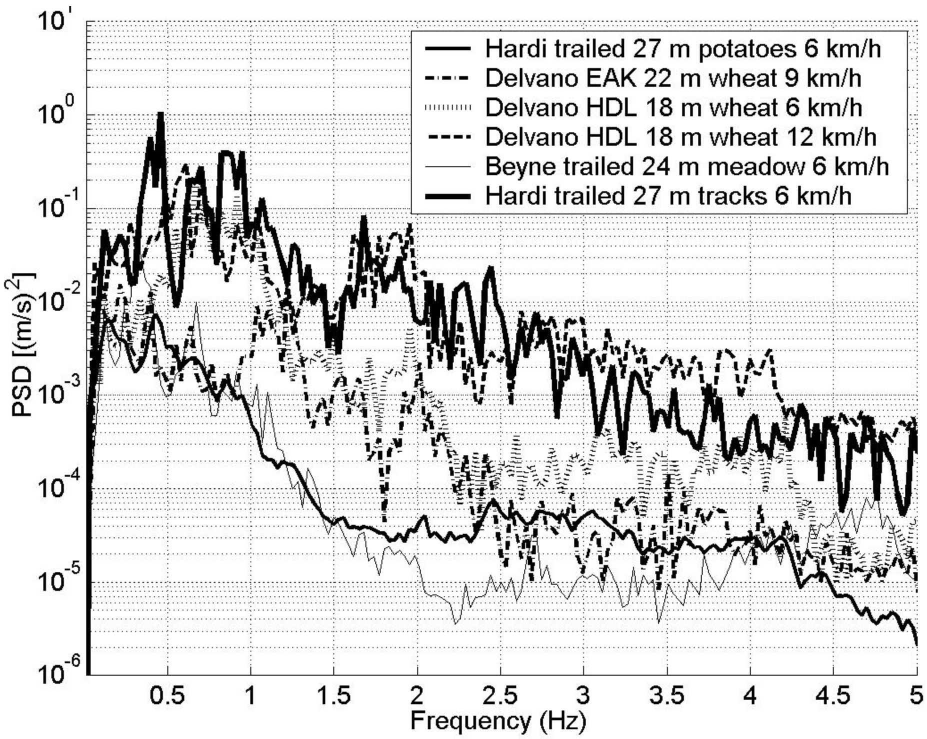


Figure 31. PSD of the boom horizontal speed at the most external measurement location. Comparison between the movements measured on the tracks and measured in fields.

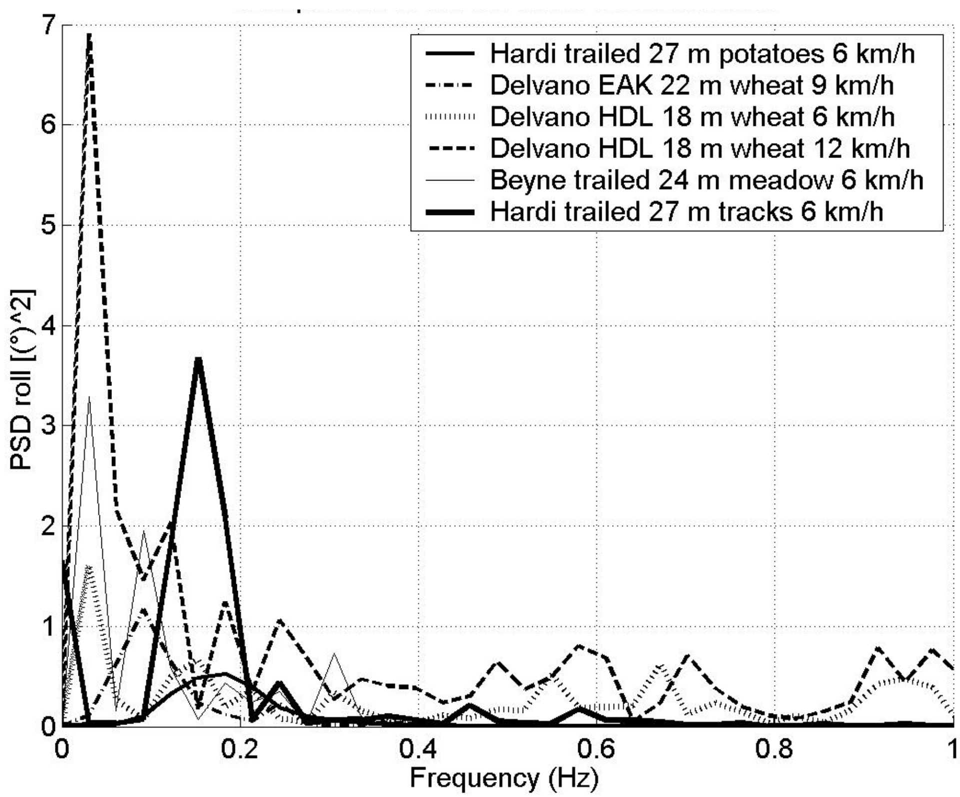


Figure 32. Boom roll. Comparison between the movements measured on the tracks and in the field.

3.3 WP-3. METHODOLOGY FOR QUANTIFYING THE EFFECT OF UNDESIRED SPRAY BOOM MOTIONS ON THE SPRAY DISTRIBUTION

3.3.1 Test set-up for automatic measurement of the static spray distribution pattern of different nozzles

The search for an automatic measuring device for 2D static spray pattern registration resulted in a totally refreshed 2D-scanner. This equipment is able to measure in a relative short time and with a good repeatability the 2D static spray pattern of different nozzles. It takes between 2 and 4 hours to measure the 2D static pattern of one nozzle, depending on nozzle type (top angle), nozzle height, pressure, … .

This improved equipment makes it easier to register for any kind of nozzle the necessary data of its 2D static spray pattern that will be used for deriving the dynamic spray pattern model (i.e. the spray deposition pattern of a nozzle mounted on a moving spray boom). In comparison with other 2D static pattern registration methods this device is accurate, quick and easy to handle. The possibility is left to automate the 2D spray scanner motion. In that case the 2D scanner will be able to operate fully independently.

Figure 33. 2D scanner with processing box and PC

The 2D static spray pattern registration is an important input for final dynamic spray pattern model. In case the static model is used to simulate the dynamic spray pattern of different sprayers with different nozzles then a database with the static spray patterns from all these nozzles is required. Therefore a quick and easy registration method is required.

The process print and the 2D scanner also has the possibility to measure the conductivity of the liquid. This is very useful when the impact of neighbouring nozzles has to be examined. The scanner is not calibrated for conductivity measurements and the software also has to be adjusted for this kind of experiments. So for performing this kind of tests some more calibrating and programming work has to be done.

3.3.2 Parameterised static spray distribution models of different nozzles

A quick look into the data of the mandatory inspection shows that the most common used nozzles in arable field spraying are the flat fan nozzles. Once the need for a more detailed view on the nozzle market is necessary, a intensive market research can be organised.

The software of the 2D scanner delivers an Excel file. This file contains a data matrix (24 x number of steps). The matrix is ready to be imported in the dynamic spray pattern simulation model. Three 2D spray patterns at different heights (30, 50 and 70 cm) are sufficient as an input for this model. An example of 2D static spray pattern is shown in figure 34.

Currently, the 2D static spray patterns of some nozzles are registered but no real extensive database is available yet. By adapting the valves and the software in the scanner it was necessary to calibrate the scanner 3 times.

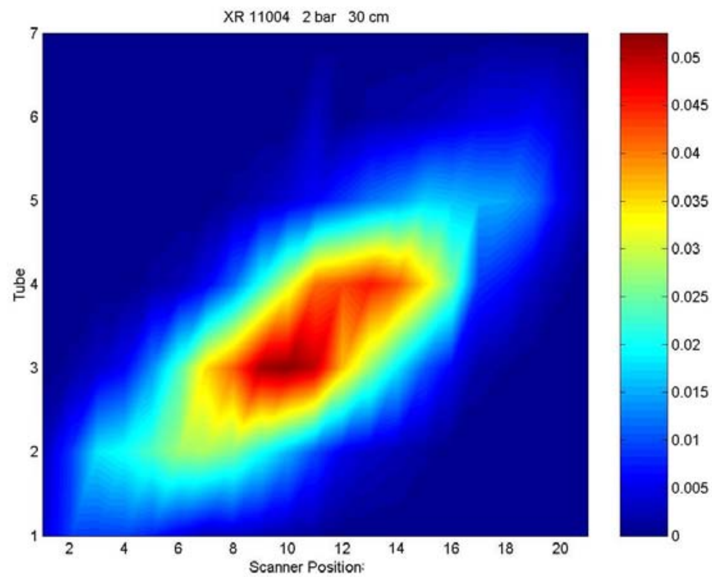


Figure 34. Static spray pattern (l/min) of a flat fan XR11004 at 2 bar and 30 cm nozzle height

3.3.3 Mechanistic model for the dynamic spray distribution pattern

During the project, a dynamic spray pattern simulation model was developed by Lebeau et al. (2002) which was used in this project. To validate the Lebeau model some experiments were carried out and new devices developed.

