Evaluating boom height control performance with variable boom roll damping in a suspended boom system on self-propelled sprayers

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“Thinking is the hardest work there is, which is probably the reason so few engage in it.”

– Henry Ford
ABSTRACT

In this research, a method for improving spray boom height stability was developed and tested. Self-propelled sprayers played a critical role in agriculture by applying chemicals to crops to control the presence of weeds and pests. The spraying process needed to be controlled in a manner such that the spray boom maintained the necessary target height for uniform coverage. Deviation from target height allowed outside factors such as wind to become more prevalent during chemical application which generated opportunities for spray drift to occur and potentially harm neighboring crops and environment.

On a suspended spray boom system, terrain influences on the chassis as well as height activation of individual wings induced boom roll that generated target height errors along the length of the boom. This research examined areas of opportunity for applying variable damping rates to boom roll with the intent of managing unwanted boom roll. Intelligent control of boom roll damping rates could minimize induced boom roll and improve target height control of the boom.

Virtual modeling software was utilized during the variable damping development process in order to simulate induced boom roll scenarios and evaluate successful application methods. Magnetorheological dampers provided the ability to further analyze variable damping methods on a full-sized sprayer in a field operating environment. A control system was designed using inputs from the sensors on the sprayer to detect induced boom roll and trigger increases in damping rates momentarily.

Increased damping rates proved to mitigate boom roll motion relative to the sprayer chassis. However, boom height control was only considerably improved when variable
damping was applied during significant chassis roll events. In many instances, controlling boom roll motion with variable damping rates induced error into the chassis roll angle, therefore still creating boom height error.

Semi-active control of boom roll influenced the dynamics of both the spray boom and chassis. There were many critical factors that impacted the target height control of the spray boom. The suspension systems of the spray boom and chassis influenced one another and should therefore be considered jointly when developing methods for boom target height control.
CHAPTER 1.  INTRODUCTION

1.1 Overview of Agricultural Spraying

Agricultural spraying is a key factor for maintaining high crop yields while controlling the negative impacts from weeds, pests, and disease (Anthonis et al., 2002). Producers can apply a variety of herbicides and pesticides to their crops using agriculture spraying equipment. Sprayers can be pulled behind a tractor (i.e., as an implement) or have the ability to be self-propelled (Figure 1.1). In both cases, there is a spray boom that applies chemicals from an onboard storage tank. Nozzles located along the length of the boom atomize liquid chemicals to disperse a uniform coverage of spray. When producers spray, they attempt to be as efficient as possible with respect to time and chemical costs. As a result, spraying equipment has become larger, faster, and more advanced with the advent of precision mapping software.

![Figure 1.1: Self-propelled John 4030 Sprayer 120’](image)

Self-propelled sprayers are commonly used in the global agriculture industry. These machines are capable of carrying up to 6060 liters of chemicals on board and have the ability to spray a path of 36 meters wide during operation. As a result of these advances, hundreds of hectares can be sprayed in a day. Sprayers may operate in various terrain conditions and travel a wide range of speeds over the course of a growing season. It is important for sprayers to adapt to their working environment and maintain a controlled application of chemicals. This
is a challenge that has many dynamic variables such as terrain, wind, and sprayer machine motion. If these factors are taken into account using advanced control systems, the process of spraying can be made more predictable and efficient which benefits the producers.

1.2 Managing Chemical Drift

Chemical drift during the spray application process is a significant reason for improving boom height control. Drift occurs when the sprayed chemicals being applied come into contact with the ground or plant off target. This can lead to damage of human health, environmental contamination, and property damage (AAPCO, 2005; Delaplane, 1996; Shaw, 1996). Many factors such as wind, boom height, terrain profiles, and spray nozzles can lead to chemical drift (Figure 1.2). If the spray particles leave the boom at a height above the target elevation, then the downward travel time is extended; thus, allowing wind (if present) to carry the spray particles off course. On the contrary, if the chemicals are applied below target height too close to the crops, the spray patterns are more concentrated and the crops will receive a higher application rate (L/ha) which may lead to future damage. Implementation of boom height and boom roll control systems during chemical application can result in the desired uniform spray dispersion over a field.
1.3 Need for Improved Boom Roll Control

Up until 2008, there were reports of self-propelled sprayer manufacturers utilizing aftermarket solutions to integrate active control systems for boom roll on production machines (Hest, 2008). These systems were expensive and complex, and manufacturers had not made the investment in developing their own active control system for boom roll. However, they had introduced and produced a boom height control system that managed individual wing height positions to maintain a target height. These systems were satisfactory and provided an improvement in boom height control, but there were continued disturbances that generated a rolling motion of the spray boom (Figure 1.3). When the sprayer chassis traveled over rolling terrain, the boom tended to follow the roll of the machine. It can be inherent to a hydraulic controlled spray boom, no matter the manufacturer, that if the wing height control system is
active, small delays in corrective actuations can lead to compounding boom roll error when attempting to achieve target height.

As sprayer manufacturers strive to develop improved controllability of the boom, boom roll is a degree of freedom that has potential to be managed and controlled. Other degrees of freedom such as hydraulic actuation delays, chassis suspension, and boom height control software are much more difficult to address due to physical constraints of the machine and sacrifices to operator comfort. The exploration of new spray boom control methods is necessary for manufacturers because the demand for maintaining target height has increased from producers.

![Rolling motion of a spray boom](image)

**Figure 1.3: Rolling motion of a spray boom**

*Source: (Anthonis et al., 2002)*

The introduction of light weight carbon fiber spray booms raised concerns about boom controllability because they are prone to breaking when making ground contact. Carbon fiber booms are mostly utilized on the widest booms in order to reduce weight; however, they make ground contact at shallower roll angles than shorter booms. They are very costly to repair, so controlling their position to avoid damage is very important.
1.4 Description of Boom Roll

A sprayer boom is designed to roll independently of the chassis to which it is fixed. For example, if the sprayer chassis experiences a change in roll position of ±2 degrees over a 10 meter distance (e.g., a low washout) the boom will essentially be unaffected by this since it not fixed to the chassis. Depending on the design and manufacturer of the sprayer, the mechanisms for allowing this boom characteristic can vary due to different boom geometries and dimensions. Some common designs include a fixed pivot and dual pendulum links. A fixed pivot is described as the boom connected to the chassis at a single point on which it is free to rotate. On a dual pendulum link design, two links connect the suspended boom to the chassis and their connection joints are free to rotate.

In all designs, there are constraints to how many degrees the boom can rotate. Physical stops placed on the boom and chassis limit roll angle. In many cases, these are used to protect other components during excessive boom roll events. These other components include boom roll dampeners and centering springs which typically have a fixed range of linear extension/compression.

Boom roll dampeners control the angular roll rate and acceleration of the boom by exerting a resistive force between the opposing motion of the boom and chassis. Higher dampening rates would result in decreasing the boom’s ability to free-float while lower dampening rates would allow for increasing boom roll motion. Centering springs are typically placed in parallel with boom roll dampers to help maintain a centered boom roll position relative to the chassis. When the sprayer is operating on a side hill or level terrain, these springs force the boom to be parallel to ground angle.

In many cases, boom roll is uncontrolled and this has a negative impact on automatic height control systems. Induced boom roll occurs when wings of the spray boom are
raised/lowered, or it can happen when the boom roll stops contact each other. Boom roll motion is an unconstrained degree of freedom that is difficult to predict and it poses a challenge to further boom height control improvements.

1.5 Sprayer Boom and Chassis Components

1.5.1 Mechanical Hardware

Self-propelled sprayers consist of a chassis with spraying equipment affixed to it. The chassis houses many components such as the engine, drivetrain, operating cab, and drive wheels. These subsystems essentially allow the sprayer to travel as a vehicle. The chassis suspension is a critical part for the sprayer and operator because it dampens/absorbs energy from the terrain during operation. Sprayers can operate at speeds above 32 kilometers per hour (km/h), so it is necessary for the chassis to have a robust suspension system than can handle a wide range of impact frequencies and magnitudes. In some designs, actively controlled airbags are used on each wheel strut to support the weight of the machine and act as a cushion to terrain impacts. There can also be shock dampeners and springs located on each wheel strut to provide further suspension control.

Spray booms that have the ability to roll typically hang from a “fixed” center frame which is constrained to the rolling motion of the chassis. Pivoting links can be used to suspend the boom from the fixed center frame. This allows the spray boom to “decouple” from the chassis and not be affected by the motions of the sprayer itself as it is operating. In this design, the roll angle path of the boom will be defined by the arc of the links when pivoting. In other designs, where the boom is suspended from a single fixed point, any rotation that occurs revolves around that fixed point. In all designs, however, boom roll is constrained to a certain
angular amount to protect the ends of the boom from ground contact and the geometry of the suspension link mechanism. Roll stops mounted between the fixed center frame and the spray boom limit the amount of roll the boom can achieve. Another way boom roll is managed is through the use of shock dampeners and springs to provide passive roll control between the boom and the chassis.

In this research, electronic actuated variable dampers replaced the industry standard constant dampers and springs in order to have the ability to change dampening rates during operation. An input current (0 to 2000mA) to each variable damper controlled their damping rates. These were installed using an adapter bracket that compensated for the variable damper’s shorter stroke length; however, the angle of placement stayed unchanged (Figure 1.4).

Figure 1.4: Variable damping boom roll shocks installed on a JD R4030

1.5.2 Sensors

Modern self-propelled sprayers use a multitude of sensors to monitor the spraying operation. Sensors communicate to the machine controllers using controller area networks
There are multiple CANbus harnesses that relay the electronic messages between the spray boom, sprayer chassis, guidance system, and powertrain.

The most relevant sensors for maintaining spray boom target height are the ultrasonic elevation sensors positioned along the length of the boom (Figure 1.5). From the boom, they measure the distance above the ground and the distance above the canopy of the crop.

A rotary potentiometer is used in some designs to measure the boom’s angle relative to the sprayer chassis. This signal is an effective way to evaluate the boom’s rolling motion during spraying operations. A linkage mechanism, connected at one end to the fixed center frame and the other end at the suspended boom, rotates this sensor as the boom moves along the arc path of the suspended links. It is important to verify for correct calibration of boom roll angle when collecting accurate data from this sensor.

Individual wing heights, left or right, can be adjusted using hydraulic cylinders connected to each wing (Figure 1.6). Active boom height control systems adjust the height of the wings during operation to maintain target heights. For the sprayer used in this research, supplemental string potentiometers were placed on the left and right wing tilt hydraulic cylinders to measure their extension distance (Figure 1.7). These values were transmitted onto the CANbus at a rate of 100 Hz. By using these calibrated sensors, it was possible to adjust the
wing heights to specific positions in order to conduct consistent replications of boom height tests. These sensors were also helpful in recognizing wing activations when automatic boom height control system was enabled.

![Wing naming convention](image1)

Figure 1.6: *Wing naming convention (facing forward in cab)*

![String potentiometers measured wing cylinder position](image2)

Figure 1.7: *String potentiometers measured wing cylinder position*

The sprayer GPS receiver is located near the front of the sprayer cab roof and has an unobstructed view of the sky for satellite communication. It collects an array of chassis measurements that can be analyzed through the CANbus of the sprayer. These measurements include roll angle, pitch angle, yaw rate, and travel speed. They are helpful in determining terrain characteristics as well as evaluating the ride performance of the sprayer. These signals were transmitted on the CANbus at a 10 Hz frequency.
CHAPTER 2. LITERATURE REVIEW

In this section, relevant research and patents pertaining to advances in sprayer boom roll control and active/semi-active suspension controls are discussed. Descriptive background information is presented on varying control methods and the experimental designs. The knowledge gained from previous research influenced the variable damping research methodology in this research.

2.1 Methods of Boom Roll Control

Methods developed for controlling boom can be found from as early as 1988 and they have continued to advance since then (Frost & O’Sullivan, 1988). Many patents and research papers have attempted to address this issue throughout the sprayer industry over the course of the last 30 years. A suspended spray boom encounters many of the same control challenges regardless of manufacturer. Active boom roll control has been a popular approach, and there have been many ways to develop an active boom roll system.

Frost & O’Sullivan (1988) conducted research on a twin link suspended boom system that demonstrated the ability to actively control boom roll position. An electrical screw jack was substituted for one of the boom suspension links which allowed for control of the boom roll angle, while still letting it hang freely from the twin links. Those adjustments showed to be beneficial in compensating for terrain angles that are not parallel with the chassis angle (Figure 2.1).
This boom roll control system was first tested in a laboratory environment using chassis roll inputs and ground angle inputs of magnitude $\pm 1.43$ degrees and $\pm 2.17$ degrees, respectively. A controller obtained ultrasonic sensor data from the end of the boom and calculated the necessary adjustment for the length of the variable link. Upon the completion of stationary testing, this system was subjected to field testing where the sprayer drove up onto a row of railroad ties at a speed of 18 km/h. The separation between the frame’s angle and the boom’s angle was an indication of the active boom roll system adjusting to keep the boom parallel to the ground. Field testing results demonstrated the ability of the boom to be actively positioned when the vehicle (frame) encountered a change in roll angle (Figure 2.2). The boom roll control systems recognized the beginning of the roll event and repositioned the boom’s angle to have a low angular displacement relative to the ground.
Figure 2.2: *Measured response of an active twin link boom suspension*

Source: (Frost & O’Sullivan, 1988)

Anthonis et al. (2002) developed and tested a slow active suspension for stabilizing the roll of spray booms through the use of cables. The cable supporting the mass of the spray boom was crossed and wrapped around a pulley that was directionally controlled using an electric motor (Figure 2.3). Adjustments to the pulley angle (γ) would directly influence the angle of the spray boom (θ). However, when operating in a passive state where the pulley was essentially rigid, the cables would adjust position on the pulley to allow the boom to hang at a perpendicular angle to gravity.
Anthonis et al. (2002) evaluated the equations of motion for their system in order to determine the power required for active roll control and configure the suspension pulley’s proportional controller. Due to the lack of power needed to actively control the boom’s position, a laboratory experiment used a simplified scaled version of a cable suspended spray boom to verify the controller strategy. This boom design worked adequately with a passive system when operating beyond the natural frequency and a slow-active system would intervene below the natural frequency. The elevation difference, measured between the ultrasonic sensors at opposite wings of the boom, was evaluated through slow-active and passive suspension testing (Figure 2.4). A swept sine wave was used as an input signal to the shaker table (simulating chassis movement) at an amplitude of 6 degrees starting at a frequency of 0.12 Hz and ending at 0.6 Hz. The swept sine wave allowed the active roll system to be tested under the range of frequencies where they are passive and active. During the active state of input frequencies less than 0.35 Hz, the controller would adjust the pulley position to maintain a distance difference of 0.0 m.
Adjusting the boom roll position below the natural frequency of the system showed an improvement in height control. Above the natural frequency, both systems behaved similarly since the roll control was passive. Anthonis et al. (2002) concluded spray boom control was possible with limited power and application of both passive and slow-active roll control.

