# INTELLIGENT ACTIVE TORQUE CONTROL FOR VIBRATION REDUCTION OF A SPRAYER BOOM SUSPENSION SYSTEM

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requirements for the award of the degree of
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To my lovely spouse Mohammad and my beloved mother and father for their endless support and encouragement

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# ABSTRACT

The most usual way of protecting crop from diseases is by using chemical method whereby mixture of chemicals and water are sprayed onto crop via nozzles. These nozzles are located consistently along a boom structure oriented perpendicular to the direction of motion to cover large areas. The most important factor on spray distribution pattern is spray boom vibration. Thus, suspension control aims to attenuate the unwanted vibration and should provide improvements in term of distribution uniformity. In this study, a combination of passive and active suspension was considered to create superior performance. A passive suspension was employed to control undesired vertical motion of sprayer boom structure while the roll movement of spray boom was reduced via active suspension. The active suspension system of sprayer was implemented by applying robust active torque control (ATC) scheme that integrates artificial intelligence (AI) methods plus another feedback control technique utilizing proportional-integral-derivative (PID) control. The proposed control system basically comprises of two feedback control loops; an innermost loop for compensation of the disturbances using ATC strategy and an outermost loop for the computation of the desired torque for the actuator using a PID controller. Two AI methods employing artificial neural network (ANN) and iterative learning (IL) were proposed and utilized to compute the estimated inertial parameter of the system through the ATC loop. The research proposes two main control schemes; the first is a combination of ATC and ANN (ATCANN) while the other is ATC and IL (ATCAIL). The suspension system was first modeled and a number of farmland terrains were simulated as the main disturbance components to verify the robustness of the system and sprayer boom dynamic performance related to distribution uniformity. The simulation results both in frequency and time domains show the effectiveness of the proposed ATC schemes in reducing the disturbances and other loading conditions. The control schemes were further implemented experimentally on a developed laboratory spray boom suspension test rig.

# ABSTRAK

Cara yang paling biasa untuk melindungi tanaman daripada penyakit adalah dengan menggunakan kaedah kimia yang mana campuran bahan kimia dan air disembur ke tanaman melalui muncung. Muncung ini terletak konsisten sepanjang struktur galang berserenjang dengan arah gerakan untuk meliputi kawasan yang besar. Faktor yang paling penting untuk menghasilkan corak taburan semburan ialah getaran galang penyembur. Oleh itu kawalan suspensi bertujuan untuk mengurangkan getaran yang tidak diingini dan harus menyediakan penambahbaikan dari segi keseragaman pengagihan. Dalam kajian ini, gabungan suspensi pasif dan aktif diguna untuk menghasilkan prestasi yang memuaskan. Suspensi pasif digunakan untuk mengawal gerakan menegak yang tidak diingini oleh struktur galang penyembur manakala pergerakan olengan galang penyembur telah dikurangkan melalui suspensi aktif. Sistem suspensi aktif penyembur dilaksanakan oleh skim kawalan daya kilas aktif (ATC) yang lasak dengan mengintegrasikan kaedah kecerdikan buatan (AI) dengan teknik kawalan suap balik iaitu gelung kawalan berkadaran-kamiran-terbitan (PID). Sistem kawalan yang dicadangkan terdiri daripada dua gelung kawalan suap balik; gelung dalaman untuk pampasan gangguan menggunakan strategi ATC dan gelung luaran untuk pengiraan daya kilas kehendak untuk penggerak yang menggunakan pengawal PID. Dua kaedah AI menggunakan rangkaian neural tiruan (ANN) dan lelaran pembelajaran (IL) telah dicadangkan dan digunakan untuk mengira anggaran parameter inersia sistem melalui gelung ATC. Kajian ini mencadangkan dua skim kawalan utama, yang pertama gabungan ATC dan ANN (ATCANN) manakala yang lain adalah ATC dan IL (ATCAIL). Sistem suspensi perlu dimodelkan terlebih dahulu dan beberapa profil permukaan tanah pertanian telah disimulasi sebagai komponen gangguan utama untuk mengesahkan kelasakan sistem dan prestasi dinamik penyembur galang yang berkaitan dengan keseragaman pengagihan. Hasil kerja simulasi dalam kedua-dua domain masa dan frekuensi menunjukkan keberkesanaan skim ATC yang dicadangkan dalam mengurangkan gangguan dan keadaan bebanan berlainan. Skema sistem kawalan ini seterusnya diimplementasi secara amali pada sistem suspensi penyembur galang yang dibangunkan di makmal.