A first new developed device was a movable spray boom and a dynamic spray pattern measurement system for registration of spray depositions under controlled laboratory conditions as a function of spray boom motions. The movable or dynamic spray boom was constructed but no real tests could be carried out any more due to a lack of time. The boom could be moved with a constant speed or the horizontal spray boom vibrations could be added to the driving speed of the tractor. In this way the boom will increase and decrease absolute speed during spraying and simulates the absolute horizontal spray boom movements.

The registration device, based on capacity measurements, was constructed and a lot of preliminary tests were done. First of all the influence of demineralised water between the capacitor plates was tested. This changing of capacity had to be large enough to create a measurable signal.
The calibration is not yet performed. This calibration is necessary to obtain the correlation between a certain amount of demineralised water between the plates and a change in capacity compared to the situation without water between the plates. Therefore the change in capacity will be measured during spraying of demineralised water and in the same time the increase of the weight of the metal plate will be registered.
The principle of these capacity measurements to register a dynamic spray pattern is not new in a way that previous measurements were done on a conveyer belt with plates from 10 by 10 cm. A nozzle was spraying on the conveyer belt and this belt was running trough the 2 plates of the capacitor. This registration was not a complete spray pattern measurement but only a small strip was measured.
The use of smaller plates (5 by 5 cm) is totally new. For processing of the data, a data acquisition card is used. This card ensures the communication between the measuring print and a computer. The card is driven by software on the PC (Labview). The program processes the data an delivers an Excel file. This file contains a matrix (24 x number of

measuring steps) In this way the measuring grid is the same as the one of the 2D scanner. The program also send information to the motor for the movement of the capacitors. It will be possible to adjust the number of steps, the moving direction and the starting point.
The great advantage of this new equipment is the quick measurement. It will take 25 to 40 minutes to read the whole five meter long spray pattern. Probably it won't be not necessary for most of the experiments to register the whole surface of the plate. After measuring it's sufficient to wipe of the water en dry the surface. After the measurement it will be possible to view and analyse the measured dynamic spray pattern in a small number of actions.

The three following methods for dynamic spray pattern registration can be used in field measurements.
The two first methods use wooden grids, placed on the ground. Depending on the method water absorbing filter papers or water sensitive paper were fixed on the grids. A first test was carried out with a trailed sprayer filled with water mixed with minerals. The wooden sticks were placed as in figure 35.

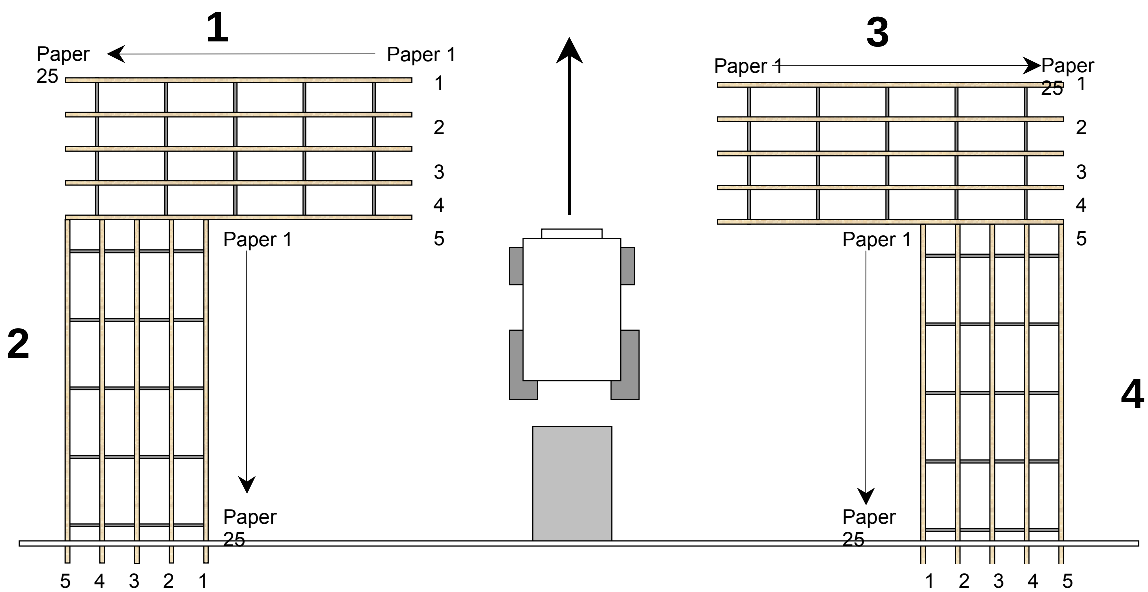


Figure 35. Placement wooden grids with water absorbing papers

The test was carried out in two repetitions. The test soil was a bare field with some small bumps. Another tracer mineral was used for each repetition. After chemical analysis the dynamic spray pattern at a certain place could be reconstructed. Figure 36 shows the results of two sticks of different grids. Perpendicular to the driving direction (grid 3) a small difference in distribution was visual. Parallel with the driving direction (grid 4) a small increase of the tracer was noticeable, due to spray boom roll. On every graph two repetitions are showed. Every time another mineral was used. The similarity between the two repetitions is high.

The analysis of the small filter papers for four grids costed about 1600 € which was too expensive for frequent tests. The advantages of this tracer were the durability (don't evaporate and not degradable under influence of sunlight) and the quantitative results