Prior attempts to introduce automatic boom roll control systems on production sprayers had been largely unsuccessful, and growing demand for boom roll control influenced aftermarket companies such as Norac Systems International Inc. to develop roll control systems for many different brands of sprayers. These systems could be factory installed or retrofitted on a sprayer. Their roll control system consisted of ultrasonic sensors on the boom,
boom roll and wing position sensors, a hydraulic actuator to position boom roll, and a controller. In 2003, Norac patented *Roll Control System and Method for a Suspended Boom* (Figure 2.5). The numerical callouts in schematics of the patent highlighted the components of the suspended boom and the hardware used to control boom at the center frame.

![Figure 2.5: Norac Active Boom Roll Control setup](image)


The hydraulic actuator (#110; Figure 2.5) had the capability to adjust the angular position of the boom roll angle to compensate for terrain conditions which posed challenges for all sprayer designs. When operating on a side hill, the boom could be positioned to be parallel to ground (Figure 2.6). Additionally, the control system could compensate for roll errors induced by the sprayer chassis when operating on uneven terrain. Norac’s active roll
control system could stabilize unwanted roll action of the boom quicker than a passive system due to the increased ability of the hydraulic actuator compared to springs and dampers.

![Diagram](image)

Figure 2.6: *Norac Active Wing Control controlling boom roll on a side hill*


The success of Norac’s active roll control product demonstrated how feasible solutions addressing boom roll are valued to sprayer manufacturers and operators. Norac recognized the limitations of only using springs and dampers in a passive roll control system and developed an alternative method to managing boom roll.

### 2.2 Active/semi-active Suspension Controls

As early as 1961, active suspension systems had been a topic of interest for many industries (Sharp, 1998). In the automotive sector, these systems had gained popularity among companies who value vehicle ride performance and were willing to invest in the technology. Research in the field of active suspension systems highlighted how vibrations and vehicle roll motions had the potential to be controlled using these systems.
Active suspension systems typically employed pneumatic or hydraulic actuators to achieve varying desired forces in the suspension system. Sensors placed at different locations in the system monitored the motions of the main body and the suspension system. A controller commanded the actuator(s) to output a specified force or movement necessary to achieve a desired outcome. One concern with using active suspensions was that they required a large power input to make these active adjustments. Additionally, actuators had to be sized properly during the design process in order to meet operating conditions.

Semi-active suspension control techniques could provide controlled real-time dissipation of energy (Karkoub & Zribi, 2006). A key difference was they do not have the ability to input energy into the system being controlled. Semi-active suspensions behave and offer the reliability of passive suspensions, yet they have the ability to be adaptable and versatile in certain scenarios like an active system. They also require much less power to operate which is convenient in situations where adequate power is an issue. In lieu of actuators, semi-active suspensions can change the damping rate of the suspension directly through the use of variable dampening shocks, more commonly known as magnetorheological dampers (Karkoub & Zribi, 2006).

Magnetorheological (MR) dampers have the ability to change damping rates through controlling an input current to them. They contain micron-sized magnetically polarizable particles which are dispersed in a carrier medium such as mineral oil (Figure 2.7). When a magnetic field is introduced to the MR damper, this internal fluid becomes semi-solid and behaves similarly to a plastic. Compression and extension of the damper forces the fluid to shear as it passes through a fixed-size orifice, thus resulting in higher damping rates when a
larger magnetic field is present. MR dampers are considered fail-safe in the sense that they become passive when they are turned off or disconnected.

Figure 2.7: *Sectional diagram of an MR damper*

Source: (Karkoub & Zribi, 2006)

Similar to the active control system, in a semi-active MR damping system a controller can monitor sensor input values and output a corresponding amperage to actively adjust the
damping rate. Karkoub & Zribi (2006) researched the integration of MR dampers in vehicle suspensions for managing vibrations and vehicle roll. The abilities for both semi-active and passive suspensions to dampen induced chassis motion from a brief 0.1 second vertical movement of 10.0 cm were evaluated and compared (Figure 2.8). The semi-active suspension not only reduced the peak chassis displacement, it significantly decreased the time of the resulting oscillations.

Figure 2.8: Comparing chassis bounce between passive (dotted) and semi-active (solid) suspension systems

Source: (Karkoub & Zribi, 2006)

Semi-active suspension systems are attractive to industries outside of automotive because they provide many of the benefits of active control systems along with the reliability
and affordability of passive systems. Wang & Liao (2009) investigated semi-active suspension systems using MR dampers for improving ride quality of railway vehicles. A mathematical model of a full-scale railway vehicle was developed which integrated semi-active controlled MR dampers in its secondary suspension to mitigate lateral, yaw, and roll motions of the car body relative to the leading truck (Figure 2.9). Sensors measuring accelerations and damping forces on the railway vehicle are utilized to calculate the optimal damping force and generate an appropriate current output to the MR dampers from the damper controller.

![Figure 2.9: Schematic of a railway vehicle integrated with the semi-active controlled secondary suspension system based on magnetorheological dampers](image)

Source: (Wang & Liao, 2009)

The drive files for the model simulated true track conditions by representing random track irregularities (installation errors, general degradation, etc.) and periodic track irregularities (staggered rail-joints) estimated from statistical spatial frequency data. The
suspension controls tested in the model included semi-active, passive on, and passive off. Passive off represented a suspension with no damping while passive on represented constant damping. The semi-active suspension reduced the car body’s roll significantly (approximately 70%) when experiencing periodic track irregularities (Figure 2.10). It is worth noting the passive off suspension performed nearly as well as the semi-active suspension due to the fact that the damping forces required to stabilize the roll were less than the passive on constant damping rate. As a result, the semi-active damping system had the ability to achieve a lower damping rate similar to the passive off state and behave nearly identical.

![Figure 2.10: Time history of car body roll accelerations during periodic track irregularities](image)

Anthonis et al. (2002) identified the importance of differentiating active and passive suspensions through their research pertaining to active boom roll control. Deprez & Lannoije (1999) were cited as the origins of an extensive study on boom roll transfer functions which indicated that all vertical boom suspensions have the same filtering characteristics when trying
to control a boom-leveling actuator. A relationship was discovered between control effort and input disturbance frequencies to the suspension system (Figure 2.11). The ratio of the absolute boom roll to the input rotation of the frame connected to the tractor was termed the gain. It is apparent that when the sprayer chassis experiences high frequency roll motions the boom was best left as passively damped. However, when the suspension neared resonance frequency and disturbances in the system became magnified there was a beneficial opportunity when transitioning to active roll control. Therefore, a semi-active suspension could follow the same logic to attenuate boom height error while minimizing the control effort of variable damping.

![Graph showing active and passive working area of the suspension](image)

Figure 2.11: *Active and passive working area of the suspension*

Source: (Anthonis et al., 2002)

### 2.3 Boom Control Testing Methods

Conducting tests on full-sized self-propelled sprayers can be challenging due to the significant width of the spray boom and the amount of ground space required to operate the vehicle. Frost & Sullivan (1988) and Anthonis et al. (2002) both developed scale models of a
spray boom on which to conduct research in a controlled laboratory setting. In order to simulate chassis dynamics for scale model tests, either shaker tables acted as the input disturbance for the boom or an active platform under the ultrasonic sensors induced corrective actions from the boom roll control system. Scale models supported proof of concept as well as controls development; however, they lacked the ability to simulate true sprayer operating conditions and experience terrains as a combined sprayer chassis and boom would.

In recent years, three dimensional (3D) modeling and simulation software has grown in popularity as an alternative method for testing sprayers. By utilizing these modern tools, there is no need for land to operate a sprayer on, no delays due to weather, and no financial obligations to procure a physical sprayer. A virtual model that has the same size dimensions and mass properties as the sprayer being investigated can be generated using 3D software. Correctly modeled designs result in similar dynamic behavior when tested with the same inputs as an actual sprayer. Terrain profiles can be used in simulations to mimic true field conditions and custom profiles can be generated for development purposes. Additionally, further benefits to using 3D software include time savings, reductions in machine wear, and lower fuel costs.

Reed (2008) evaluated the adaptation of using 3D models in order to predict the motion of spray boom and their suspensions. Previously utilized mathematical models had become outdated for sprayer boom development while modern 3D modeling and simulation tools were evolving to be faster, more efficient, and more widely used within the industry for equipment development. Reed (2008) developed a 3D model (SolidWorks) of a complete sprayer boom (Figure 2.12) and validated its dynamics against a real full-sized sprayer. Cosmos Motion was the rigid body analysis software used for the dynamic testing. Identical boom roll tests were conducted on both the model and real sprayer, and the data collected was used to further tune
the model parameters to more accurately simulate the real sprayer. The tuning compensated for friction in the system located at contact surfaces and pins. Other adjustable parameters for boom roll included the damping rates and recentering springs (Figure 2.13). However, for the validation tests their values matched the factory settings.

![3D modeled spray boom (24 m)](source: Reed, 2008)

Two of the tests conducted in the research, both model and experimental, were very simple and could be completed using any model of sprayer with a suspended boom; the first being a 5 degree step input to the chassis from which the boom is suspended. The second test involved rolling the spray boom 5 degree from its natural resting angle then releasing it. In both tests, the spray boom’s settling time and angular position were analyzed in order to make tuning adjustments in the 3D model that would result in similar boom dynamics.
Reed (2008) concluded his research provided evidence that CAD based dynamic modeling potentially offered a convenient method of simulating and comparing spray boom suspension characteristics. Computer models of sprayers could be validated by comparing test results between real sprayers and the model then making necessary tuning adjustments within the model. Reed (2008) lacked the ability to test and measure spray boom roll during field operations; however, the stationary testing conducted was a necessary first step in the development process for successfully modeling a suspended boom system for use in a dynamic environment.
More recently, Cui et al. (2018) further demonstrated the capability of using 3D modeling tools to optimize parameters in the boom suspension and reduce boom roll error. An extensive study was conducted on the dynamic behavior of the spray boom suspension system in the virtual realm and then validated on a physical model, similar to Reed (2008). The spray boom suspension virtual optimization process utilized Latin hypercube design, radial basis function neural network, and a multi-objective optimization genetic algorithm; all of which aided in the process of quickly identifying influential parameters such as boom roll damping rates and spring rates then adjusted their characteristics to solve for the optimums as a system.

The drive file inputs for the model were simulated at the plane the sprayer chassis was resting on, thus representing field operating dynamics in an accurate manner (Figure 2.14). The initial validation of the model compared its boom roll results to that of the Stewart motion simulator (Figure 2.15) when experiencing the same drive file inputs. The root mean square error (RMSE) of boom roll was calculated to be 0.01 degrees which demonstrated the model’s accurate representation of boom dynamics.

Figure 2.14: Model of self-propelled sprayer with pendulum boom suspension

Source: (Cui et al. 2018)
Upon validating the model, 128 modeling simulations were conducted where varying combinations of boom roll damping rates and spring rates were evaluated in order to locate their optimum values. Next, hardware matching the optimum boom roll damping rate and centering spring rate determined in the model were installed and validated using the Stewart motion simulator. This simulator (#3; Figure 2.16) had six degrees of freedom in which the boom could be moved. Lateral positions in the x, y, and z directions could be adjusted as well as the angles along those axis. These drive file motions induced boom roll motions through the pendulum suspension system to the spray boom (#1; Figure 2.16). Data collected from the boom roll sensors (#2; Figure 2.16) was transmitted to a computing station (#4; Figure 2.16) for analysis. The overall goal from the simulations was to improve boom roll control through minimizing the standard deviation of boom roll angle. Even though the spray boom was isolated and not suspended from a real chassis, the Stewart motion simulator had the same
capability to provide similar inputs that a chassis could.

![Stewart motion simulator used for model validation](Source: (Cui et al. 2018))

Results from the optimization experiment concluded the standard deviation of the boom roll angle was reduced 14.76% compared against the original suspension system. These optimization results indicated the optimization method was effective and the dynamic characteristics of the suspension and spray boom stability were improved.

The drive file used in both the model and simulator during the optimization process was representative of a freshly plowed field when traversed at 7 km/h. This shape of ground profile with its irregularities and random elevation shifts was a more realistic terrain than the swept sine wave used in Anthonis et al., (2002). The model predicted boom roll angles nearly
identical to the Stewart simulator’s experimental results when given the same chassis inputs (Figure 2.17). Therefore, the model had the ability to be an effective tool and resource in boom height control developments as well as ensuring the quality of the simulation model and the optimization process.