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| | | |
|---|---|---|
| A | - | Actuator |
| A/D | - | analogue-to-digital |
| AFC | - | Active force control |
| AI | - | Artificial intelligent |
| ANN | - | Artificial neural network |
| ATC | - | Active torque control |
| ATCAIL | - | Active torque control and IL |
| ATCANN | - | Active torque control and ANN |
| ATC-PID | - | Active torque control with PID |
| am | - | Amplitude |
| BP | - | Back propagation |
| CLTF | - | Close loop transfer function |
| DAQ | - | data acquisition |
| DOF | - | Degree of freedom |
| D/A | - | digital-to-analogue |
| EI | - | Estimated inertia |
| f | - | Frequency |
| FF | - | Feed forward |
| FFBP | - | Feed forward with back propagation |
| FFT | - | Fast Fourier Transformation |
| G | - | Gain of system |
| IL | - | Iterative learning |
| ILC | - | Iterative learning control (ILC) |
| $H^{\infty}$ | - | Infinite Hankel matrix |
| LEARNGDM | - | Gradient descent with momentum weight |

| | | |
|---|---|---|
| | | and bias learning function |
| LM | - | Levenberg-Marqurdt |
| LPF | - | Low pass filter |
| LQG/LTR | - | Linear quadratic Gaussian technique with loop transfer recovery |
| MIMO | - | Multi input multi output |
| MSE | - | Minimum squared error |
| NN | - | Neural network |
| P | - | Proportional |
| PC | - | Personal computer |
| PD | - | Proportional-Derivative |
| PI | - | Proportional-Integral |
| PID | - | Proportional-Integral-Derivative |
| P.T.O | - | Power take off |
| RMS | - | Root mean square |
| RMSE | - | Root mean square error |
| RVTR | - | Roll vibration transmissibility |
| SVD $H^{\infty}$ | - | Singular value decomposition infinite Hankel matrix |
| SISO | - | Single input single output |
| TANSIG | - | Hyperbolic tangent sigmoid transfer function |
| TRAINLM | - | Levenberg-Marquardt back propagation algorithm |
| TR | - | Transmissibility |

# LIST OF SYMBOLS

| | | |
|---|---|---|
| A | - | Actuator |
| AS | - | Active suspension |
| am | - | Amplitude |
| $a_{in}$ | - | Input acceleration |
| $a_{out}$ | - | Output acceleration |
| $a_t$ | - | Tangential acceleration |
| b | - | Bias |
| c | - | Internal friction coefficient |
| C | - | Damper coefficient |
| D | - | Angel |
| e | - | Error |
| $e(s)$ | - | Error signal |
| $e_k$ | - | Current positional error input |
| f | - | Frequency |
| f( ) | - | Nonlinear function |
| G | - | Gravitational torque vector |
| $G(s)$ | - | Dynamic system transfer function |
| $G_a(s)$ | - | Actuator transfer function |
| $G_c(s)$ | - | Outer loop controller |
| $h$ | - | Length of boom |
| $h$ | - | Centripetal and coriolis torque vector |
| $H$ | - | $N \times N$ inertia matrix of actuator (plus drive) and plant |
| $H(s)$ | - | Sensor transfer function |
| $I$ | - | Mass moment of inertia of boom |