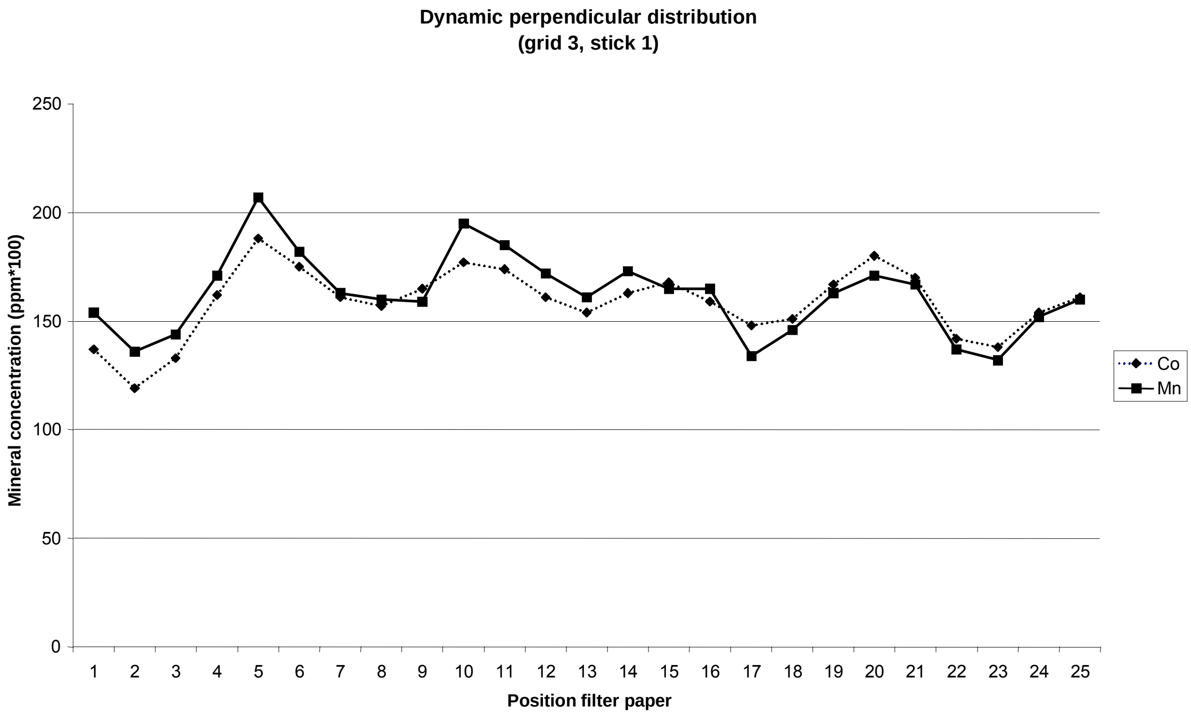


Figure 36. Dynamic distribution perpendicular to the driving direction

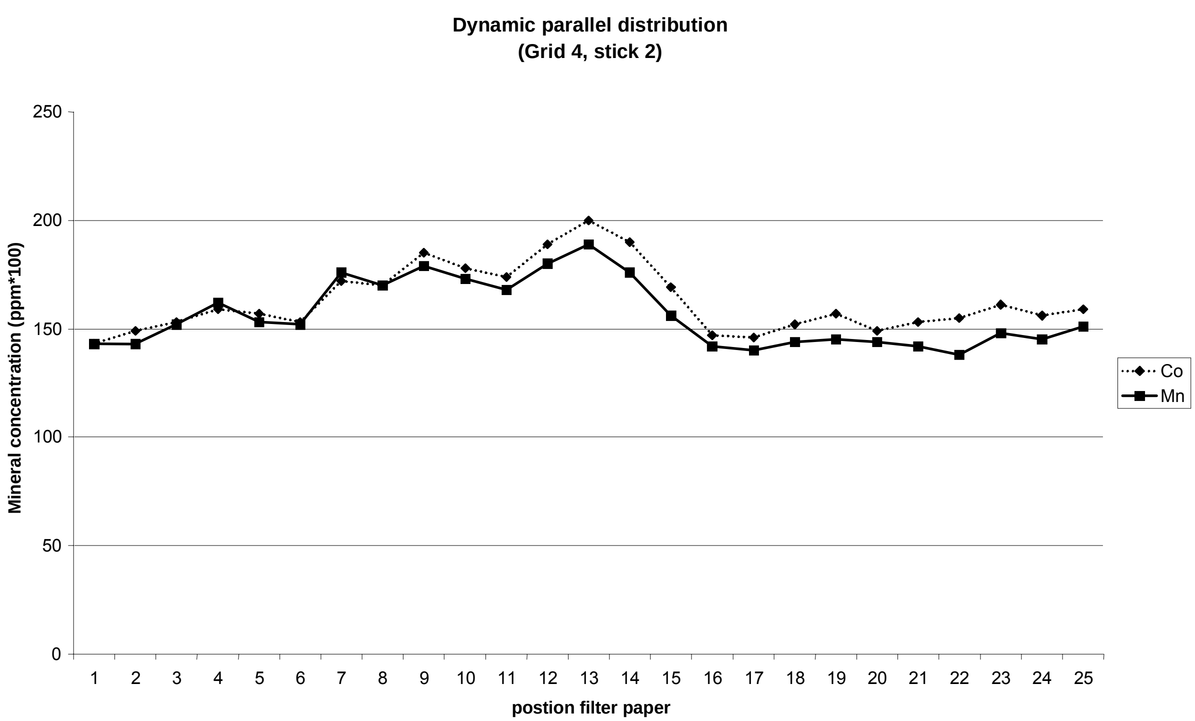


Figure 37. Dynamic distribution parallel to the driving direction

A second, more qualitative way of registering was performed by means of water sensitive paper. This water sensitive paper strips (500 mm long) were stuck together to form a strip of 2.5 meter. These strips were fixed on the wooden sticks of the grids. Different experiments were carried out with this water sensitive papers. The placement of this paper took some time and had to be done carefully. Every wet finger or droplet of water caused blue spots on the paper.
This technique was, compared with the mineral tracer technique, cheap. Materials and analyses costed for 4 grids between 250 and 300 €. This registration technique is however qualitative. The 2D patterns could be compared with the simulated spray patterns but the matrix did not contain absolute numbers.

The registration by means of absorbing papers or water sensitive paper resulted in a data matrix. Measurement of the spray distribution pattern was only performed on the five sticks. To get the spray distribution in between these sticks and create in this way a 2D spray pattern from 1 by 2.5 meter, interpolation between the results of each stick was necessary. A linear interpolation was used to create these 2D patterns. Figure 38 shows the spray distribution calculated from the deposition measurements with water sensitive paper. The colours represent the percentage of coverage of the paper.

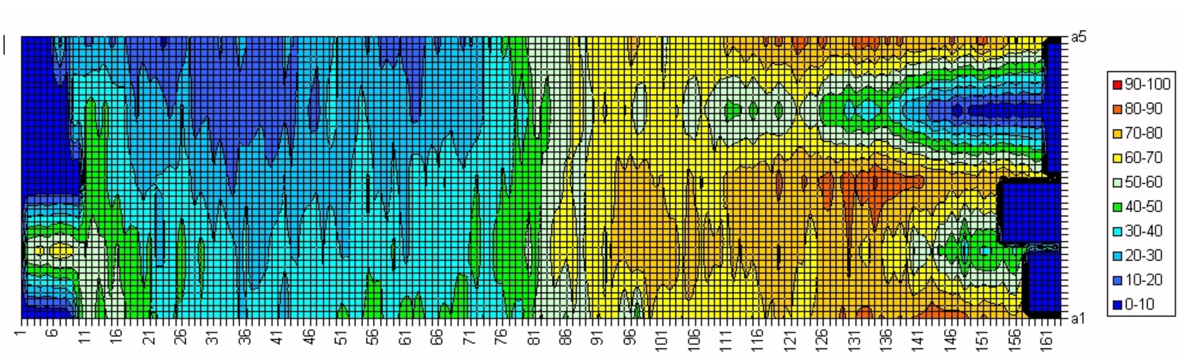


Figure 38. Interpolated 2D spray distribution registered with water sensitive paper (parallel with the driving direction)

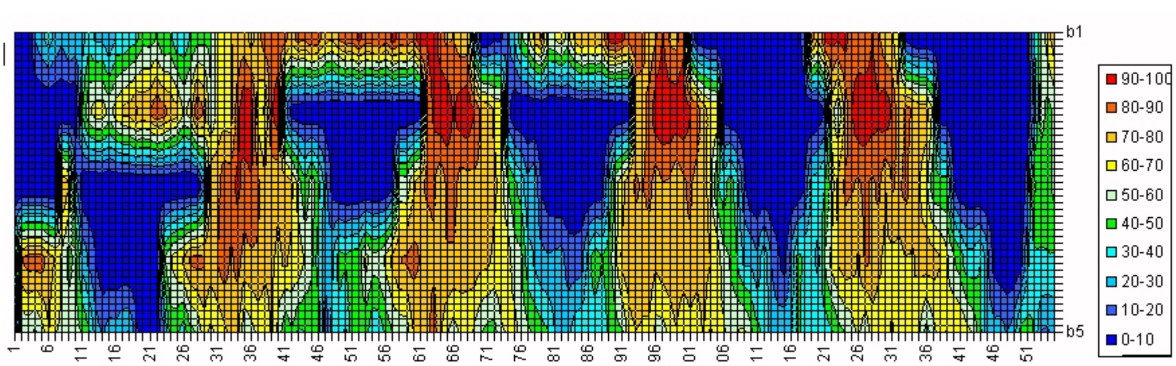


Figure 39. Interpolated 2D spray distribution registered with water sensitive paper (perpendicular with the driving direction)

The last more destructive way of spray pattern visualisation in field conditions was by means of a herbicide in grass land. This kind of experiments was also used to define the maximal acceptable tolerance for spray unevenness. Spray patterns become visual when the spray distribution is very bad. This happens when on some places in the field no or a very low amount of spray liquid reaches the grass due to horizontal or vertical spray boom movements. Overdoses result in a faster killing of the grass. The follow up of the grass happened by means of taking photographs from a mast (figure 40). The frequency of taking pictures changes in function of the weather conditions. The warmer the weather the faster the grass will be killed and the more often pictures have to be taken to evaluate the spray test.

The spray boom movements and driving speed were registered during the field experiment. After processing, this data was used as an input for the dynamic spray distribution model. The model simulated then the spray pattern. Figure 40 shows the visual comparison of the simulated and the real dynamic spray distribution. A good compatibility is visible.