![Graph of boom roll angle over time](image)

**Figure 2.17: Field profile input results comparison**

Source: (Cui et al., 2018)

Cui et al. (2018) harnessed the tools of 3D modeling and simulations to better understand the dynamics of a suspended spray boom and optimize the boom roll dampers and springs to minimize boom error when operating in field conditions. While having the ability to validate the model using a Stewart motion simulator, Cui et al. (2018) noted the absence of a production sprayer with which to conduct field testing and gather more realistic ground profile data for drive files in the virtual model. A collection of these drive files fed to the model would represent typical excitations when evaluating the boom suspension. Had this been possible, the
optimization of the boom suspension in their research may have been more applicable to a broader scope of environments that sprayers operate in.

Miles (2018) created a general procedure for evaluating the performance of automatic boom height control systems (the boom height control systems tested in the research adjusted the heights of the individual wings to maintain target height, however the testing procedure developed can also be used for boom roll control tests). Miles (2018) saw the need for a field testing method that could compare tests fairly and provide a metric for producing replicable tests in the future. Field testing allowed the sprayer to operate in natural terrain conditions and experience chassis dynamics normally seen during the operating service lifespan of the sprayer. Therefore, the data collected from field tests was more representative of actual conditions and more accurate decisions could be made with regards to the testing and development process of the boom control system.

Miles (2018) developed a quantitative metric to effectively characterize the terrain traversed during field tests. Through collecting the 10 Hz raw chassis roll angle data from the GPS receiver, a filtered chassis roll rate was calculated from which its standard deviation was evaluated to represent the severity of the terrain. A lower standard deviation value represented a terrain profile where there was less changes in chassis roll angle, thus suggesting a milder terrain. On the opposite end, high standard deviation values for chassis roll rates indicated the sprayer chassis was subjected to harsh terrains that caused the roll angle direction of the sprayer to change frequently. Miles (2018) executed field tests in which multiple waterways were crossed (noted by the numbers 1-6; Figure 2.18). For sections of the test run, the terrain was characterized using chassis roll rate data to generate a performance metric (Table 2.1). The sections where more waterways were present resulted in higher standard deviations of chassis
roll rate. By taking this terrain characteristic metric into account, it was possible to place a numerical value on field test conditions and conduct consistent chassis inputs for test runs.

![Figure 4.7: Test Field Data Collection Sections](image)

**Figure 2.18:** *Field test path identifying test sections A, B, C, D*

Source: (Miles, 2018)

**Table 2.1:** *Sample standard deviation of filtered chassis roll rate sections A-D*

<table>
<thead>
<tr>
<th>Test Section</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>σₜ(CRR)</td>
<td>1.30</td>
<td>0.61</td>
<td>0.45</td>
<td>0.74</td>
<td>Degrees/second</td>
</tr>
<tr>
<td>μ(CRR)</td>
<td>-0.07</td>
<td>0.03</td>
<td>0.03</td>
<td>0.01</td>
<td>Degrees/second</td>
</tr>
</tbody>
</table>

Source: (Miles, 2018)
Also highlighted in the research, Miles (2018) noted the importance of documenting the testing procedures, field conditions, machine parameters, and assumptions in order to be confident in test comparisons. Conducting research using the same machine for all tests was recommended since the dynamics of the sprayer chassis would be nearly identical for all tests. Any variables in the system, physical or electrical, should be kept constant and comparable between tests.
CHAPTER 3.  OVERVIEW OF RESEARCH OBJECTIVES

3.1 Research Objectives

The goal of this research was to minimize unwanted spray boom roll in suspended boom systems on self-propelled sprayers. As a result, spray drift and application rates can be greater controlled to improve crops yields and health. The experiments conducted pertained to designing and evaluating variable boom roll damping control methods. Initially, the boom height control characteristics of a suspended boom system with constant damping must be evaluated in order to benchmark against. Through the use of computer modeling tools, the implementation of variable damping was tested and situationally optimized. Lastly, boom roll control knowledge gained from the virtual experiments was tested on a full-scale sprayer retrofitted with variable boom roll dampening hardware.

**Objective 1: Characterization of Constant Damping Boom Roll Performance**

Characterize the existing performance of boom height stability on a production self-propelled sprayer having constant damping shocks.

**Objective 2: Simulation Analysis of Variable Damping with 2D Modeling Software**

Utilize modeling software to examine the influence of variable damping on boom height control and test actuation logics to improve controllability.

**Objective 3: Characterization of Variable Damping Boom Roll Performance**

Evaluate the performance of boom height control on a production self-propelled sprayer when applying variable damping to decrease unwanted boom roll. Determine how to effectively decide when to increase and decrease damping rates to influence boom roll control.
CHAPTER 4. CHARACTERIZATION OF CONSTANT DAMPING BOOM ROLL PERFORMANCE

The goal of this chapter was to characterize boom height performance of a self-propelled sprayer with constant damping shocks. This information was used to establish a baseline for which variable damping research would be compared to. A self-propelled sprayer with a 30 meter spray boom was used for the tests. There were no liquids in the spray tank and the adjustable tread width was set to 3 meters.

The characterization process consisted of stationary wing activation tests and dynamic field tests that were an accurate representation of sprayer environments and operations. Single sprayer wing height adjustments, which are extensively utilized when in “automatic spray height control” mode, were prone to inducing boom roll and affecting the opposite wing’s spray height. Additionally, chassis roll from terrain features also induced boom roll which resulted in boom target height errors.

4.1 Methods

4.1.1 Stationary Testing

In order to evaluate the effects of induced boom roll motion during sprayer wing height adjustments, stationary tests were conducted which involved raising the sprayer’s left wing and monitoring the elevation reaction at the right boom (Table 4.1). A CAN access programming language (CAPL) script within the CANbus development and testing software (CANoe) allowed for consistent wing activations on the sprayer by harnessing the control of the spray boom’s wing lift cylinders through the CANbus. Before each test repetition the spray boom was set to a level position relative to the ground. Each wing was positioned to a pre-
determined extension length using data from rotary potentiometers on the wing cylinders. When the left wing was raised, maximum rated current was sent to the proportional solenoid valve on the wing cylinder. This current resulted in a similar wing raise speed as using the raise button from the sprayer cab. The wing raise motion was stopped once the rotary potentiometer measured 0.15 m of wing cylinder retraction. The benefits of using the CAPL script included consistent repetitions and removed the chance for human error during the testing process. Data logs collected using the CANbus were utilized to evaluate the sensor outputs of the sprayer during testing in order to quantify the effects of wing motions on induced boom roll.

<table>
<thead>
<tr>
<th>Damping Type</th>
<th>Engine Speed (RPM)</th>
<th>Left Wing Cylinder Raise Velocity (mm/s)</th>
<th>Actuation Duration (s)</th>
<th>Replicates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>2450</td>
<td>90</td>
<td>1.0</td>
<td>15</td>
</tr>
</tbody>
</table>

4.1.2 Field Testing Terrain Conditions

Field testing was utilized to expose the sprayer to natural terrain conditions which influenced boom roll dynamics and vehicle operating characteristics. The sprayer was operated in a local field in central Iowa, where only mowed bluegrass was present. This field had diverse terrain features including flat bottom ground, rolling hills, and a grass-strip waterway that was prone to erosion. As a result, it was possible to subject the sprayer to varying degrees of terrain severity. For these field tests, three styles of terrain aggressiveness were used and they were created by driving the sprayer in different locations of the field (Table 4.2).
Table 4.2: Terrain Characterization Testing Description

<table>
<thead>
<tr>
<th>Terrain</th>
<th>Automated Boom Height Control</th>
<th>Damping Type</th>
<th>Travel Speed (km/h)</th>
<th>Replicates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mild</td>
<td>Off</td>
<td>Constant</td>
<td>19.3</td>
<td>10</td>
</tr>
<tr>
<td>Medium</td>
<td>Off</td>
<td>Constant</td>
<td>19.3</td>
<td>10</td>
</tr>
<tr>
<td>Aggressive</td>
<td>Off</td>
<td>Constant</td>
<td>19.3</td>
<td>10</td>
</tr>
</tbody>
</table>

The “Mild” terrain consisted of flat bottom ground with no ditches, waterways, or berms. The smooth profile of the terrain extended past the ends of the sprayer boom, so the entire sprayer system was able to operate in a near level state with minimal elevation changes. Chassis roll dynamics influenced by “Mild” terrain were common in the upper Midwest plains where spraying was prevalent and were therefore, important to evaluate during field testing.

The “Medium” terrain was generated by operating the sprayer in an area where broad and gentle rolling hills were present. These oscillations were driven into the sprayer chassis and could be felt by an operator in the cab. Although there were roll direction changes during a pass, it was never uncomfortable as an operator. These conditions represented average terrain dynamics for which the suspended boom systems were most likely designed for. Spray boom height control was more challenging due to these oscillating terrain factors. The ground profile beneath the entire boom length was constantly changing when operating in these conditions, and terrain like this is representative of what many farms are like.

The “Aggressive” terrain was representative of corner conditions that a sprayer may see. These included very harsh and abrupt shifts in chassis position caused by driving through
a waterway. To create this test run, the sprayer crossed a grass-strip waterway at a 45 degree angle from perpendicular. The significant change in vehicle roll position effected the chassis’s suspension as well as boom roll. The full potential of boom roll could occur and the boom roll stops physically limited the angle the boom could roll. An operator’s perspective would describe this terrain as violent when the travel speed is not reduced to compensate for the ground conditions, yet for testing purposes there was no reduction of speed at any point during the test run.

Miles (2018) recommended sprayer testing conditions be characterized by measuring the chassis roll rate during the testing event and calculating its standard deviation (Equation 1). This metric provided information about the terrain during the test which would be used for comparison against other tests or validating multiple tests in the same location for consistency. The method for calculating standard deviation was also applicable to other metrics such as boom roll rates and boom ultrasonic sensor height. The mean chassis roll rate standard deviation was calculated using chassis roll data (from GPS receiver) from the 10 passes for each terrain type. The automated boom height control system was disabled during the characterization tests in order to eliminate any induced influences from boom height activations and subject the sprayer chassis to only terrain inputs.
Equation 1: *Mean and Standard Deviation of Chassis Roll Rate*

\[
\sigma_s(CRR) = \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} |A_i - \mu(CRR)|^2}
\]

\[
\mu(CRR) = \frac{1}{N} \sum_{i=1}^{N} A_i
\]

\(N = \text{Number of Filtered Chassis Roll Rate Observations}\)

\(A_i = \text{ith Filtered Chassis Roll Rate Observation (deg/s)}\)

\(\sigma_s(CRR) = \text{Sample Standard Deviation of Filtered Chassis Roll Rate (deg/s)}\)

\(\mu(CRR) = \text{Average of Filtered Chassis Roll Rate (deg/s)}\)

### 4.1.3 Field Operational Testing

For each terrain type (Mild, Medium, and Aggressive), 10 passes were made with the automated boom height system off and on (Table 4.3). Again, this control system adjusted the individual wing heights to maintain a set height based on data from the boom’s ultrasonic sensors. Sprayer sensor data was collected from the CANbus during field testing. The raw data was filtered to eliminate noise so accurate rate calculations could be made (Equation 2). All signals were filtered using a five value moving average. The sensors utilized for measuring chassis roll, boom roll, and spray boom deviation from target height were the GPS receiver, boom roll rotary potentiometer, and the R2 ultrasonic sensor, respectively. The roll angle measurements were used to characterize the dynamics between the spray boom and chassis as well as between the chassis and terrain. The R2 ultrasonic sensor provided the ability to measure the height of the spray boom above the ground and was an indicator of how well the system maintained target height.
Table 4.3: Field Operation Testing Description

<table>
<thead>
<tr>
<th>Damping Type</th>
<th>Terrain</th>
<th>Automated Boom Height Control</th>
<th>Travel Speed (km/h)</th>
<th>Replicates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>Mild</td>
<td>Off</td>
<td>19.3</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>On</td>
<td>19.3</td>
<td>10</td>
</tr>
<tr>
<td>Constant</td>
<td>Medium</td>
<td>Off</td>
<td>19.3</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>On</td>
<td>19.3</td>
<td>10</td>
</tr>
<tr>
<td>Constant</td>
<td>Aggressive</td>
<td>Off</td>
<td>19.3</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>On</td>
<td>19.3</td>
<td>10</td>
</tr>
</tbody>
</table>

Equation 2: Filtered Chassis Roll Angle

\[
\text{Filtered Chassis Roll Angle (deg)} = \frac{y(i - 2) + y(i - 1) + y(i) + y(i + 1) + y(i + 2)}{5}
\]

\[y(i) = \text{ith Raw Chassis Roll Angle (deg)}\]

Boom roll rates and chassis roll rates were both filtered in the same manner using raw data from the filtered roll angles (Equation 3, Equation 4).

Equation 3: Raw Chassis Roll Rate

\[
\text{Raw Chassis Roll Rate (deg/s)} = \frac{c(i) - c(i - 1)}{\Delta t}
\]

\[c(i) = \text{ith Filtered Chassis Roll Angle (deg)}\]

\[\Delta t = \text{Sensor Frequency (0.1 seconds)}\]
Equation 4: Filtered Chassis Roll Rate

\[
\text{Filtered Chassis Roll Rate (deg/s)} = \frac{z(i - 2) + z(i - 1) + z(i) + z(i + 1) + z(i + 2)}{5}
\]

\[z(i) = \text{ith Raw Chassis Roll Rate (deg/s)}\]

4.2 Results

4.2.1 Boom Height Error Induced From Wing Activations

During stationary testing, it was evident that raising the left wing resulted in induced boom roll and errors in target height for the right wing. This movement of the boom could be observed from the operating cab of the sprayer and was supported by the data. Four key dynamic responses of the sprayer were measured: R2 ultrasonic sensor height (Figure 1.5), boom roll angle, boom roll rate, and chassis roll angle (Figure 4.2). In each plot, the 15 test run results were overlaid. Since all tests experienced a nearly identical step input, there was little variation in the responses (Figure 4.1).
Figure 4.1: Step input to left wing cylinder extension position for stationary testing. Multiple individual replicated experiments showed.