| | | |
|---|---|---|
| $I$ | - | Identity matrix |
| $I_k$ | - | Current EI |
| $I_{k+1}$ | - | Next step value of EI |
| $I_t$ | - | Current |
| J | - | Jacobin matrix |
| $K$ | - | Spring constant |
| $K$ | - | Constant gain |
| $K_i$ | - | Integral gain |
| $K_d$ | - | Derivative gain |
| $K_p$ | - | Proportional gain |
| $K_t$ | - | Motor torque constant |
| l | - | Length of boom |
| m | - | Mass of boom |
| M | - | Mass of sprayer frame and spray boom |
| Q | - | Disturbance torques |
| r | - | Rotation radius between rotation axis and accelerometer attachment point |
| $r_i$ | - | Inner radius of boom |
| $r_o$ | - | Outer radius of boom |
| s | - | Laplace operator |
| $t_{max}$ | - | Minimum step size |
| $t_{min}$ | - | Maximum step size |
| T | - | Torque of actuator |
| $T_0$ | - | No external disturbances |
| $T_d$ | - | Constant disturbance torques at revolute joint |
| $T_r$ | - | Sinusoidal wave disturbances |
| TR | - | Transmissibility |
| $u(s)$ | - | Control signal |
| $u_k$ | - | Current output value |
| $u_{k+1}$ | - | Next step value of output |
| V | - | Voltage |
| w | - | Weight |

| | | |
|---|---|---|
| $W(s)$ | - | Weighting function |
| $W_{ij}$ | - | Weight change matrix |
| X | - | Longitudinal |
| $x_0$ | - | Spray boom displacement |
| $x_i$ | - | Sprayer body displacement |
| $y$ | - | Relative displacement of spray boom and sprayer body |
| Y | - | Lateral |
| $y_d$ | - | Desired output of the trained network |
| $y_n$ | - | Predicted output of the trained network |
| Z | - | Vertical |
| $\alpha$ | - | Tilt angle of tractor chassis |
| $\alpha$ | - | Angular acceleration of spray boom |
| $\theta$ | - | Spray boom tilt angle |
| $\theta$ | - | Pitching |
| $\theta_d$ | - | Desired angular position |
| $\dot{\theta}_i$ | - | Sprayer body angular velocity |
| $\dot{\theta}_0$ | - | Boom degree angular velocity |
| $\theta_m$ | - | Measured angular position |
| $\phi.$ | - | Rolling |
| $\Phi$ | - | Proportional learning parameter |
| $\Psi$ | - | Derivative learning parameter |
| $\Gamma$ | - | Integral learning parameter |
| $\mu$ | - | Learning rate |
| $\tau$ | - | Actuated torque vector |
| $\tau_d$ | - | External disturbance torque vector |
| $\tau_e$ | - | External disturbance torque |
| $\omega$ | - | System natural frequency with damping |
| $\omega_n$ | - | Natural frequency of system without damping |
| $\zeta$ | - | Damping ratio |
| $\delta$ | - | Logarithmic decrement of amplitude |
| $\psi$ | - | Yawing |

## LIST OF APPENDECES

# CHAPTER 1

# INTRODUCTION

## 1.1 Introduction to Crop Protection

When human life changed from hunting and immigrating to settle down and start to farm, one of the serious problems was crop protection. Nowadays, agriculture productions are counted on main source of nutrition, and crops must be protected against animals, pathogens, weeds, pests, insects, and diseases.

### 1.1.1 The Use of Pesticides and Poisons in Field

Crop protection techniques have five major types: mechanical, chemical, biophysical, biological, and agronomical methods. Chemical methods are employed widely and in this method, chemicals are dissolved in water and spread by sprayer. Chemicals have many various kinds such as insecticides, fungicides, herbicides, and others that are many useful, and sometimes those are preventable for crop protection against critical risk. Besides, chemical method is ideal for conventional agriculture methods because it needs less labor, and distribution is easy. Although spray application is effective to solve problems of weeds, pests and disease in field, the use of chemicals treatment has side effects, and care must be taken when applying them. Sometimes under dose is not absolutely effective on crop yield whereas overdose has environmental pollution and poisonous remains in water, air, soil, and food (Langenakens *et al*., 1999). Residual poisonous threats the environment and humankind for many years later.