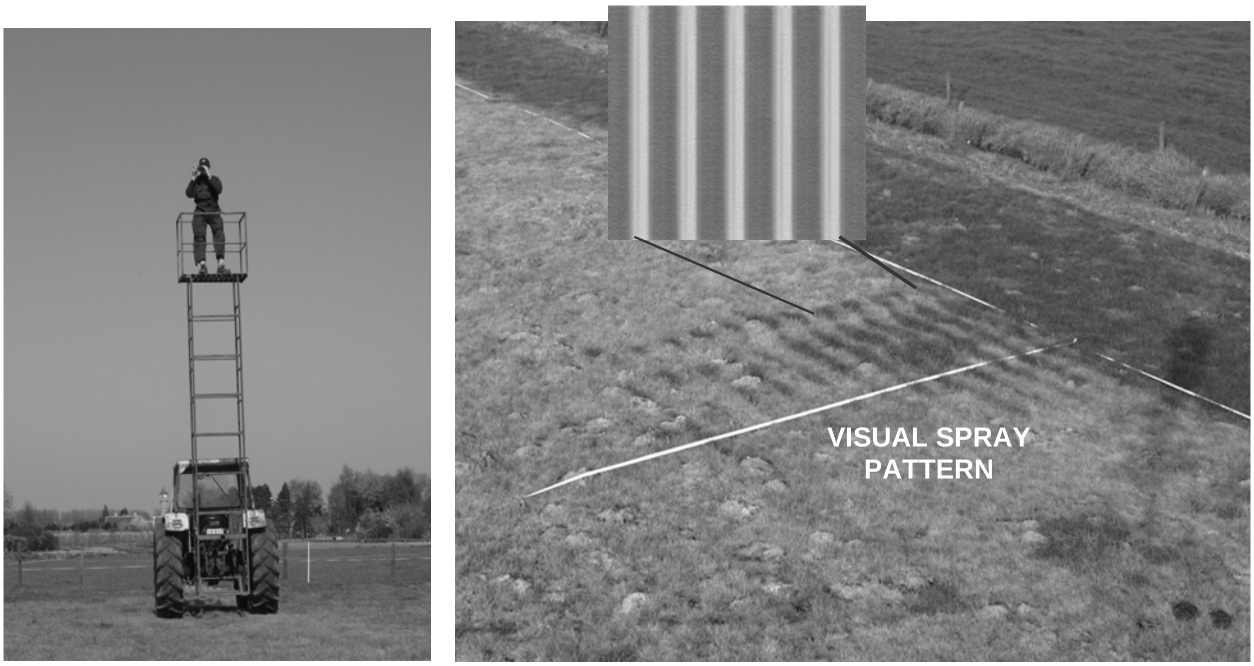


Figure 40. Mast to take evaluation pictures (left) of the visual spray pattern (right).

Besides the graphical evaluation and registration a physical measurement of the green grass lines was carried out. Unfortunately, the evaluation was very labour intensive. For this kind of experiments also a huge grass land was requested that might be destroyed, especially when a certain amount of repetitions is expected.
This destructive method was also tested during potato haulm burn off treatments. During this chemical burn off of the potato leaf the spray boom movements were measured. The spraying was performed with different nozzle types, water volumes and doses. The results of these experiments didn't show any visual influence on the potato haulm burn off treatment because of the small spray boom movements.

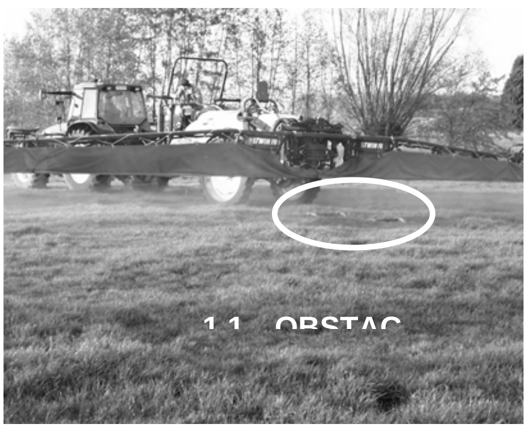
3.3.4 Maximal acceptable tolerance for unevenness in the spray distribution

Only tests with herbicides were carried out each time in combination with the destructive test as described in 3.3.3.

One of the conditions to perform acceptable tolerance tests in field circumstances is the creation of a spray distribution that is not acceptable. By this it is possible, especially for boom roll, to define the critical height of the spray boom and the nozzles for which a bad and insufficient spray distribution is obtained. These field experiments were carried out on grass land. To create boom movements wooden obstacles (10x10x50 cm) were placed on the ground and ditches were dug. The wooden obstacles (figure 41) were placed in line in a way that only one wheel of the sprayer runs over the obstacles at once alternating at the left and at the right side seen from the centre line so that both wheels touch alternately the obstacles. The distance between the obstacles was decreased so the frequency of the excitation increased. Depending on the kind of suspension of the spray boom, the driving speed and the underground conditions, these wooden obstacles caused quite intense spray boom movements. Ditches also created movements but in a way that the spray boom became unparallel with the soil surface. After a while during the tests, most booms stabilised. Digging ditches was labour intensive and was only carried out once.

The field experiments were carried out in 3 repetitions. The experimental plots were between 20 and 45 m long. The sprayers used for this experiments were trailed sprayers. These sprayers offered enough free space to mount the registration devices and settle the operator of these devices.

During the experiment driving speed and movements of the spray boom and chassis were registered. After processing the data the movements could be presented in graphs. An example of a graph is shown in figure 41. This graph represents the height of the spray boom above the ground during the experiment. The height is not measured at the boom tip but more or less 8 m from the centre point. The distance between the IR height sensor an the suspension (i.e. central) point of the boom was known so the height of every separate nozzle at every moment could be calculated.



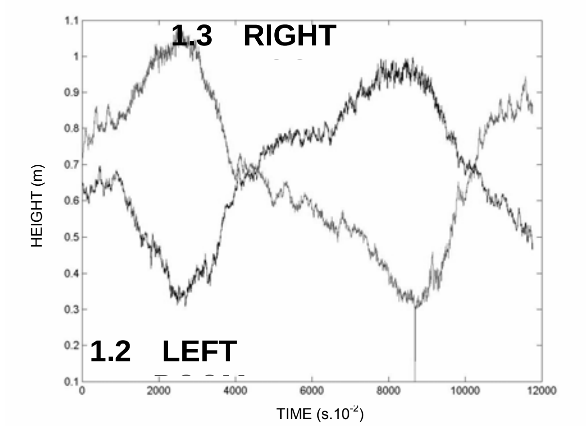


Figure 41. *Left*: view on the wooden obstacles *Right:* Measured spray boom movements (X= time axis [s.10^{-2}], Y= Height above the ground [m])

By means of photographs the status of the grass was evaluated (see also 3.3.3). After a few days or weeks the spray pattern became visible. The exact position of the green lines was measured and the dimensions of the green lines were registered. The boom vibrations were performed in the time domain. Therefore it was necessary to record the driving speed to calculate afterwards the position of the boom on every place of the experimental plot.

The green grass lines, caused by the not killing the grass is the criterion to determine if the unevenness in the spray pattern is acceptable. The starting points of the green lines was localised on the experimental plot. When these coordinates are known the corresponding nozzle height at this place can be calculated. This height is the critical height in these conditions. As visible on figure 42 the spray pattern caused by the rolling of the boom looked like a triangle. For every green line the start position and corresponding nozzle height was calculated. This results were, for the few tests carried out during this project, all between the 20 and the 30 cm.

These tests provided good indications about the critical heights and the acceptable tolerance for the unevenness in the spray distribution. To get more absolute data about these matter, more field test are necessary. Moreover there were no tests carried out with fungicides and insecticides. These plant protection products must also be involved in field tests before realistic standards can be derived from these experiments. Therefore phytopathologists have to be involved in the experiments.

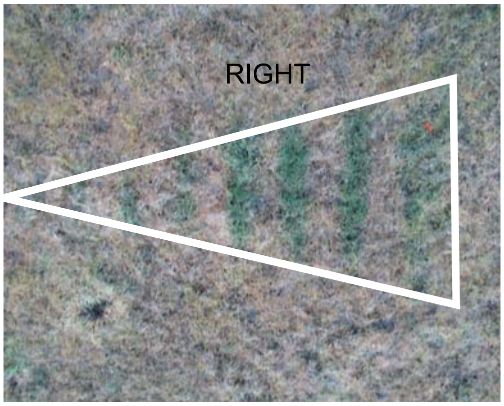


Figure 42. Spray patterns caused by the rolling of spray boom presented in figure 41.

3.4 WP-4. TEST SYSTEM FOR EVALUATING THE MECHANICAL STATUS OF FIELD SPRAYERS

3.4.1 Description of the test system

The specifications of the sensors to be used in the measurement of boom movements are given below.

General rule: sensors with current input > 0.25 A should be avoided. Sensors with current input > 0.5 A must not be used to avoid power shortage and electrical noises.