Figure 4.2: Boom control response to step input. Multiple individual replicated experiments showed.
Data collected from the outer right ultrasonic sensor (R2) and the boom roll sensor effectively indicated how the initial force induced when beginning and stopping a wing motion affected boom roll and boom height. Initially, the raise motion of the left wing caused the boom to roll counter-clockwise (viewed from behind) which raised the right wing above its set height. Then as left wing stopped, its upward momentum redirected the boom roll motion clockwise and the right wing dipped below the initial set height. For approximately 3-4 seconds after the left wing stopped its upward travel, there was a settling time for the boom where it slightly oscillated until it reached a balanced state and boom roll motion ceased.

The stationary tests had minimal impacts to the sprayer’s chassis roll angle. There was not a significant amount of energy being transmitted through the chassis because the suspended boom system was transferring it to boom roll. The deviations in chassis roll angle data between the test runs were due to the airbags in the machine’s suspension making adjustments during the set of tests. In stationary tests, these effects were seen and felt in the cab; however, during field testing it was impossible to distinguish any airbag adjustments to the chassis since the magnitudes of chassis motion were so high and constantly fluctuating.

The data collected from stationary testing were numerically quantified to illustrate boom height performance metrics (Table 4.4). The metrics used to evaluate boom roll and boom height error were the standard deviations of the spray boom roll, spray boom roll rate, and R2 ultrasonic sensor. These data exhibited normal distribution; therefore, normality was assumed (Figure 4.3). By taking the standard deviations of these measurements over a 6 second period of time that started when the left wing began to raise, the results represented a 1 sigma spread of the values from their mean. With respect to boom roll, boom roll rate, and boom
height, the standard deviation of the collected sensor data provided an indication of how much movement occurred and the range of angular boom roll rates.

Figure 4.3: Normally distributed boom roll rate data collected from stationary testing

Table 4.4: Numerical data from stationary test results

<table>
<thead>
<tr>
<th>Test run data</th>
<th>Units</th>
<th>Mean $\mu$</th>
<th>Standard Deviation $\sigma$</th>
<th>Reps</th>
</tr>
</thead>
<tbody>
<tr>
<td>StDev Boom Roll</td>
<td>deg</td>
<td>0.53</td>
<td>0.01</td>
<td>15</td>
</tr>
<tr>
<td>StDev Boom Roll Rate</td>
<td>deg/s</td>
<td>0.53</td>
<td>0.01</td>
<td>15</td>
</tr>
<tr>
<td>StDev R2</td>
<td>mm</td>
<td>115</td>
<td>6</td>
<td>15</td>
</tr>
</tbody>
</table>
4.2.2 Terrain Aggressiveness Characterization

Data collected from the sprayer during field testing was used to characterize terrain profiles and evaluate the performance of boom roll and boom height. Three terrain types, Mild, Medium, and Aggressive were traversed in the sprayer at a speed of 19.3 km/h. Ten passes were made for each terrain type. Miles (2018) expressed the significance for using the standard deviation of chassis roll rates during field tests in order to quantify the profile of the terrain the sprayer was operating on. As a result, during field testing conducted in this research, chassis roll angle data was collected from the GPS receiver on top of the sprayer cab. Knowing this signal was transmitted at 10Hz, the corresponding chassis roll rate was calculated with the same frequency as the roll angle signal. For each test pass the standard deviation of chassis roll rate was calculated, and the average chassis roll rate standard deviation was determined for each 10 rep set of terrain types (Figure 4.4). This value increased from Mild to Medium terrain because the sprayer chassis experienced more rolling motions at higher frequencies; however, the mean standard deviation of chassis roll rates measured during Aggressive terrain was slightly less than Medium. The waterway crossed in that terrain exposed the chassis to large magnitudes of chassis angle, but the chassis roll rates did not deviate as often as the Medium terrain. The field testing terrain was characterized using this metric to distinguish between minimal and excessive chassis motion inputs for boom roll motion field tests.
4.2.3 Characterizing Field Operation Performance

Similar to how the mean values of chassis roll rate standard deviations were calculated for each terrain, the mean of boom roll rate standard deviations was evaluated with respect to terrain types and automatic boom height control systems. The raw boom roll angular data were collected from the boom roll rotary potentiometer which measured the relative angle between the suspended boom and the sprayer chassis. Data analyzed from field testing indicated the standard deviation of boom roll rate increased with more aggressive terrains. With the boom height control system off and operating in Mild terrain, the mean boom roll rate standard deviation was 0.15 degrees per second (deg/s) whereas in Medium terrain this value increased to 0.42 deg/s (Figure 4.5). However, the Medium and Aggressive terrains used for field testing had similar effects on the standard deviation of boom roll rates because there was not a

Figure 4.4: Characterizing the field testing terrains using StDev of chassis roll rates

```
<table>
<thead>
<tr>
<th>Terrain</th>
<th>StDev Chassis Roll Rate (deg/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aggressive</td>
<td>1.0</td>
</tr>
<tr>
<td>Medium</td>
<td>0.8</td>
</tr>
<tr>
<td>Mild</td>
<td>0.6</td>
</tr>
</tbody>
</table>
```

*Speed = 19.3 km/h
n=10 for each mean
Individual standard deviations are used to calculate the intervals.*
significant difference between chassis roll rate inputs (mean chassis roll rate standard deviations of 0.94 deg/s and 1.04 deg/s, respectively).

Figure 4.5: Evaluating boom roll performance for each field terrain

Complimentary to analyzing boom roll rates, the standard deviation of R2 ultrasonic sensor data provided information about the fluctuating boom elevation when trying to maintain a target height. This metric correlated with how well the boom was performing and was affected by boom roll and dynamic changes in terrain elevations; lower values indicated less variation from target height while higher values signified a wider spread of height error. R2 standard deviation values were influenced by terrain conditions (Figure 4.6). It was important to note that increasing terrain severity did not lead to increasing R2 standard deviation for this field.
Medium terrain resulted in the greatest R2 standard deviation while the aggressive terrain was slightly less. This discrepancy could be explained by the aggressive terrain generating the highest magnitude of chassis roll angles from which the suspended boom was isolated from and had the ability to maintain spray elevation more consistently. The Medium and Aggressive terrains resulted in similar standard deviations for boom roll rates (Figure 4.5), and this suggested the spray boom was moving in similar amounts relative to the chassis to decouple from chassis roll events. However, the R2 standard deviation results exhibited the ability of the angular motion of the boom to better follow the dynamic terrain during the aggressive terrain testing. The consistent profile of the Mild terrain induced the least amount of boom roll error and was able to maintain target height the best.

Figure 4.6: Evaluating boom height performance for each field terrain
4.3 Conclusions

As a result of these tests, effective benchmarking values were generated for future comparison of boom roll damping research. Data collected from these tests would be used to tune the 2D model used in the next chapter of this research and benchmark the variable dampers performance. Chassis roll data from each terrain condition had the ability to be used as drive files in the sprayer modeling realm.

The stationary testing provided results for quantifying boom roll and boom height error induced from single wing actuations. An automated procedure for conducting the wing raise tests was developed using CANbus interfacing CAPL scripts in Vector software. These tools allowed tests to be carried out with limited variation to the input variables such as wing raise actuation speeds and wing raise distances.

As a result of field testing, three terrain severities were distinguished and characterized. The terrain severity was analyzed using the standard deviation of the chassis roll rate data from sprayer test passes on those terrains. The data collected pertaining to boom roll rates showed an increasing standard deviation across the three terrain types from Mild to Aggressive due to the increase in motion of the spray boom angle relative to the chassis. The decoupling between the spray boom and chassis was a result of the suspended boom twin-link design which attempted to mitigate the translation of chassis motion to the spray boom. Consequently, the standard deviation of R2 boom height data increased from testing on Mild terrain to Medium, but the results for Aggressive terrain was in between. Although the standard deviation of boom roll rates had the trend of increasing with terrain aggressiveness, the boom roll motion assisted in keeping the boom more parallel with the Aggressive terrain which resulted in lower R2 standard deviation values than the Medium terrain yet larger than the Mild.
CHAPTER 5. SIMULATION ANALYSIS OF VARIABLE DAMPING WITH 2D MODELING SOFTWARE

In this chapter, modeling software was utilized to examine the influence of variable damping on boom height control and test actuation logics to improve controllability. The validation procedure for the virtual model was described and the results from validation testing were shown. Upon verification of the ability of the model to simulate suspended boom dynamics, the model was then used in multiple simulations that evaluated the effectiveness of variable dampening rates for boom roll and the actuation timing necessary for optimal performance in varying terrain conditions. Knowledge gained from these variable boom roll damping simulation tests would be applied towards field testing in Chapter 6.

5.1 Methods

5.1.1 Model Development

Working Model 2D (Design Simulation Technologies, Inc.) was the 2D kinematics and modeling software used in this research. A simplified suspended boom system was designed using dimensions from a self-propelled sprayer with a 36 meter spray boom. In Working Model 2D, pins and joints were used to connect components together and this provided the necessary constraints of motion for the model in order to dynamically behave as a real sprayer. The model had the capability to include suspension systems (i.e., springs and dampers) between two points which simulated certain spring rates and damping rates.

The sprayer 2D model had many of the critical components necessary for developing similar dynamic characteristics (Figure 5.1 and Table 5.1). The sprayer was placed on a “shaker table” that simulated chassis roll inputs during testing. Similar to a production sprayer, the suspended center frame of the boom was connected to the chassis fixed frame using twin links.
Boom roll motion was managed using two sets of springs and dampers and the chassis suspension system was simulated with spring and dampers. A length actuator affixed to both wings provided individual wing height controls similar to how hydraulic cylinders were used on the production sprayer. These actuators generated the induced boom roll from wing motions to be investigated in the virtual realm. Additional length actuators located above the suspended center frame controlled the set height for the boom and were not adjusted during testing.

Figure 5.1: 2D model of suspended boom system
Table 5.1: Callout description for Figure 5.1

<table>
<thead>
<tr>
<th>Callout #</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Tire support suspension system</td>
</tr>
<tr>
<td>2</td>
<td>Spray boom twin suspension link</td>
</tr>
<tr>
<td>3</td>
<td>Fixed center frame/chassis</td>
</tr>
<tr>
<td>4</td>
<td>Actuators used for adjusting boom set height</td>
</tr>
<tr>
<td>5</td>
<td>Sprayer chassis suspension system</td>
</tr>
<tr>
<td>6</td>
<td>Wing height hydraulic cylinder</td>
</tr>
<tr>
<td>7</td>
<td>Suspended center frame</td>
</tr>
<tr>
<td>8</td>
<td>Boom roll dampening system</td>
</tr>
</tbody>
</table>

During the development process of the model, an additional suspension system was added which allowed the tires to have an angular degree of freedom around the tire contact point with the ground. This motion represented a realistic behavior of sprayer chassis suspension seen during earlier field testing and model development work.

Measurements of both roll angles and roll rates for the chassis and spray boom, along with boom height elevation data, were recorded during model simulations at a frequency of 20 Hz. The angles were calculated using the difference in angle of solid bodies (i.e., between the chassis and spray boom or between the chassis and ground) and the roll rates were a function of the change in angle during a single 0.05 second step during the simulation. In order to measure boom height similar to the way ultrasonic sensors function on a production sprayer, points were added on the boom at the same dimensional location and their vertical position relative to level ground was also logged at a 20 Hz frequency. These measurement metrics in the model allowed the results from sprayer field testing to be comparable because they measured the same dynamic motions. The chassis roll drive file for the model was up-sampled from the 10 Hz field data to 20 Hz simulation using the “last known value”.

5.1.2 Model Validation

The validation process for the model consisted of subjecting the model to a stationary wing raise test and a field test where the boom control dynamics could be compared to known results. Since the purpose of the model was to evaluate varying dampening strategies and compare them to a constant damping base condition, the numerical results from validation were not as critical as the dynamic behaviors of the spray boom during wing height activations and chassis roll events. The model needed to represent the same spray boom behavior; however, a small error in magnitude between model and field results was inherent due to the simplistic approach using a rigid body model.

The first validation test consisted of inputting a similar left wing raise motion, described in Chapter 4, to the model and analyzing the induced boom roll and target height error (Table 5.2). The speed and duration of the wing raise motion was determined using data from the wing cylinder rotary potentiometers and replicating the motion in the model using an input file to control the actuator that simulated the wing hydraulic cylinder. The simulated wing raise test used the same command signal input from stationary field testing to raise the left wing at the same speed for a set amount of distance (Figure 4.1). The duration from which data was collected to evaluate the necessary test metrics was 6 seconds and was identical to the stationary field testing for comparative purposes.

<table>
<thead>
<tr>
<th>Damping Type</th>
<th>Left Wing Cylinder Raise Speed (mm/s)</th>
<th>Actuation Duration (s)</th>
<th>Replicates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>90</td>
<td>1.0</td>
<td>1</td>
</tr>
</tbody>
</table>
The second validation test utilized the chassis roll angle data from the Medium terrain field testing, described in Chapter 4, as an input file to the chassis roll angle of the model (Table 5.3). This drive file subjected the model to the same chassis roll angle and roll rates in order to compare the resulting spray boom dynamics with the results from field testing. The simulated duration of the test was approximately 40 seconds. The results of chassis roll, boom roll, and R2 height were compared by measuring the mean error between the model and field testing to evaluate the performance of the model and the ability to exhibit realistic spray boom dynamics.