These threats and high expense of the chemical have economic consequences and pressure on farmers and governments to reduce the amount of chemicals materials applied in the farms. However, under dose of chemical materials leads to negative effect on crop yield and some farmers usually apply too much chemicals to maximize crop yield (Ozkan and Reichard, 1993). Thus, it is important to control the amount of chemical used and one way is to ensure correct and consistent amount of spray distribution of chemical (Alness *et al.*, 1996).

There are two imperative reasons for under dose and overdose in the field. First, defects in hydraulic system such as leaking hoses, worn nozzles, malfunctioning of manometers or pumps, connections, and others. Second, vertical and horizontal vibrations when sprayer boom is moved on the unsmooth fields (Langenakens *et al*., 1999). In addition to spray boom vibration, the wind affects uneven doses in the field (Langenakens *et al*., 1995). Therefore, one of the crucial factors for reduction of pesticide consumption in field is the decrease of sprayer boom vibration (Anthonis and Ramon, 2003).

### 1.1.2 Sprayer Boom Vibrations

The most usual way of using chemical method to protect crop is spraying the mixture of chemicals and water onto crop by nozzles. The nozzles are located on a horizontal frame which named boom and are moved slowly on the field. The sprayers which are based on propulsion factor have three models: tractor-mounted, self-propelled, or trailed. All of them contain horizontal boom, large tank, hoses, and pump that pumped the mixture of chemicals and water from tank to sprayer nozzles.

Nozzles of sprayers have a distribution pattern that the uniformity of that is influenced by several factors:

- Type and quality of nozzle
- Distance of nozzle to plant leaves
- Distance between nozzles on the boom
- Travel speed of sprayer
- Pressure perform on poison liquid
- Flow rate
- Wind
- Air assistance

Three types of nozzles are applied on the booms: hollow cone, full cone, and flat fan nozzles. They have a number of differences like as pressure for atomizing of liquid, flow rate, place of nozzle connection to the boom, and uniformity of distribution pattern. Typically the tip of nozzles is used up or closed, and this fact affects on distribution. Besides, when droplets go down from the nozzles, they are influenced by wind flow which can be decreased by use of air assistance. Air assistance generates the air flow by a blower and conducts the droplets downward to plant leaves.

The main procedure for evaluation of spray application is spray distribution test (Göhlich, 1985). Several factors affect spray distribution pattern, namely, the soil unevenness, spray boom width, the type of suspension system, perfect connection between spray boom and tractor, the amount of poison and liquid inside the tank, the straight driving speed in field, and sprayer general conditions (Pochi and

Vannucci, 2001, 2002a; Ramon & Langenakens, 1996). One of the crucial effects on the spray distribution is the nozzle movements which mostly induced by soil unevenness. For instance, cone nozzle shows more response to the vertical movement; in comparison, the flat fan nozzle is a little responsive to the horizontal movement.

The influences of sprayer motions are optimized with use of springs and dampers. The boom motions and spray distribution can be controlled by adjusting the spring and damper parameters.

## 1.2 Background of the Research

Presently, field sprayers' width is raised to 45 m because fields are getting larger and work labor is expensive; therefore, the farmers require the agriculture instruments that covered more area in every traveling in the field (Serneels & Decattillon, 1993). But after these developments, flexible behavior of sprayer booms is crucial, and each motion of the boom leads to the movement on the tip of nozzles. Thus, the uniformity of distribution pattern will change. Another aspect is width of sprayer boom although obvious relationship between amount of sprayer boom movement and width of boom is not specified yet now. Mounted or trailed sprayer is another important factor (Herbst & Wolf, 2001). The most important factor on spray distribution pattern that were illustrated by theoretical researches, field experiments and simulations is sprayer boom vibration which must be controlled. The reported movements that can affect the spray distribution pattern (Figure 1.1) are jolting and yawing (two kinds of motion in the horizontal plane), and rolling that due to spray boom vibration in the vertical plane (Anthoni *et al.*, 2005) that will be shown by detail in Figure 2.3. Vertical vibration, rolling and yawing of sprayer boom are resulted of tractor vibration that induced by soil surface unevenness. One of the earliest studies about effects of tractor rolling on sprayer boom distribution pattern was done by Mahalinga Iyer and Wills in 1978. Later, sprayer boom suspension has been initialized in practice to decline these influences (Nation, 1980).