1. Accelerometers (horizontal boom movements)

Minimum measuring range: ± 2 g
Maximum measuring range: ± 4 g
Minimum frequency range: 0.2 Hz - 10 Hz
Noise: < 10 mg rms
Output: analogue voltage*
All accelerometers must by of the same type and model
Maximum size: 40 x 40 x 40 mm

2. Gyroscope (or DMU)

Quantity: 1 (two axes) or 2 (one axis)
Minimum measuring range: ± 15 °/s
Maximum measuring range: ± 30 °/s
Minimum frequency range: 0.02 Hz - 0.3 Hz
Output: analogue voltage*
Maximum size: 100 x 100 x 100 mm

3. Distance sensors (horizontal movements of the boom)

Type: ultrasonic or infrared
Minimum measuring range: 0.1 - 1 m
Minimum frequency range: 0 - 0.3 Hz
Output: analogue voltage*
The two sensors must be of same type and model
Maximum size: 100 x 100 x 100 mm

4. Radar sensor

This sensor must have European agreement for use on agricultural vehicles
It should be coupled with an impulse counter with analogue output voltage.
Minimum frequency range: 0 - 0.3 Hz
Maximum size: 250 x 250 x 250 mm

5. Accelerometers (vertical boom movements)

Minimum measuring range: ± 3 g
Maximum measuring range: ± 4 g
Minimum frequency range: 0.1 Hz - 10 Hz
Noise: < 10 mg rms
Output: analogue voltage*
Maximum size: 40 x 40 x 40 mm

6. Infrared Distance sensor for measurement of the relative inclination between the sprayer's frame and the boom

Minimum measuring range: 3 - 8 cm
Maximum measuring range: 0 - 20 cm
Minimum frequency range: 0 - 0.3 Hz
Output: analogue voltage*
Maximum size: 30 x 30 x 100 mm

*The output range must be similar for each sensor and related to the acquisition devices. The output range of each sensor must be at minimum 10% of the effective input range of the acquisition device For example, if the acquisition device has an input range of +- 5 V, the output range of each signal must be at least A ± 0.5 V, within the ± 5 V limit (A = constant)

7. Acquisition device

Number of input signals: minimum 16
Resolution: minimum 12 bit
Sample rate: minimum 1000 Hz
Type: PC-MCIA card of other compatible with the chosen computer (but not external)

8. Computer

Processor: Intel Pentium III of higher
Memory: 128 Mb of higher
Operating system : following acquisition device and software

9. Acquisition software

Following acquisition device. The output format will be a text file with Tab separator between columns.

10. Wires

Use shielded wires for exposed wires. The noise generated along the wires must not exceed the sensor noise specifications (see above)

11. Connecting box

This box will contain stabilised power sources for the sensors, the data acquisition connector and all on/off switches.

12. General power source

Sensors must be powered by battery with a sufficient capacity. Alternative power sources must be checked to ensure that the generated noise is not prejudicial to the output signal of each sensor.

The base of the test system is the physical track. The selection of the test track is described in 3.4.1.. The test track is divided in 34 parts. This is necessary to transport the track. The total weight is about 4000 kg.

The whole measuring train consists of accelerometers (5), a gyroscope, distance sensors (2 or 4), a radar sensor, acquisition device, a computer, wires, a connecting box and a general power source. This sensors are positioned and used as described in WP-2.

To place the computer and the connection box during the testing a van (figure 43) or trolley can be used. It’s also possible to place this equipment on the trailed sprayer but then it’ll take more time to change the measurement train from sprayer to sprayer. Once all the wires are connected only the sensors have to be changed if another machine is tested.

Figure 43. Test driving on the test track. Van with PC and DAQ follows the sprayer

3.4.2 Evaluation results of the test system

The placement of the physical track takes less then 2 hours with 4 men. A trailer is used to transport the track. To handle the track loading equipment (like a tractor) is necessary.

The mounting of the sensors on the sprayer, the measurement itself (3 repetitions) and the dismounting of the sensors takes between 50 and 100 minutes for one person. The variation depends on the machine type. This ‘testing time’ can be reduced if the installation is carried out by 2 or more persons.

This ‘testing time’ doesn’t include the installation of the computer an the placement of the wires. Once these devices are installed they can stay in the van to perform the tests of different machines.

A covered place is recommended to be independent of the weather conditions.

The track was tested at 2 different speeds with one trailed machine.

3.4.3 Directives about the test procedure

The lack of time caused that only one real test of the test track could be performed. During the project different field experiments were carried out.

For the moment there is not enough data available to write real standards. The equipment and test protocols are available, only more test have to be carried out. Especially to determine the acceptable tolerances more field experiments are necessary.

The sensors must be placed on the sprayer following the rules presented below. The methodology to follow for obtaining the boom movements from the signals of the sensors has been fully described above. More details are provided in [1], § 4.3.

1) Radar sensor : this sensor must be rigidly fixed to the sprayer frame or to the tractor (trailed sprayer) following the instructions of the manufacturer (height, orientation, …). No sprayer part must interfere in its operating range.

2) Gyroscope : this sensor must be rigidly fixed to the sprayer frame or a sprayer part rigidly fixed to the frame. The orientation of the yaw axe will be vertical, with a tolerance of ± 10°, and the roll axe will be following the forward direction, with the same tolerance.

3) Ultrasonic distance sensors: these sensors must be placed on the sprayer boom symmetrically from the boom centre (tolerance = ± 10 cm, figure 45). They must be at a minimum distance of 45 cm from the centre of the boom, and may not be fixed to a mobile part of the suspension. The ultrasonic signal must hit the target at a minimum distance of 15 cm from the edges (or following manufacturer instructions). The targets must be vertical and parallel to the rear axle of the vehicle (tolerance ± 5°). The ultrasonic beam must be horizontal and parallel to the forward direction (tolerance ± 5°). The minimum distance between the sensors and their targets must be respected (10 to 20 cm).

4) Accelerometers (horizontal movements) : these five sensors must be placed horizontally following the forward direction (± 10°). One of them must be placed on the centre of the boom, the others near the articulations of the boom (maximum 25 cm, interior side : 1,2,4 and 5, figure 44). If the conditions (a) and (b) (figure 45) are not verified with this configuration, the combinations (c) and (d) may be used (figure 45) with the same restrictions concerning the distances. If none of these configurations may be applied with the restrictions (a) and (b), the minimum distance of 25 cm from the articulations may be ignored. The placement of the sensors on the last, very mobile part of the boom should be avoided, if possible.