<table>
<thead>
<tr>
<th>Damping Type</th>
<th>Terrain Simulated</th>
<th>Boom Height Control System</th>
<th>Travel Speed (km/h)</th>
<th>Replicates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>Medium</td>
<td>Off</td>
<td>19.3</td>
<td>1</td>
</tr>
</tbody>
</table>

### 5.1.3 Development of Semi-active Control Logic

Upon completion of validation, the model was then used to test various methods of semi-active boom roll control using variable boom roll damping rates. Increased damping rates slowed the relative angular motion between the spray boom and the chassis; thus, decelerating boom roll and coupling their angular motions together. Instances during spraying operations when this would be beneficial to boom roll control were during single wing activations and chassis roll events. By intelligently increasing the damping rates during these events, induced boom roll could be reduced which would overall reduce the amount of target height error.
A triggered increase in damping rate during wing activations was accomplished simultaneously with the commanded raise/lower signal to the wing. During the stationary testing from Chapter 4, this event was recognized using the CANbus to monitor the output from the string potentiometer position of the wing height hydraulic cylinders. During the wing cylinder activation period the triggered damping rate was held constant at a specified value, then once the activation had stopped, the triggered damping rate was still held constant for 0.5 second and then linearly decreased (ramped down) over another 0.5 second period. This “wing motion trigger” was tested in the simulation model and utilized the same left wing raise test as in the validation procedure. The left wing cylinder raise speed was 90 mm/s and the actuation duration was 1.0 second. The test evaluated how the magnitude of triggered damping rates affected R2 height performance (Table 5.4). One replication for each damping rate was testing in the model.

Table 5.4: Description of wing activation tests for variable damping trigger development

<table>
<thead>
<tr>
<th>Damping Type</th>
<th>Damping Rate (kN*s/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>8</td>
</tr>
<tr>
<td>Variable</td>
<td>12</td>
</tr>
<tr>
<td>(Triggered on Wing Motion)</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>44</td>
</tr>
<tr>
<td></td>
<td>88</td>
</tr>
<tr>
<td></td>
<td>175</td>
</tr>
</tbody>
</table>
Triggering damping rates during chassis roll events was more challenging because the frequency and magnitude of the events were ever-changing. The goal was to decrease boom height error through controlling boom roll overshoot as well as reposition the boom angle to decrease target height error using the appropriate direction of chassis roll. There were many methods which had the capability to perform actions similar to this, but they used different sensor measurements and control logics to activate the damping rate trigger (Table 5.5). Therefore, the model was used to conduct an experiment comparing these different methods and locate the one that exhibited the best boom height control (i.e., lowest R2 standard deviation). A sinusoidal chassis roll input generated the induced boom roll necessary for the evaluation of the chassis trigger styles. For these tests, the hold time and ramp down time of the triggered increase in damping rates was 0.5 second and 0.5 second, respectively (Table 5.6).

<table>
<thead>
<tr>
<th>Trigger Style</th>
<th>Description of event that activates trigger</th>
<th>Sensor signal being monitored</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant Damping</td>
<td>Constant damping rate, production sprayer</td>
<td>N/A</td>
</tr>
<tr>
<td>2</td>
<td>Change in chassis roll direction</td>
<td>Chassis roll angle</td>
</tr>
<tr>
<td>3</td>
<td>Chassis roll and boom roll move in opposite directions</td>
<td>Chassis roll angle, boom roll angle</td>
</tr>
<tr>
<td>4</td>
<td>Angle of the boom relative to ground exceeds the chassis angle</td>
<td>Chassis roll angle, boom roll angle</td>
</tr>
<tr>
<td>5</td>
<td>Boom roll rate relative to ground exceeds chassis roll rate</td>
<td>Chassis roll rate, boom roll rate</td>
</tr>
<tr>
<td>6</td>
<td>Spray boom target height error is minimized using the appropriate chassis roll direction</td>
<td>R2 and L2 height, chassis roll rate</td>
</tr>
</tbody>
</table>
Table 5.6: *Description of model simulations used to determine effective chassis triggered variable damping logic*

<table>
<thead>
<tr>
<th>Damping Type</th>
<th>Damping Rate (kN*s/m)</th>
<th>Chassis Trigger Style</th>
<th>Hold Time (s)</th>
<th>Ramp Down Time (s)</th>
<th>Roll Amplitude (deg)</th>
<th>Roll Period (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>3.5</td>
<td>4</td>
</tr>
<tr>
<td>Variable</td>
<td>123</td>
<td>2</td>
<td>0.5</td>
<td>0.5</td>
<td>3.5</td>
<td>4</td>
</tr>
<tr>
<td>Variable</td>
<td>122</td>
<td>3</td>
<td>0.5</td>
<td>0.5</td>
<td>3.5</td>
<td>4</td>
</tr>
<tr>
<td>Variable</td>
<td>122</td>
<td>4</td>
<td>0.5</td>
<td>0.5</td>
<td>3.5</td>
<td>4</td>
</tr>
<tr>
<td>Variable</td>
<td>122</td>
<td>5</td>
<td>0.5</td>
<td>0.5</td>
<td>3.5</td>
<td>4</td>
</tr>
<tr>
<td>Variable</td>
<td>122</td>
<td>6</td>
<td>0.5</td>
<td>0.5</td>
<td>3.5</td>
<td>4</td>
</tr>
</tbody>
</table>

Upon the determination of the most successful triggering method, that specific method was optimized by testing multiple combinations of trigger hold times and ramp down times over a range of chassis roll frequencies and magnitudes in the model simulation (Table 5.7 & Table 5.8). The optimum parameters determined from these tests would be used in field testing evaluation for the triggering method, discussed in Chapter 6.

Table 5.7: *Terrain inputs used for variable damping optimization*

<table>
<thead>
<tr>
<th>Roll Amplitude (deg)</th>
<th>Roll Period (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>5</td>
</tr>
<tr>
<td>2.0</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>5</td>
</tr>
<tr>
<td>3.5</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>5</td>
</tr>
</tbody>
</table>
Table 5.8: Configurations evaluated for variable damping optimization

<table>
<thead>
<tr>
<th>Damping Type</th>
<th>Constant Damping Rate (kN*s/m)</th>
<th>Triggered Damping Rate (kN*s/m)</th>
<th>Hold Time (s)</th>
<th>Ramp Down Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant (Production Sprayer)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Variable</td>
<td>123</td>
<td>0.5</td>
<td>0.5</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>123</td>
<td>0.1</td>
<td>0.1</td>
<td></td>
</tr>
</tbody>
</table>

5.2 Results

5.2.1 Validating Model with Stationary Testing

As a part of the model validation process, a left wing raise motion was simulated and the effects of induced boom roll and boom height error were compared to results from an actual sprayer highlighted in Chapter 4. The damping rate and spring rate boom roll parameters in the model were set to the factory settings of the sprayer compared against. The error between the model and the stationary testing results from Chapter 4 was calculated from the tests (Table 5.9). The minimal percentage errors demonstrated the ability for the model to exhibit similar boom roll and boom height errors during a left wing raise event.
Table 5.9: Comparing stationary testing results between model and sprayer

<table>
<thead>
<tr>
<th>Data source</th>
<th>StDev R2 (mm)</th>
<th>StDev Boom Roll Angle (deg)</th>
<th>StDev Boom Roll Rate (deg/s)</th>
<th>Reps</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (μ)</td>
<td>SD (σ)</td>
<td>Mean (μ)</td>
<td>SD (σ)</td>
</tr>
<tr>
<td>Actual sprayer</td>
<td>115</td>
<td>6</td>
<td>0.53</td>
<td>0.01</td>
</tr>
<tr>
<td>Model</td>
<td>108</td>
<td>-</td>
<td>0.43</td>
<td>-</td>
</tr>
<tr>
<td>% Error</td>
<td>6.09</td>
<td>-</td>
<td>18.87</td>
<td>-</td>
</tr>
</tbody>
</table>

The model best represented the standard deviation of R2 height during the test where only a 6.09% error was seen. This measurement examined the spray boom deviation from target height due to induced boom roll motion. There was an 18.87% error when comparing the standard deviation of boom roll angle, an indication of the boom roll induced, because the model experienced lower magnitudes of roll angles during the test. Lastly, the boom roll frequency was slightly higher in the model, and as a result, the standard deviation of boom roll rate had a 20.75% error. The model errors relating to boom roll were most likely due to the absence of pin friction in the model as well as damping rates and spring rates which might not have been the exact manufacturer specification. However, the model showed similar boom height control behaviors during induced boom roll motions from wing height adjustments. The similar dynamics of boom roll motion provided a reputable foundation for developing boom roll control methods. Although the magnitudes of roll angles and roll rates were not perfectly identical, the ability of the modeled sprayer boom to behave dynamically similar with induced boom roll inputs was essential for this research.
5.2.2 Validating Model with Field Operation Testing

Evaluating the model by simulating a realistic terrain profile (Medium) was another key aspect for validating the ability of the model to exhibit boom roll and height dynamics similar to field results. Very minimal error existed in a time series comparison between the chassis roll angle data seen during field testing and how the model experienced that same chassis roll when it was input into the simulation as a drive file (Figure 5.2). The model exhibited very similar chassis dynamics, and as a result, the model had a mean error of 0.28 degrees less than the field chassis roll angle. The model most likely experienced less chassis roll due to the fact the suspension system in the model absorbed impacts from the simulation chassis roll drive file, whereas the field data used for the drive file included both the terrain angle and the chassis roll from suspension movement. Therefore, the chassis suspension in the model was functioning properly by dampening the effects terrain had on the movement of the chassis, but this decrease in chassis motion was minimal. For the purposes of boom roll damping research, chassis roll drive files collected from field testing could be simulated in the model for comparison and evaluation.
Figure 5.2: Evaluating the ability of the model to simulate a terrain profile

When comparing the model simulation boom roll angle results against field results, the model had a mean error of 0.16 degrees more than the field. The modeled spray boom had the ability to behave dynamically similar to boom roll motion measured during field testing when experiencing similar chassis roll (Figure 5.3). Again, the slight increase in the magnitude of boom roll motion could be explained by the lack of pin friction in the model; however, the key conclusion from these results was that the boom roll motion was accurately represented using the model.
Lastly, the R2 height was compared between the model simulation and field testing in order to evaluate the validity of the model. The time series of R2 height during testing displayed similar characteristics of motion, but the results were not identical (Figure 5.4). The R2 height measurement accounted for boom roll motion as well as the elevation change of the ground under the R2 sensor. The simplistic approach of the model began to lose the ability to predict the same R2 results as field testing. In the model, the ground profile was assumed to be flat and never-changing, whereas in a field terrain profile the ground was changing elevation underneath the wings of the sprayer. At 25 seconds into the plotted R2 height results, the R2 sensor of the field tested sprayer passed over a brief 400 mm low spot in the field and the sensor measured a higher elevation above the ground. The simulation could not replicate the
dynamic changes in terrain underneath the full width of the spray boom. Consequently, the model had a challenge attaining the results from field testing and the mean R2 height error calculated during the simulation was 115 mm below field testing. However, the model accurately represented the upward and downward motion of the R2 sensor on the spray boom as the chassis experienced dynamic rolling motions at varying magnitudes and frequencies.

![Comparing R2 Height Between Model and Field Testing](image)

Figure 5.4: *Comparing R2 results of model simulation and field tests*

Mean error and standard deviation of error for each metric were calculated from the dynamic model validation tests in order to compare the results of the model to field data (Table 5.10). A two-sided t-test of the mean (\(\alpha=0.05\)) was conducted for the critical metrics (Table 5.11). Chassis roll rate and boom roll rate were the only metrics that did not reject the null
hypotheses that the true mean error was 0. The other metrics showed evidence against the null hypothesis that the actual mean error was 0. While these calculations allowed the error between the model and field to be quantified, the time series plots provided visual information relating to the ability of the model to accurately simulate the dynamic characteristics of a physical sprayer and behave similarly when subjected to the same chassis roll profiles.

**Table 5.10: Evaluating the error between model simulation and field testing**

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Mean Error (μ)</th>
<th>Standard Deviation of Error (σ)</th>
<th>Data Points (n)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chassis Roll Angle (deg)</td>
<td>-0.18</td>
<td>0.26</td>
<td>760</td>
</tr>
<tr>
<td>Boom Roll Angle (deg)</td>
<td>0.16</td>
<td>0.26</td>
<td>760</td>
</tr>
<tr>
<td>R2 Height (mm)</td>
<td>-115</td>
<td>231</td>
<td>760</td>
</tr>
<tr>
<td>Chassis Roll Rate (deg/s)</td>
<td>0.00</td>
<td>0.41</td>
<td>760</td>
</tr>
<tr>
<td>Boom Roll Rate (deg/s)</td>
<td>0.01</td>
<td>1.09</td>
<td>760</td>
</tr>
</tbody>
</table>

**Table 5.11: Results from two-sided t-test of mean error, α = 0.05**

| Measurement                        | SE  | DF  | Null Hypothesis | Alternative Hypothesis | Test Statistic | Prob > |t| |
|------------------------------------|-----|-----|-----------------|------------------------|----------------|---------|
| Chassis Roll Angle (deg)           | 0.01| 759 | μ = 0           | μ ≠ 0                  | -18.9          | <.0001  |
| Boom Roll Angle (deg)              | 0.01| 759 | μ = 0           | μ ≠ 0                  | 16.94          | <.0000  |
| R2 Height (mm)                     | 8.38| 759 | μ = 0           | μ ≠ 0                  | -13.66         | <.0001  |
| Chassis Roll Rate (deg/s)          | 0.02| 759 | μ = 0           | μ ≠ 0                  | -0.02          | 0.98    |
| Boom Roll Rate (deg/s)             | 0.04| 759 | μ = 0           | μ ≠ 0                  | 0.29           | 0.77    |

**5.2.3 Performance of Variable Boom Roll Damping**

After the performance of the model was validated, the next step was to develop a logic within the model to vary the damping rates of the boom roll dampers. A triggered increase in damping rate was implemented in the model and the activation of the trigger would have the ability to mitigate induced boom roll from wing height activations and chassis roll events. The
boom roll damping rates would have the ability to be triggered at varying magnitudes and utilize combinations of trigger hold times and ramp down times (Figure 5.5).