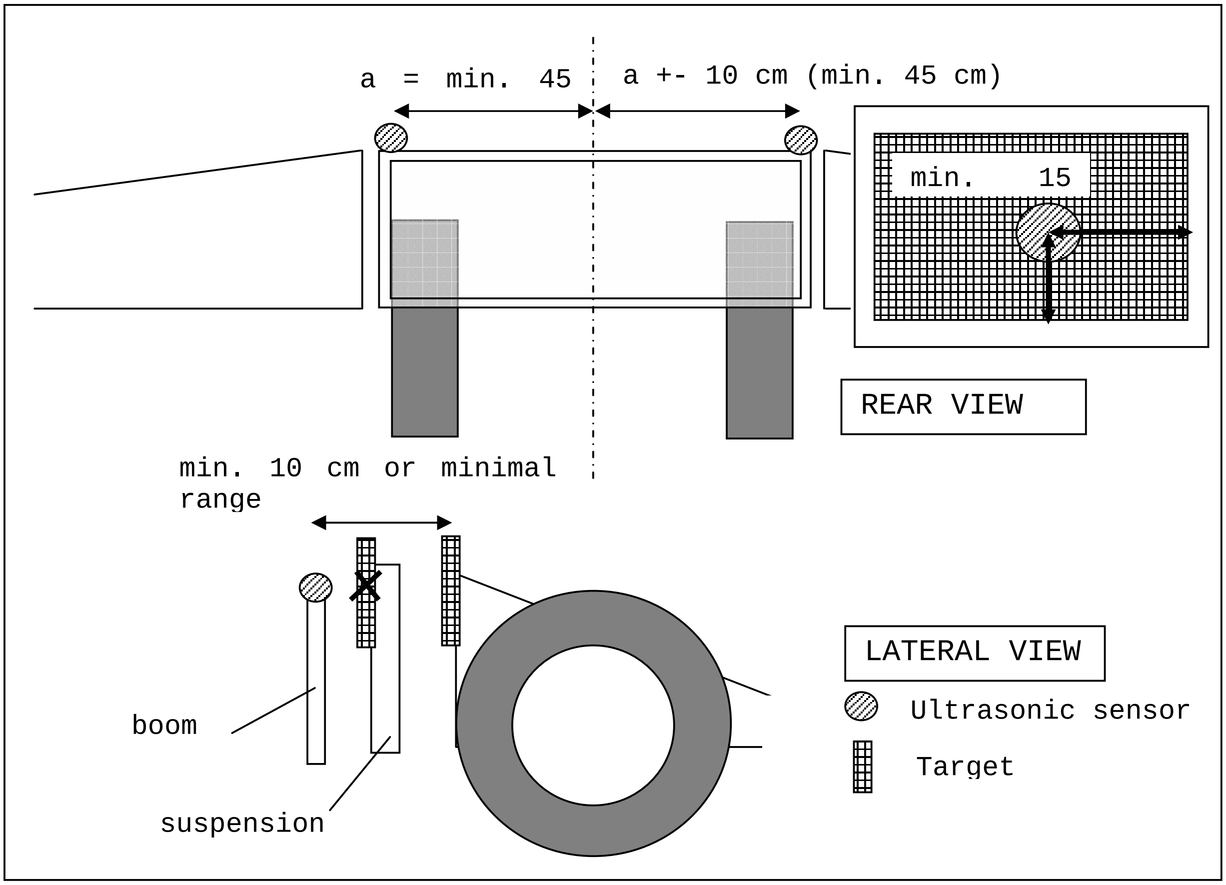


Figure 44. Disposition of the ultrasonic sensors.

5) Accelerometers (vertical movements): these two sensors must be placed at the same location as the accelerometers (2) and (4) of figure 45, or following the scheme of figure 46. The use of bi- or tri-axial accelerometers allows the measurement of horizontal and vertical movements with the same sensors. These sensors must be placed vertically (± 10°).

6) Infrared sensor: this sensor (minimum range: 3 to 5 cm, maximum 8 to 20 cm) must be placed on the suspension, to provide a distance modification of the measured distance related to the relative inclination between the boom and the sprayer frame. The sensor has to be calibrated using the following procedure (figure 47):

a) The sprayer is standing on a flat surface, the boom unfolded.
b) An operator is standing at the boom tip, with a graduated rule and a notepad. These elements may be replaced by an appropriate distance sensor mounted on the boom.
c) The operator moves the boom tip up and down at the following levels:

- on the ground;
- at half the initial height of the boom;
- at the initial boom height;
- at the three halves of the initial boom height;
- at twice the initial boom height.

The inclination angles are derived from the boom length and the heights of the boom tip.

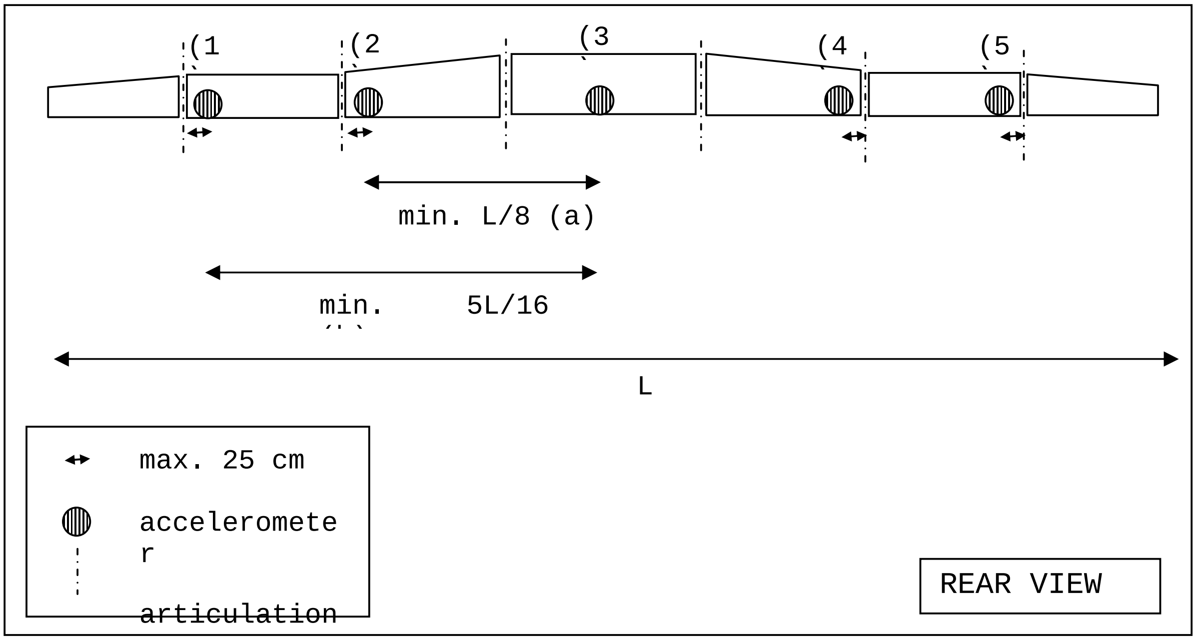


Figure 45. Location of the accelerometers.

d) At each boom position, an operator notes the output of the distance sensor located on the suspension. This operation may be automated.
e) The relation between the measured distance and the relative inclination boom/frame is established using a calibration straight line. If the maximum linearity error is above 5%, a cubic interpolation will be used instead.

Notes:
- For a mounted sprayer, the « frame » is related to the tractor frame or the part of the sprayer rigidly fixed to that frame.
- It is better to fix the sensors while the sprayer is unfolded at the work height, and not to fold it while the sensors are fixed on it. If it is necessary to fold it with the sensors on it, the targets of the distance sensors have to be removed and a special attention is necessary not to damage the wires.
- If the frame also moves during the calibration of the infrared distance sensor, the use of a tilt sensor is necessary to measure its roll position. A DC coupled accelerometer may alternatively be used for that purpose.

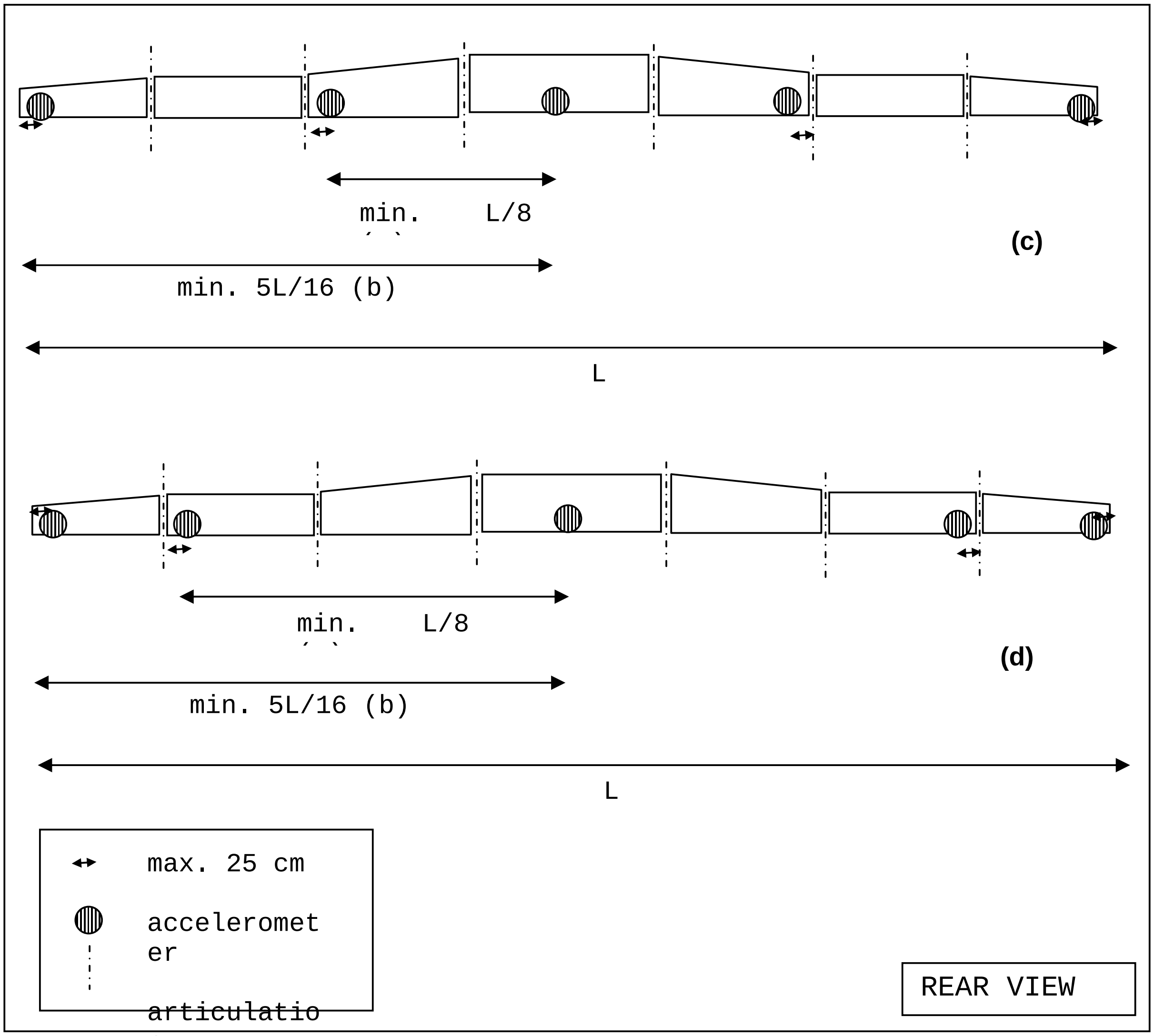


Figure 46. Alternative locations for the accelerometers.