Figure 5.5: Graphical representation of triggered damping rates during a detected event (1), hold time (2), and ramp down time (3)

An increase in damping rate would be triggered immediately when a monitored sprayer event occurs (i.e., left wing raise) and held at the increased rate until the event stops. Next, the trigger hold time would occur. This was defined as the amount of time between the end of the triggering event and the beginning of the ramp down time in which the damping rate continued to hold constant at the increased damping rate. Then the ramp down time would occur, which was the amount of time over which the damping rate linearly decreased back to the initial
value. The addition of post-triggered event hold times and ramp down times allowed any
induced motions into the system to settle out before returning the boom roll damping rate to
the initial value. During the initial phases of developing variable boom roll damping control
logics, both the trigger hold time and ramp down time were set to 0.5 seconds.

A triggered increase in damping rate was simulated in the model using the same left
wing raise motion described in the validation procedure. The magnitude of the damping rates
being triggered ranged from 0 kN*s/m to 175 kN*s/m. Increasing the magnitude of triggered
boom roll damping rates decreased the amount of boom height deviation at the R2 sensor on
the spray boom (Figure 5.6). The majority of the improvement for boom height control
occurred when using damping rates up to 88 kN*s/m. Above this damping rate, there was less
standard deviation R2 reduction with increasing damping rates because height error induced
into the boom was from chassis roll which could not be resolved by increasing the damping
rate of the boom roll.
Next, the damping triggers were tested during chassis roll events to measure how the active variability in boom roll damping rates influence boom height control performance. Multiple methods for detecting boom height error and triggering an increase in damping rate were evaluated using the model with a sinusoidal chassis roll input. The overall goal of each method was to minimize overshooting boom roll and utilize the direction of chassis roll to aid in the positioning of boom roll by managing the dampening rate between the relative motion of the chassis and boom (i.e., boom roll dampers). Overshooting boom roll occurred when the spray boom continued to roll in a direction from which the chassis had stopped or reversed direction. The opposing chassis roll direction could trigger an increase in damping rates to slow the angular roll rate of the boom roll overshoot and drive the angular position of the boom in
the same direction as the chassis until it achieved target height. Initial target height errors from boom roll overshoot included being both below or above the set spray height. Therefore, the direction of chassis roll needed for boom roll correction in either target height scenarios was simply opposite the direction of boom roll error. A list of methodologies for detecting overshooting boom roll scenarios with differing sensors was evaluated using model simulations in order to determine which method decreased boom height error the most when compared to a constant damping rate boom roll system (Table 5.5).

The simulation to evaluate the trigger styles consisted of a sinusoidal chassis roll with 3 degrees amplitude and a 4 second period. These parameters represented chassis dynamic conditions similar to crossing a grass strip waterway at the field testing site. The trigger hold time and ramp down time were set to 0.5 seconds each which was proven to be effective in earlier stationary wing raise simulations. Every trigger style simulation was 30 seconds in length and had a 123 kN*s/m triggered damping rate. For each simulation, the resulting R2 height data (relative to unchanging level ground in the model) was analyzed and the R2 standard deviations reported (Figure 5.7).
Figure 5.7: Simulation results from testing multiple methods that trigger an increase in damping rates to control overshooting boom roll.

Trigger style 5 had the most effective logic to decrease the spray boom deviation from target height. It had a 50% reduction in R2 standard deviation compared to a boom roll system with constant damping similar to a production sprayer. Specifically, the logic of this successful trigger style applied an increased damping rate when the boom roll rate relative to ground (calculated using the summation of chassis roll rate and boom roll rate since they have the same sign convention) was measured to be greater than the chassis roll rate. This event could be imagined by visualizing the spray boom continuing to roll in a direction relative to ground the chassis was no longer rolling (Figures 5.8: #1 through 5.11: #4). Boom roll induced from a progression of chassis roll events would cause one wing of the sprayer to be below target height and continue downward towards the ground. The other end of the wing was above target height.
height and moving upwards away from target height. This situation was detected (by monitoring chassis roll rates and boom roll rates) and a triggered increase in boom roll damping slowed the angular velocity of the boom relative to the chassis. Since the chassis was rolling in the other direction, the angular velocity of the boom relative to ground was decreased and eventually reversed; thus, keeping the low wing from contacting the ground and raising it upwards towards target height. Once the spray boom was stabilized near target height, the damping rates were lowered to the default operating rate. The trigger hold time and ramp down time enabled the damping rates to stay at the increased rate for an adequate amount of time (total of 1.0 second in this simulation) in order to recover the overshooting boom roll and then return to the pre-triggered damping rate setting. The lower R2 standard deviation results from trigger style 5 indicated the elevation of the spray boom did not fluctuate nearly as far as the other trigger styles. This demonstrated the effectiveness for controlling spray boom height using variable damping rates between the relative motion of the chassis and boom.
- Level terrain
- Minimal chassis roll inputs
- Low boom roll damping rate

![Diagram](image1)

**Figure 5.8: #1: Initial level operating conditions**

- Clockwise chassis roll motion
- Maintain low boom roll damping rate to allow boom frame to decouple from chassis

![Diagram](image2)

**Figure 5.9: #2: Dynamic behavior resulting from a chassis roll input**
- Counterclockwise chassis roll motion
- Increased boom roll damping rate to utilize chassis roll motion
- Position boom roll towards target height

Figure 5.10: #3: Damping rate response for correcting boom height position

- Clockwise chassis roll motion
- Increased boom roll damping rate controls overshooting boom roll
- Chassis roll direction positions boom roll towards target height

Figure 5.11: #4: Utilizing chassis roll direction and increased damping rates to control boom roll overshoot
Trigger style 5 was further evaluated in order to examine its capabilities over a broader range of chassis roll conditions (Table 5.7 & Table 5.8). The model simulated chassis roll periods ranging from 2 to 5 seconds with chassis roll amplitudes of 1.0, 2.0, and 3.5 degrees for each period. These combinations represented events from slow rolling slow magnitude to fast rolling high magnitude, all of which a sprayer may be exposed to when operating. Additionally, two more trigger hold time and trigger ramp down time combinations were analyzed. They included 0.5, 0.1 seconds and 0.1, 0.1 seconds, respectively. All simulations were 30 seconds long. Testing these various combinations of chassis conditions and trigger parameters provided an opportunity to determine optimum timing parameters of the trigger and minimize R2 standard deviation for all terrain conditions simulated.
Figure 5.12: Evaluating trigger style 5 performance in various chassis roll periods and amplitudes with 3 combinations of trigger hold and ramp down times

The simulation results provided a side-by-side comparison for evaluating R2 standard deviation (Figure 5.12). A constant damping system with rates similar to a production sprayer for comparison is reflected using blue bars. Increasing roll amplitudes generated the same trend of increasing R2 standard deviation throughout each variable damping treatment (0.5, 0.5; 0.5, 0.1; 0.1, 0.1) which are distinguished by color. For the multiple combinations of roll period and amplitude, the trigger hold time and ramp down 0.5, 0.1 seconds exhibited less R2 standard deviation than a constant damping system for all roll periods except 2 seconds. At the faster roll periods 2 and 3, the shortened ramp down time (0.1 seconds) aided in the ability for the boom roll damping rates to be decreased faster, thus not over positioning the boom from target height like the 0.5, 0.5 second trigger did. At the slow roll periods 4 and 5, the longer hold time
(0.5 seconds) maintained the increased damping rates to stay activated longer, resulting in the boom staying closer to target height than the 0.1, 0.1 second trigger. The other trigger parameters tested, 0.5, 0.5 and 0.1, 0.1 seconds, only performed better than the constant dampening scenario in two roll periods, 4 and 5, and 2 and 3, respectively. As a result, the trigger parameters 0.5, 0.1 seconds were implemented in field testing and further researched in Chapter 6.

5.3 Conclusions

The 2D sprayer model exhibited very similar boom roll and boom height characteristics during simulations compared to data collected from field tested sprayers. In certain tests, the error between the model and field results was less than 6%. The ability for the model to accurately simulate boom roll legitimized further development work pertaining to testing triggered increases in boom roll dampening rates. Simulations showed that boom height error induced from boom roll during wing height activations was reduced over 50% when triggering a boom roll rate increase during the activation period. The increased rate decreased the relative motion between the chassis and spray boom, acting like a brake.

Further model simulations evaluated different methods for triggering a temporary increase in boom roll damping rates when experiencing a chassis roll input that induced unwanted boom roll. It was determined that by monitoring chassis roll rates and boom roll rates, excessive boom roll overshoot could be targeted to use as a trigger for increasing boom roll damping rates. Results from simulation testing showed a decrease of over 50% in the spray boom deviation from target height at the R2 sensor. The triggered increase in damping rate acted like a brake and slowed excessive boom roll, then used the chassis rolling motion to
redirect the roll of the boom toward the target height before the damping rate trigger deactivated and the rate returned to the initial value.

The triggered damping rate utilized the triggered hold length and ramp down time to decrease the damping rates to the default value in a gradual controlled manner. Both were optimized using simulations where combinations of all variables were each tested. The chassis conditions simulated in the tests included roll periods from 2 to 5 seconds and roll amplitudes ranging from 1 to 3.5 degrees which represented a broad spectrum of operating terrain conditions. The most effective parameter in the chassis roll conditions for the temporary triggered increase in damping rates was holding the trigger on for 0.5 seconds and ramping it down quickly within 0.1 second. The optimization tests concluded that when triggered, a 0.5 second increase in boom roll damping rate was an appropriate amount of time for slowing unwanted boom roll, while a brief 0.1 second ramp down of the triggered rate ensured the boom did not receive too much rotational energy from the chassis during this time that would reintroduce boom height error.

Overall, the model simulations aided in the development of a variable boom rate control logic that would be evaluated in field testing using a sprayer retrofitted with variable damping technology. The simulation capabilities of the model streamlined the development process and used less resources than conducting all the aforementioned tests using a sprayer in the field.
CHAPTER 6. CHARACTERIZATION OF VARIABLE DAMPING BOOM ROLL PERFORMANCE

Using the self-propelled sprayer tested in Chapter 4, the production boom roll dampers were replaced with magnetorheological (MR) dampers. The variable damping rate capability of the MR dampers was examined in stationary and field testing to evaluate the boom roll control methods discussed in Chapter 5. Boom height control and boom roll control were the performance metrics examined during testing to determine the effectiveness of variable damping rates on influencing boom roll control.

6.1 Methods

6.1.1 Installing and Benchmarking MR Dampers

On the same production sprayer tested in Chapter 4, the constant dampers were replaced with MR dampers to evaluate the variable damping methods that were proven to be effective in simulation models. Due to slight dimensional differences between the two styles of dampeners, an adapter bracket was necessary to account for the shorter stroke length of the MR damper, and boom roll was limited to ±2.5 degrees (±3.0 degrees was stock production) through adjusting the boom roll stops in order to protect them from over-extension and over-compression. At the time of this research, this dimensional size of MR damper was closest to the production damper and was also readily available.

Four MR dampers, two per side, were hypothesized to exhibit a similar damping rate when operating in an off state (0 Amp) as the production sprayer. This was important because when the sprayer was not experiencing an induced boom roll or target height error event, the
variable damping rate was the equivalent of a stock production sprayer. The ability for the variable damping system to return to the original stock boom roll rate was necessary because the damping triggers functioned in this manner during model simulations. Additionally, the variable damping sprayer would have the ability to mimic the boom roll characteristics of a production sprayer without having to change out the boom roll dampers which allowed for seamless transitions between identical tests that compared variable and constant boom roll damping. The current commanded to the MR dampers, which was nearly proportional to the total damping rate, was managed using a CANbus controller (Table 6.1).

Table 6.1: *Damping rates vs. current*

<table>
<thead>
<tr>
<th>MR Damping Current (Amp)</th>
<th>Total Boom Roll Damping Rate (kN*s/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>5</td>
</tr>
<tr>
<td>0.25</td>
<td>13</td>
</tr>
<tr>
<td>0.50</td>
<td>24</td>
</tr>
<tr>
<td>0.75</td>
<td>39</td>
</tr>
<tr>
<td>1.00</td>
<td>64</td>
</tr>
<tr>
<td>1.50</td>
<td>93</td>
</tr>
<tr>
<td>2.00</td>
<td>123</td>
</tr>
</tbody>
</table>

.075 m/s compression & extension velocity
4 individual variable dampers

To test the hypothesis that a production sprayer boom roll damping rate exhibited similar boom roll characteristics as the MR dampers when commanded a low amperage, stationary and field tests were conducted with the MR dampened sprayer for comparison against the stationary and field testing results of the production sprayer in Chapter 4.
The stationary tests were conducted as described in section 4.1.1 using a left wing raise motion having a cylinder raise speed of 90 mm/s for a duration of 1 second. The variable dampers were evaluated at 0.0, 0.25, 0.50, 0.75, 1.00, 1.50, 2.00 Amp command levels to the MR dampers in order to determine which current represented a production sprayer damping rate as well as analyze the effectiveness of increasing damping rates during wing activations. There were 15 repetitions for each amperage level, resulting in a total of 105 tests (Table 6.2). The standard deviation of the right wing elevation was the test metric for this evaluation.

Table 6.2: Damping method description for model validation through stationary testing

<table>
<thead>
<tr>
<th>Damping Method</th>
<th>MR Control Current (Amps)</th>
<th>Damping Rate (kN*s/m)</th>
<th>Replicates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production Damper</td>
<td>-</td>
<td>5</td>
<td>15</td>
</tr>
<tr>
<td>MR Damper (Continuous rate applied)</td>
<td>0.00</td>
<td>5</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>0.25</td>
<td>13</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>0.50</td>
<td>24</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>0.75</td>
<td>39</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>1.00</td>
<td>64</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>1.50</td>
<td>93</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>2.00</td>
<td>123</td>
<td>15</td>
</tr>
</tbody>
</table>

The MR dampers were field tested in Medium terrain employing the same testing method and travel path outlined in section 4.1.2 (Table 6.3). Four command currents, 0.0, 0.25, 0.50, and 2.0 Amps, applied at a constant rate throughout each pass, were tested using the MR dampers to further establish which current exhibited similar boom roll characteristics as the stock production sprayer. There were 10 repetitions for each amperage level, resulting in a total of 40 tests that were randomly ordered. All tests were conducted in the same travel direction.
and at the same spray boom set height (1 meter). The standard deviation of the right wing elevation was the test metric for this evaluation. Medium terrain was selected for this test because it consistently generated an adequate amount of boom roll to induce detectable boom height error; it contained more ground profile features than Mild to induce boom roll, yet was not as extreme as Aggressive where it was common for the boom roll stops to contain boom roll within the operating range of motion.

Table 6.3: Damping method description for model validation through field operation testing

<table>
<thead>
<tr>
<th>Damping Method</th>
<th>MR Control Current (Amps)</th>
<th>Terrain</th>
<th>Travel Speed (km/h)</th>
<th>Replicates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production Damper</td>
<td>-</td>
<td>Medium</td>
<td>19.3</td>
<td>10</td>
</tr>
<tr>
<td>MR Damper (Continuous rate applied)</td>
<td>0.00</td>
<td>Medium</td>
<td>19.3</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>0.25</td>
<td>Medium</td>
<td>19.3</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>0.50</td>
<td>Medium</td>
<td>19.3</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>2.00</td>
<td>Medium</td>
<td>19.3</td>
<td>10</td>
</tr>
</tbody>
</table>

Upon determining the MR damper current setting that exhibited the same damping rate as the stock production sprayer, the wing activation and chassis roll motion methods described in Chapter 5 for triggering damping rate increases were tested. In these methods, when the damping rate increases were not triggered, the damping rate defaulted to a low constant damping rate.
6.1.2 Variable Damping Triggered by Wing Activations

The first triggering method tested increased the boom roll damping rates during wing activations. In order to simulate realistic sprayer conditions, the sprayer was not tested stationary using a single wing raise, but rather in a field test in which the spray boom height control system was activated. The control system adjusted the individual wing heights to maintain target height during operation by actively monitoring the ultrasonic sensors on the boom. The wings were actuated frequently to maintain target height; thus, providing detectable wing activation events upon which increased damping rates would be triggered to reduce induced boom roll. Medium terrain was used for this test because it provided variations in ground profile to warrant individual wing height corrections without the aggressive chassis roll inputs to the system. There were five test runs each for both constant damping and variable damping boom roll rates. This comparison would allow a passive damping boom suspension to be compared to a semi-active system (Table 6.4). The parameters of the damping rate trigger included a 64 kN*s/m triggered damping rate (1.0 Amp commanded current), a 0.5 second hold time at the triggered rate, and a 0.5 second trigger ramp down time to the default damping rate. String potentiometers detected length changes on either wing height hydraulic cylinder to initiate the trigger sequence. The field tests were conducted in the same travel direction and speed as described in section 4.1.2. The standard deviations of R2 height position, chassis roll rate, and boom roll rate were evaluated to analyze performance characteristics.
Table 6.4: Description of test methods for wing activated trigger evaluation

<table>
<thead>
<tr>
<th>Damping Method</th>
<th>Triggered MR Current (Amps)</th>
<th>Damping Rate (kN*s/m)</th>
<th>Hold &amp; Ramp Down Time (s)</th>
<th>Automated Boom Height Control</th>
<th>Terrain</th>
<th>Travel Speed (km/h)</th>
<th>Replicates</th>
</tr>
</thead>
<tbody>
<tr>
<td>MR Damper (Variable)</td>
<td>0</td>
<td>-</td>
<td>On</td>
<td>Medium</td>
<td>19.3</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>64</td>
<td>0.5</td>
<td>On</td>
<td>Medium</td>
<td>19.3</td>
<td>5</td>
</tr>
</tbody>
</table>

6.1.3 Variable Damping Triggered by Terrain Inputs to Sprayer Chassis

The second triggering method tested was the chassis roll trigger developed and optimized in sections 5.1.3 & 5.2.3 (Trigger Style 5). For comparison, the boom suspension with constant damping was also tested. The chassis roll trigger used the same trigger parameters (0.5 second hold time, and 0.1 second ramp down time) as the model simulation and the triggered current to the MR dampers was 2.0 Amp (123 kN*s/m). The descriptions of the triggering method and the conditions for triggering were detailed within Table 5.11. Initially, the three terrain types Mild, Medium, and Aggressive, were field tested to evaluate the effectiveness of the variable damping logic over natural ground profiles (Table 6.5). Four repetitions of test passes were made on each terrain for both constant and variable damping boom roll rates. However, these terrain profiles did not subject the sprayer to the excessive chassis roll the damping trigger was optimized for in the model simulations so there was an opportunity for further testing.
Table 6.5: Description of test methods for chassis roll trigger evaluation

<table>
<thead>
<tr>
<th>MR Damping Method</th>
<th>Damping Rate (kN*s/m)</th>
<th>Hold Time (s)</th>
<th>Ramp Down Time (s)</th>
<th>Automated Boom Height Control</th>
<th>Terrain</th>
<th>Travel Speed (km/h)</th>
<th>Replicates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuous</td>
<td>-</td>
<td>-</td>
<td>Off</td>
<td>Mild</td>
<td>19.3</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Variable</td>
<td>123</td>
<td>0.5</td>
<td>0.1</td>
<td>Off</td>
<td>Mild</td>
<td>19.3</td>
<td>4</td>
</tr>
<tr>
<td>with Triggered</td>
<td>123</td>
<td>0.5</td>
<td>0.1</td>
<td>Off</td>
<td>Medium</td>
<td>19.3</td>
<td>4</td>
</tr>
<tr>
<td>Damping Rates</td>
<td>123</td>
<td>0.5</td>
<td>0.1</td>
<td>Off</td>
<td>Aggressive</td>
<td>19.3</td>
<td>4</td>
</tr>
</tbody>
</table>

In order to field test the sprayer similar to the chassis roll simulations in the modeling environment, a new testing method was developed. Driving the sprayer over a ramp generated a significant chassis roll event while maintaining a level terrain profile under the spray boom. This method resembled the model simulation environment which was important for validating the damping trigger in field testing since the parameters of the damping triggers were optimized for those conditions. The field testing terrains lacked the capability to roll the chassis in a sinusoidal roll angle; however, the ramp provided a single significant chassis roll input to the system which induced periodic boom roll motion. The ramp testing method was a repeatable environment in which constant and variable boom roll damping would be evaluated (Table 6.6). The triggered damping rate was 123 kN*s/m, and the hold time and ramp down time were 0.5 seconds and 0.1 seconds, respectively.

The ramp was built using steel and wooden beams (Figure 6.1). At both ends there were 3 meter long, 10 degree inclines leading up to the 3 meter long elevated platform. The height
of the elevated platform was 0.45 meters. Driving the sprayer over the ramp at 16 km/h generated 8 degrees of chassis roll and the boom roll oscillations lasted for approximately 6 seconds after the sprayer drove off the ramp. The resulting boom height error induced from boom roll and chassis roll provided opportunities for the variable damping rates to be effective in controlling boom roll overshoot and boom angle repositioning.

Figure 6.1: *Ramp developed to induce repeatable large-magnitude chassis roll*

Table 6.6: *Description of test methods for ramp testing evaluation*

<table>
<thead>
<tr>
<th>MR Damping Method</th>
<th>Damping Rate (kN*s/m)</th>
<th>Hold Time (s)</th>
<th>Ramp Down Time (s)</th>
<th>Automated Boom Height Control</th>
<th>Terrain</th>
<th>Travel Speed (km/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuous</td>
<td>-</td>
<td>-</td>
<td>Off</td>
<td>Ramp</td>
<td>16.0</td>
<td></td>
</tr>
<tr>
<td>Variable with Triggered Damping Rates</td>
<td>123</td>
<td>0.5</td>
<td>0.1</td>
<td>Off</td>
<td>Ramp</td>
<td>16.0</td>
</tr>
</tbody>
</table>

Unlike the model simulation, which had no sensor range limitations or sensor noise, the implementation of the damping trigger logic on sprayer during ramp testing needed to account for these natural occurrences. The R2 and L2 ultrasonic sensors experienced out of
range occurrences during ramp testing. Therefore, much of data collected from them was null and did not represent the true motions of the spray boom. As a result, the angle of the boom relative to the ground was developed as the test metric to measure boom height performance (Figure 6.2). Since the ground profile under the spray boom during ramp testing was nearly flat, this angle was calculated by adding the angle of the chassis (relative to the ground) to the angle of the boom (relative to the chassis). To account for sensor noise and unnecessary damping trigger actuations during field and ramp testing, a dead band was implemented in the variable damping control software limiting the trigger damping actuations to chassis roll rates having a magnitude greater than 0.50 degrees/second.

![Boom angle relative to ground](image)

Figure 6.2: *Boom angle relative to ground was the summation of chassis roll angle ($\theta_1$) and boom roll angle ($\theta_2$)*

6.2 Results

6.2.1 Boom Height Performance Characteristics with MR Dampers

The stationary left wing raise tests validated the hypothesis that when the MR dampers were commanded 0 Amps, the behavior of boom height performance would be similar to a
production sprayer having a constant damping rate. The results from the tests showed no statistical difference between the two (Figure 6.3). A one-way between subjects ANOVA was conducted to compare the effect of a left wing raise event on R2 standard deviation in production damping and 0 amp MR damping conditions. There was no significant effect of these two damping conditions on R2 standard deviation at the $\alpha=0.05$ significance level (Table 6.7). Post hoc comparisons using the Tukey HSD test indicated that R2 standard deviation for the production damping rate ($\mu = 99\text{mm}, \sigma = 3\text{mm}$) did not significantly differ from the 0 amp MR damping condition ($\mu = 107\text{mm}, \sigma = 5\text{mm}$). Therefore, the MR dampers could be used to resemble the production spray dampers for comparison in future tests.

Additionally, increasing the commanded current to the MR dampers decreased R2 standard deviation. The damping rates increased and there was less induced boom roll. However, from 0.75 Amps and greater, there were no measurable improvements in decreasing R2 standard deviation because the spray boom had inherent vertical flex in the wings that could not be reduced as well as induced chassis roll from the dampened boom roll that affected the boom roll angle relative to the ground.
Figure 6.3: Results from stationary testing matching the MR current that exhibited similar StDev R2 as the production damping rate.