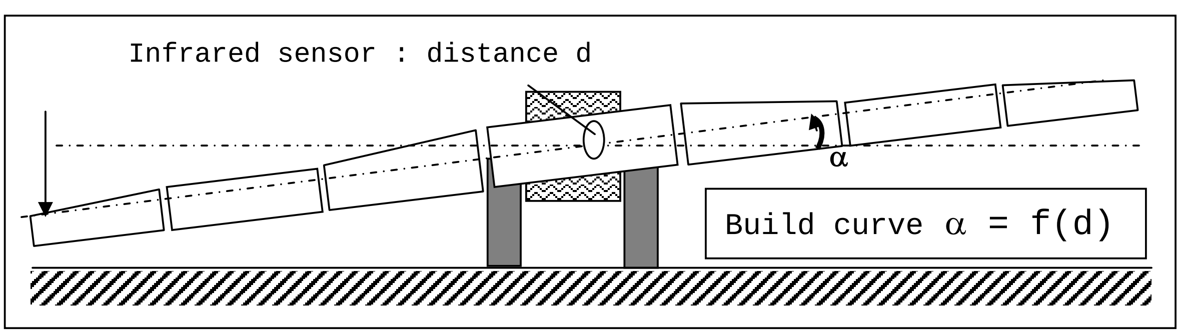


Figure 47. Building the relation between the relative roll (boom/frame) and the output signal of the short-range infrared distance sensor.

3.5 CONCLUSIONS

3.5.1 Multibody model of a trailed and self propelled sprayer

A multibody model of a trailed sprayer from the company Beyne and the self propelled sprayer "EUROTRACK" from the company Delvano was built with the general purpose software ADAMS and DADS respectively.
The model of the trailed sprayer consisted of two parts: a detailed model of the boom with suspension and a model of the carrying frame with the tires. Boom roll and hop could be predicted accurately. Predictions of horizontal boom movements were not so reliable. Roll of the frame could be well predicted contrary to yaw of which the model could not provide reliable results.
In the model of the EUROTRACK much attention was paid on a detailed model of the tractor. The model of the boom with suspension was conceived in less detail. Based on measurements of machine vibrations, unknown machine parameters were estimated through an optimisation procedure in OPTIMUS. To this end a mono poster mobile shaker was conceived. Tractor roll, tractor hop and boom roll could be predicted accurately. Prediction of tractor pitch and yaw gave unreliable results.

From the results it may be concluded that multibody models are an interesting tool for predicting the dynamic behaviour of machines. However, the accuracy of the prediction of the dynamic behaviour of both sprayers depends on the modes considered. Vibrations in the modes roll and hop can be well predicted, vibrations in the modes yaw and pitch are much more difficult to predict. The accuracy of the models could be improved by increasing the number of bodies in the multibody and the introduction of more precise parameter values (masses, centres of mass, moments of inertia for the different bodies, damping and stiffness coefficients of tires and suspensions, better tire models, …). This problem could be (partially) solved by setting up extensive experiments for a precise determination of these parameters.

The model of the self propelled sprayer was used for deriving excitation tracks in a formal way. The model of the trailed sprayer was used to determine the optimal position and number of sensors for measuring the mechanical integrity of the spray boom and suspension and for evaluating the derived tracks.

3.5.2 Derivation of representative tracks as excitation source of the tested sprayer

Currently, the ISO5008 track is available for testing the dynamic behaviour of mobile agricultural machinery. From a stochastic viewpoint this track was not rich enough such that not all the modes of interest on a spraying machine could be excited in a proper way.
Representative tracks were derived according to a unique procedure:

- Measurement of vertical (rolling) and horizontal (yawing) boom vibrations of different spraying machines under different field conditions. The newly designed tracks had to be able to reproduce similar (i.e. realistic) boom vibrations.
- Traditional derivation of excitation tracks is a tedious and extremely time consuming work. Fortunately, a formalised procedure for deriving representative tracks has been proposed called "service load simulation". The procedure is has been developed in the road vehicle industry and was used for the first time on agricultural machinery in this project. Normally, a four poster electro-hydraulic shaker should be available for reproducing iteratively measured accelerations on the wheel axles. The vertical movement of each hydraulic cylinder under the tyres of the vehicle is a representation of a wheel track. For heavy vehicles, a powerful four poster had to be available. In this project, the real vehicle was replaced by a multibody model with which the measured vertical axle accelerations were reproduced by a virtual four poster placed under the tyres of the model. The vertical motion of each poster represented the wheel tracks. Although the accuracy of the EUROTRACK model was not complete, the axle accelerations could

be reproduced very precisely by the introduction of four feedback control systems, increasing the robustness of the reproduction procedure against model uncertainties. This procedure, based on multibody models is unique

- Based on this information 16 short tracks with the shape of a multisine and a block profile were derived with a power spectrum as close as possible to that of the reproduced tracks. An important conclusion was that a simple block profile could reproduce a spectrum as rich as any other type of track (e.g. multisine) which is an important conclusion from a practical viewpoint (easy to construct, …).
- The two virtual tracks that could reproduce most accurately realistic boom vibrations were selected with the model of the trailed sprayer. Although the selected tracks were much richer than the ISO5008 track, they were unable to provide satisfactory results (i.e. reproduction of realistic boom vibrations) especially for boom roll. From this it seemed clear that representative tracks may not be derived based on one machine.
- Finally the block profile with a constant block height of 5 cm and a total length of 51.2 m with an adaptable distance between the blocks and lengths of the blocks.
- The designed track was finally tested. Measured boom movements of a trailed sprayer while crossing the track were higher than under field conditions, especially between 0.1 and 0.2 Hz. This problem could be solved by smoothen the edges of the blocks and/or by lowering the blocks (e.g. by filling up the space between the blocks).

3.5.3 Determination of the type of sensors to be used, their number and position on the spraying machine

- Radar sensor: rigidly fixed to the sprayer frame or to the tractor (trailed sprayer), measures tractor or sprayer forward speed.
- Gyroscope: rigidly fixed to the sprayer frame or a sprayer part rigidly fixed to the frame, measures yaw and roll.
- Ultrasonic distance sensors: placed symmetrically on the sprayer boom at a minimal distance of 45 cm from the boom centre, measure the relative displacement of the boom with respect to the vehicle
- Five accelerometers: placed on five different predefined locations on the spray boom, measure the absolute horizontal boom accelerations
- Two accelerometers: placed on two different predefined locations on the spray boom, measure the absolute vertical boom movements.
- Infrared sensor: placed on the suspension, measures the distance related to the relative inclination between the boom and the sprayer frame. In addition, a detailed procedure is given for describing the calibration of the infrared sensor.

It is the first time according to the most recent literature that such a detailed procedure for measuring boom movements has been described.

3.5.4 Development of reliable spray deposit distribution models to simulate the spray distribution as a function of boom vibrations

In a next stage, after registration of horizontal and vertical boom movements of the sprayer under consideration, these movements should be related to a so called dynamic spray deposition pattern. The latter is extremely difficult to obtain directly. Therefore, an indirect method was worked out consisting of four steps:

- Registration of the static spray distribution pattern of different nozzles. Based on a 2D-scanner, developed at the University of Uppsala, Sweden, in the framework of the SPECS project, a totally refreshed 2D- scanner was designed. The scanner consists of 24 liquid tubes that are filled with liquid from the nozzle during a predefined number of steps the scanner moves at constant time intervals under the nozzle during the experiment. With this scanner it is possible to measure the static spray distribution of any kind of nozzle at a certain liquid pressure and height of the nozzle by measuring the evolution of the liquid height in the tubes during the experiment. The time needed to register one static spray pattern is between 2 and 4 hours. Since it took quite a lot of time to upgrade the SPECS scanner, only about 20 static spray patterns of different nozzles could be registered yet.