Table 6.7: ANOVA results distinguishing statistically similar damping methods from stationary testing ($\alpha = 0.05$)

<table>
<thead>
<tr>
<th>Damping Method</th>
<th>MR Current (Amps)</th>
<th>N</th>
<th>Mean</th>
<th>Lower 95%</th>
<th>Upper 95%</th>
<th>Grouping</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stock Damper</td>
<td>*</td>
<td>15</td>
<td>99</td>
<td>97</td>
<td>102</td>
<td>A</td>
</tr>
<tr>
<td>Variable Rate 0.00</td>
<td>15</td>
<td>107</td>
<td>102</td>
<td>111</td>
<td></td>
<td>A</td>
</tr>
<tr>
<td>Variable Rate 0.25</td>
<td>15</td>
<td>72</td>
<td>68</td>
<td>76</td>
<td></td>
<td>B</td>
</tr>
<tr>
<td>Variable Rate 0.50</td>
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<td>65</td>
<td>60</td>
<td>69</td>
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<tr>
<td>Variable Rate 0.75</td>
<td>15</td>
<td>58</td>
<td>54</td>
<td>63</td>
<td></td>
<td>C</td>
</tr>
<tr>
<td>Variable Rate 1.00</td>
<td>15</td>
<td>58</td>
<td>54</td>
<td>63</td>
<td></td>
<td>C</td>
</tr>
<tr>
<td>Variable Rate 1.50</td>
<td>15</td>
<td>60</td>
<td>56</td>
<td>64</td>
<td></td>
<td>C</td>
</tr>
<tr>
<td>Variable Rate 2.00</td>
<td>15</td>
<td>63</td>
<td>59</td>
<td>67</td>
<td></td>
<td>B C</td>
</tr>
</tbody>
</table>

The Medium terrain field testing results also verified the hypothesis that MR dampers commanded 0 Amps had a similar damping rate as a production sprayer (Figure 6.4). A one-
way between subjects ANOVA was conducted to compare the effect of a Medium terrain field testing on R2 standard deviation in production damping and 0 amp MR damping conditions. There was no significant effect of these two damping conditions on R2 StDev at the $\alpha=0.05$ level (Table 6.8). Post hoc comparisons using the Tukey HSD test indicated that R2 StDev for the production damping rate ($\mu = 234\text{mm}$, $\sigma = 5\text{mm}$) did not significantly differ from the 0 amp MR damping condition ($\mu = 233\text{mm}$, $\sigma = 2\text{mm}$). Increasing the MR damping current, thereby increasing the variable damping rate, resulted in a StDev R2 increase. The explanation for this occurrence was similar to the trend seen in the previous stationary testing; a higher boom roll damping rate transmits the roll forces, once seen by only the suspended boom, to the chassis because of the increased damping rates between the relative angular motions of the two. However, the variable damping rates were held to a constant value in these tests and did not reflect the boom height control performance of a true semi-active variable damping system.
Figure 6.4: Results from field testing that matched the MR current exhibiting similar StDev R2 as the production constant damping rate

Table 6.8: ANOVA results distinguishing statistically similar damping methods from field testing (α = 0.05)

<table>
<thead>
<tr>
<th>Damping Method</th>
<th>MR Current (Amps)</th>
<th>N</th>
<th>Mean StDev (mm)</th>
<th>Lower 95% (mm)</th>
<th>Upper 95% (mm)</th>
<th>Grouping</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stock Damper</td>
<td>*</td>
<td>10</td>
<td>234</td>
<td>229</td>
<td>239</td>
<td>A</td>
</tr>
<tr>
<td>Variable Rate</td>
<td>0.00</td>
<td>5</td>
<td>233</td>
<td>230</td>
<td>235</td>
<td>A</td>
</tr>
<tr>
<td>Variable Rate</td>
<td>0.25</td>
<td>5</td>
<td>251</td>
<td>245</td>
<td>257</td>
<td>B</td>
</tr>
<tr>
<td>Variable Rate</td>
<td>0.50</td>
<td>5</td>
<td>264</td>
<td>258</td>
<td>270</td>
<td>C</td>
</tr>
<tr>
<td>Variable Rate</td>
<td>2.00</td>
<td>5</td>
<td>269</td>
<td>263</td>
<td>275</td>
<td>C</td>
</tr>
</tbody>
</table>

The results from these stationary and field tests exhibited the capability of the MR dampers to simulate a similar damping rate as a production sprayer. This allowed for comparative tests to be conducted without having to exchange the MR dampers for the constant
dampers between tests. Also, the MR dampers defaulted to this damping rate when the triggers were not activated to increase damping rates during trigger tests.

### 6.2.2 Integration of Wing Height Activation Damping Trigger with Boom Height Control Software

The field test comparison between the constant damping rate and variable damping rate (triggered by wing height activations) evaluated the standard deviations of R2, boom roll rate, and chassis roll rate. Applying variable boom roll damping rate increased StDev R2 and StDev chassis roll rate while decreasing StDev boom roll rate (Figure 6.5). One explanation for the increase in boom height error was that the induced boom roll forces from wing activations, typically isolated to only the suspended boom, were transmitted to the chassis through the forces exerted on the boom roll dampers. This resulted in chassis roll that induced boom height error further, thus requiring wing height adjustments to achieve target height.
Another explanation was that the wing height activations were so frequent the damping rates were increased a majority of the test runs leading to essentially a system with a higher constant damping rate. Higher constant damping rates were seen to negatively impact boom height control when operating in field conditions (Figure 6.3). MR damping current data obtained during the field testing measured full damping rate trigger activation approximately 70% of the time (Figure 6.6).

Figure 6.5: Comparing results from testing wing height activation triggers with constant and variable damping rates
6.2.3 Performance of Chassis Roll Triggered Variable Damping

Trigger style 5 performed similar to a constant damping rate when field tested in each Mild, Medium, and Aggressive terrain. There was 95% confidence the constant and variable damping true means of StDev R2 were similar for each terrain (Figure 6.7). A one-way between subjects ANOVA was conducted to compare the effect of terrain severity on R2 standard deviation in constant damping and variable damping conditions. There was no significant effect of damping conditions on R2 StDev for any terrain profile at the $\alpha=0.05$ level (Table 6.9). Post hoc comparisons using the Tukey HSD test indicated that R2 StDev for each terrain profile was significantly different for both constant and variable damping conditions. Triggering increased damping rates to control boom roll overshoot did not appear to improve boom height control performance.
Figure 6.7: R2 StDev results comparing field tests between variable damping and constant damping for various terrain profiles

Table 6.9: ANOVA analysis of field test comparison for trigger style 5 in varying terrain profiles ($\alpha = 0.05$)

<table>
<thead>
<tr>
<th>Terrain</th>
<th>Damping</th>
<th>N</th>
<th>Mean StDev (mm)</th>
<th>Lower 95% (mm)</th>
<th>Upper 95% (mm)</th>
<th>Grouping</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mild</td>
<td>Constant</td>
<td>4</td>
<td>99</td>
<td>87</td>
<td>111</td>
<td>A</td>
</tr>
<tr>
<td>Mild</td>
<td>Variable</td>
<td>4</td>
<td>122</td>
<td>109</td>
<td>135</td>
<td>A</td>
</tr>
<tr>
<td>Medium</td>
<td>Constant</td>
<td>4</td>
<td>170</td>
<td>158</td>
<td>182</td>
<td>B</td>
</tr>
<tr>
<td>Medium</td>
<td>Variable</td>
<td>4</td>
<td>182</td>
<td>169</td>
<td>195</td>
<td>B</td>
</tr>
<tr>
<td>Aggressive</td>
<td>Constant</td>
<td>4</td>
<td>229</td>
<td>217</td>
<td>241</td>
<td>C</td>
</tr>
<tr>
<td>Aggressive</td>
<td>Variable</td>
<td>4</td>
<td>209</td>
<td>196</td>
<td>221</td>
<td>C</td>
</tr>
</tbody>
</table>

Boom Set Height: 1 meter
Travel speed: 19.3 km/h
Number of reps for each test=4
Individual standard deviations are used to calculate the intervals.
The large chassis roll events necessary to generate the necessary sprayer motions for activating the triggers did not occur frequently in these field conditions in order to detect a measurable StDev R2 decrease. Therefore, a subsequent field testing method was developed to address this issue which generated the substantial chassis roll motions that field testing terrains did not have the capability of generating. Driving the sprayer over the ramp generated a significant chassis roll event causing overshooting boom roll similar to the model simulations used during trigger development research. Trigger style 5 increased damping rates to the maximum rate (123 kN*s/m at 2 Amp) when overshoot was detected to manage boom roll. Since the ground profile stayed level for this test, the target angle for the boom relative to ground was 0 degrees in order to maintain a level spray height above the ground. In comparison to a constant damping system, the variable damping rates decreased the magnitude of error for the boom angle relative to ground during multiple overshooting boom roll events (Figure 6.8). Upon the initial contact with the ramp that increased the chassis roll angle, the resulting increase in boom angle relative to ground was nearly the same for both constant and variable damping (#1, Figure 6.8). Both systems were not able to reject chassis roll motion when the boom roll angle relative to the machine reached the maximum angle and the roll stops contacted the boom. However, the resulting boom roll overshoot angle (deg) immediately after driving off the ramp was reduced 16% using the damping trigger (Event 2, Figure 6.8). At this moment in the ramp test, the angular deceleration of boom roll induced 3% increase in chassis roll angle (deg).

At the next opportunity for controlling boom roll overshoot, the variable dampers reduced the boom roll angle relative to ground 39% which positioned it near the target height angle of 0 degrees. Nonetheless, this induced 23% more chassis roll as a result of limiting the
boom motion (Event 3, Figure 6.8). Thereafter, the oscillation magnitudes of the boom angle relative to ground were decreasing as the induced roll motions to the chassis and boom settled out. The damping trigger was able to manage the roll angle of the boom from deviating from the 0 degree target height angle once more (Event 4, Figure 6.8), decreasing the angular motion of the boom relative to ground 44% while inducing 28% more chassis roll angle.

Figure 6.8: Time series results highlighting the events where variable damping impacted boom roll and chassis roll during critical overshoot events

The damping trigger was very active during the ramp event. Overshooting boom roll was detected multiple times using the CANbus data from the chassis roll rate and the boom
roll rate relative to the chassis. The chassis roll rate dead band programmed into the MR damper controller proved to limit the trigger actuations to only chassis roll rate events indicative to situations where overshotting boom roll was present (i.e., ramp). Although boom height error was improved through applying variable damping rates to manage overshoot in boom roll angles, the magnitude of induced chassis roll was significant and noticeable from the standpoint of an operator (Table 6.10).

Table 6.10: Evaluating the effects of variable damping to control overshooting boom roll error during ramp testing

<table>
<thead>
<tr>
<th>Event</th>
<th>Boom Angle to Ground Percent Reduction (deg)</th>
<th>Chassis Roll Angle Percent Increase (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.0</td>
<td>0.0</td>
</tr>
<tr>
<td>2</td>
<td>16.0</td>
<td>3.0</td>
</tr>
<tr>
<td>3</td>
<td>39.0</td>
<td>23.0</td>
</tr>
<tr>
<td>4</td>
<td>44.5</td>
<td>28.0</td>
</tr>
</tbody>
</table>

*All percentages are relative to identical tests with constant damping rates

6.3 Conclusions

The MR dampers demonstrated the ability for variable boom roll damping to be applied as a semi-active boom roll control system. They exhibited constant damping rate characteristics of a production sprayer along with variable damping rate capabilities utilized for managing induced boom roll from wing activations and chassis roll events. Applying increased boom roll damping, regardless of whether it was triggered or held at a constant rate, limited the capacity for the spray boom to isolate from chassis roll motion and vice versa. This was taken advantage of during the ramp testing when boom roll overshoot was captured using increased damping rates. However, it induced a significant amount of chassis roll. Triggering damping rates during
wing activations decreased the amount of relative motion between the boom and chassis as intended to manage induced roll, but it led to increased chassis roll motions that induced boom target height errors.

A successful application of variable damping was observed in the ramp testing where significant chassis roll events were present. The chassis roll motion was similar to the terrain conditions the damping trigger was designed for, therefore improvements in boom height control were seen. Implementing the logic for monitoring sensors that detected boom roll overshoot induced from chassis roll required intelligent dead bands to target only significant events where the improvement in boom height control exceeded the error induced from chassis roll. Timely actuations were also necessary in order for the variable damping to perform as predicted in the model simulations.

During sprayer field testing where significant chassis roll events were not present, the results from field testing indicated lower damping rates generated less boom height error due to the suspended boom system being more isolated from chassis roll inputs. At lower damping rates, less force was transmitted through the dampers to affect the position and motion of the boom.
CHAPTER 7. CONCLUSIONS AND FURTHER RESEARCH

Variable damping presents opportunities to improve boom height control performance through intelligent application for managing boom roll on sprayers with suspended boom systems. Minimizing spray boom target height error induced from boom roll is critical for meeting the growing demand for precise application of chemicals. In this research, multiple methods for employing variable boom roll damping were explored and analyzed to examine their effects on boom target height performance. The 2D modeling tools were useful in simulating the dynamic characteristics of a suspended spray boom suspension. Multiple iterations of variable damping application methods were tested in this controlled environment; thus, saving time and machine wear before implementing a successful variable damping strategy on a sprayer for field testing.

MR dampers permitted the concept of variable damping to be implemented on a sprayer. Damping rates were proportional to applied currents (0-2 Amps). This enabled the control strategies developed using the model to be further evaluated in field testing. Triggering brief increases in boom roll damping rates proved to decrease the amount of relative motion between the boom and chassis, in order to control induced boom roll from wing activations and chassis roll. However, limiting the ability for the suspended boom to be isolated from the chassis resulted in induced roll angle motion at the chassis suspension on the sprayer. Compared to constant damping rates of a production sprayer, the variable damping methods during extreme chassis roll events and stationary wing raises decreased wing height standard deviation, a measurement of the spray boom deviation from target height. In all other variable damping tests conducted, the constant damping rate of the production sprayer exhibited the
least amount of wing height standard deviation because it had the ability to let the suspended boom behave more dynamically independent from external factors.

During the MR damper benchmark testing in this research, increased constant damping rates produced more R2 standard deviation. The MR dampers installed on the sprayer in Chapter 6 could only produce damping rates equal to or greater than a production sprayer. Therefore, further research opportunities exist to evaluate damping rates lower than the production sprayer utilized in this research.

In order to better simulate the sinusoidal chassis roll evaluated in the model simulation, multiple ramps could be placed in an alternating sequence (left and right) to generate a similar chassis roll input. Adjusting the heights of the ramps would vary the amplitude of the roll angle and the roll period would be proportional to travel speed.

The boom roll stops constrained the boom roll angle relative to the chassis thus affecting boom roll whenever contact was made during large chassis roll motions. Large chassis roll motions would cause the boom roll stops to be contacted and the suspended spray boom would lose the ability to “decouple” from the chassis. This resulted in overshooting boom roll when the chassis roll direction changed, but the boom continued rolling in the direction the boom roll stops were directing it. Although the boom roll angle relative to the chassis was constrained by the stroke length of the dampers and the physical geometry of the suspension system, extending the boom roll capabilities would decrease the recurrence of boom roll overshoot, thereby improving boom height performance.

In future research, it is recommended the GPS receiver be replaced with an inertial measurement unit (IMU) that has the ability to measure chassis roll angles and rates in the X, Y, and Z directions at 100Hz frequency. Delays in sensor readings and any lags when
transmitting on the CANbus network will affect the performance of the control system and the ability for the spray boom to maintain stability.
REFERENCES