- Preparation of the data for developing the dynamic spray distribution pattern. The data should be presented as a data matrix in excel (24 liquid tubes of the scanner x the number of steps the spray scanner has been executing).
- A mathematical relation between the static spray distribution model and the dynamic spray distribution model has been established by F. Lebeau whose model is an improvement of the model of H. Ramon.
- A methodology for the validation of the dynamic spray distribution model was executed. A laboratory set up intended for validation under more controlled conditions, was constructed but calibration and experiments could not be performed yet. The experiment makes use of differences in capacity between two steel plates depending of the amount of demineralised water between the plates. The principle is not new but the precision is increased significantly compared to the existing set ups owing to the use of smaller steel plates. In addition, a large surface of 5mx1.2m could be measured in one test instead of a small strip. Three field tests were examined. In the first test or mineral tracer test, the sprayer crossed wooden grids covered with special absorbing paper, sprayed with mineral water. By chemical analysis of the papers, on which the tracer was grafted, undesired boom movements during spraying could be quantified. Unfortunately, this is an expensive method that limited the number of experiments. In the second test water sensitive paper strips were fixed on wooden sticks and placed on regular distances in the field. After spraying, the strips were treated by image analysis techniques. A full 2D spray distribution pattern was obtained by interpolating the measured data. This method is cheap but gives only qualitative results. In the third method, a pesticide is used and meanwhile boom movements are recorded. Boom movements were induced by crossing wooden obstacles or small ditches with the sprayer. In this research a round up was used and its effect was successfully reproduced by the dynamic spray distribution model.

3.5.5 Establishment of the maximum tolerances for variation in liquid distribution under a spray boom during operation

Field experiment three was used to establish the relation between boom movements and efficiency of the pesticide. Only round up was used. In more extensive experiments the relation between boom movements and the efficiency of other pesticides should still be investigated. Conclusion from the project is that phytopathologists had to be involved in the project to derive the relation between tolerable boom movements and pesticide efficiency. Final directives and standards about tolerable boom movements is however an international matter in which the project results and developed methodologies can contribute significantly as it is the first project in succession of the SPECS project that provides a well established and systematic procedure for investigating tolerable boom movements.

3.5.6 Development of a test rig for rapid testing the mechanical status of sprayers

As a final result of this project, a detailed description of a test procedure with necessary equipment, for evaluating the mechanical status of spraying-machines is established. The proposed test procedure is unique in the sense that it has been performed for the first time.
The procedure includes the following steps:

- Description and calibration of the sensors used together of the data acquisition apparatus and the power source.
- Description of the test track with proposed travel speed for excitation of the sprayer.
- Placement of the sensors and acquisition equipment on the machine.
- Description of the configuration of the boom and suspension during preparation and during the test.

4 DISSEMINATION AND VALORISATION

4.1 MULTIBODY MODEL OF A TRAILED AND SELF PROPELLED SPRAYER

A multibody model of a trailed sprayer was developed and used to predict the sprayer movements (boom and frame) on rigid tracks. The two interconnected parts of the model may be used separately or successively to predict the roll movements of the frame of any trailed sprayer or the boom movements of nearly any sprayer. The model was designed as a tool for developing normalised track. Some results were presented at the International Conference on Agricultural Engineering in Budapest (2002), under the title : « Development of a Multibody Model of a Sprayer » (Ooms et al. (2002b)).

A multibody model of the self propelled sprayer EUROTRACK was conceived. Special attention was paid to the tractor model, carrying the spray equipment. With this model, excitation tracks were developed in a more formal way. This methodology has been presented in the ACOMEN workshop (Vanden Boer et al., 2002). Currently, two journal papers are in progress that will be submitted before the summer 2003 to the journal “Biosystems Engineering”.
The Leuven group has recently been approached by Dr. Andreas Herbst, senior research engineer at the BBA (Biologische Bundesanstalt für Land- und Forstwirtschaft, Application Techniques Division, Germany). Dr. Herbst is currently involved in a CEN working group responsible for the standardisation of an excitation track for the evaluation of vibrations on agricultural machinery. The Leuven group was contacted for joining a discussion forum to give advise about the reliability and performance of excitation tracks.

4.2 MEASUREMENT METHOD OF BOOM MOVEMENTS

The proposed method is well-suited to measure the horizontal and vertical boom movements of sprayers in the field (Ooms et al. (2002a)). It was applied to gather data concerning boom horizontal movements in a wide range of field conditions to evaluate the spray coverage due to these movements. Five sprayers from two manufacturers were tested during the years 2000-2001 period: one mounted, two trailed and two self-propelled ones, with boom lengths comprised between 18 and 33 m. More than 28 km of field tracks corresponding suited to with a large wide range of uses spectrum of use were covered: wheat (36%), meadow (19%), chicory (18%) and unplanted fields (27%). Only one sprayer was equipped with an horizontal suspension. Two trailed sprayers with boom length of 27 m were tested during the year 2002 at the CLO-DVL of Gent. The sprayers were running on meadows and potatoes fields. An herbicide (meadow) and a fungicide (potatoes) were applied during the trials.

It was shown that the horizontal movements largely influence the spray deposit longitudinal distribution, even if other parameters such as boom height variations and wind effect are present. A sprayer equipped with an horizontal suspension should thus therefore be a good choice to reduce for reducing spray coverage variations in the longitudinal direction. The additional cost of such a device should be compared to the economy savings made by reducing the spray coverage variations. The suspension efficiency, the product costs and the ecological benefits are the other parameters to take into account (Ooms et al, (2003)).

Initial contacts have been layed to present the results of this project in one of the coming meetings of the CEN working group within CEN TC 144/WG3, responsible for the standardisation of allowable boom movements.

5 BALANCE AND PERSPECTIVES

5.1 MULTIBODY MODEL OF A TRAILED SPRAYER AND A SELF PROPELLED SPRAYER

Thanks to its flexibility and its ability to predict roll motion, the multibody models are an interesting tool to improve the sprayer design, allowing to find the best combination of parameters that satisfy predefined constraints in the sprayer behaviour. Using the data bank that includes the frame movements of several sprayer types measured in several types of fields, the behaviour of a sprayer boom can be analysed in function of the type of solicitation, as well as the type of suspension of the boom. This may help a purchaser to choose the right suspension type taking into account the future range of use of his sprayer.

5.2 EXCITATION TRACKS FOR OFF ROAD MACHINERY

First development of excitation tracks shaped as an easy to construct block profile, for off-road (agricultural) machines in a scientific way based on service road simulation by the aid multibody models of two types of sprayers.

It has been shown that it is very delicate to use one standardised excitation track for different agricultural machinery (e.g. sprayers, combines, …), even for different types of machinery with the same functionality (trailedsprayers, self-propelled sprayers, …). This can be solved by the construction of modular tracks (replacing the flexibility of shakers). Block profiles are simple tracks which are easy to adapt and are at least as rich with respect to their power spectrum, as other types of tracks.

5.3 MEASUREMENT OF BOOM MOVEMENTS BY SENSOR DATA FUSION

Within the context of a more intensive control of residues on food, the measurement chain combined to spray deposit models allows the generation of database that can contribute to traceability.

5.4 TEST METHOD AND CRITERIA FOR EVALUATING THE MECHANICAL INTEGRITY OF BOOM SPRAYERS

The comparison between the boom movements of a trailed sprayer while running on the test tracks or in the field indicates that the roll motion and the horizontal movements of the boom were higher on the tracks. For other sprayers, the frequency content of the roll movements was different from that measured on the tracks.

This suggests that the tracks could be improved. For example, it may be suggested to smooth the block edges and reduce their height.

However, the huge variability of the movements measured in the field shows that the representativity of the test tracks remains difficult to ascertain.

5.5 REFINEMENT OF EXISTING LABORATORY EQUIPMENT TO REGISTER THE SPRAY DISTRIBUTION PATTERN OF A NOZZLE

A refined 2D spry-scanner was developed with which the static spray pattern of any nozzle can be registered between 2 and 4 hours.

Based on the principle of electrical capacity measurements, a laboratory setup for registering the dynamic spray pattern of a moving nozzle was conceived. Unique is that the large steel plate of the capacitor is 5mX1.2m and by this one spray motion of 5m can be measured The small steel plates are 5cmx5cm that increased the accuracy of the current laboratory setups.

Description and results of these two laboratory devices will be published in the near future in the appropriate international journals.

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