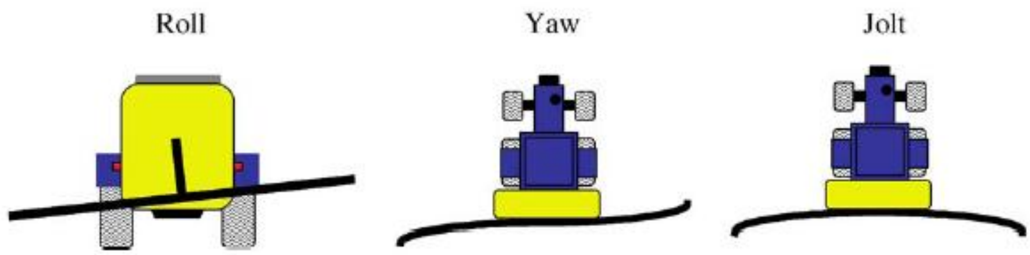


**Figure 1.1** Effective movements on the spray distribution pattern (rolling, yawing, and jolting) (Anthoni *et al.*, 2005)

Ramon and Langenakens (1996) mentioned that vertical flexible deformations of the sprayer boom are excited by vertical acceleration and rolling angular of the tractor. These deformations have less effect on the spray pattern because they are neutralized by the structure of boom frame. Moreover, they expressed horizontal flexible deformations of the spray boom are caused by yawing angular accelerations and transversal accelerations of the tractor. Field experiments, theoretical studies and simulation demonstrated that spray distribution pattern is different between 0 and 800% (Sinfort *et al*., 1997; Ramon and De Baerdemaeker, 1997; Ramon *et al*., 1997; Ooms *et al*., 2002). Field measurements (Speelman, 1974) and simulations with experimental modal models of different spray booms (Langenakens *et al*., 1993) illustrated under dose and overdose are caused by horizontal vibration of spray boom, and it can be varied from 20 to 600%. Other simulating models also describe differences in spray deposit distribution between 20% and 600% for the horizontal vibration and between 0% and 1000% for the vertical vibration (Langenakens *et al*., 1995).

As stated earlier, to control undesired vertical and horizontal vibrations of sprayer booms, suspension systems have been used to keep the boom stable by isolating the boom frame from the yawing and rolling movements of sprayers. The common suspensions which are located between the boom and the frame, isolate the boom from the sprayer frame rolling although some of these suspensions which are located between the frame and the wheel axle have especially design. Recently horizontal suspensions are applied to attenuate effect of the frame jolting and yawing motions on boom (Ooms *et al.*, 2002).

From 1980s twin link or pendulum suspensions have been applied to explain dynamic behavior of sprayer booms until recently when Anthonis *et al.* (2000) introduced horizontal active suspension.

Although large number of suspensions has been made by manufacturer, some of them are based on theoretical researches (Frost, 1984; O'Sullivan, 1986; Nation, 1987a & 1987b; O'Sullivan, 1988; Frost & O'Sullivan, 1988; Ramon & De Baerdemaeker, 1995; Deprez *et al.*, 2002). Anthonis and Ramon (2003), based on theoretical and experimental research, believed that horizontal vibrations (yawing and jolting) are more critical than vertical vibration (rolling) in the same condition (Ramon & De Baerdemaeker, 1997). Though horizontal spray boom vibration is more important on spray distribution efficiency (Wolf, 2002; Ramon & De Baerdemaeker, 1997), Anthoni *et al.* (2005) investigated rolling as more effective vibration on spray distribution pattern. They illustrated that the vertical suspension is still challenging.

Normally, two kinds of suspensions are used to attenuate the unwanted vibration in spray booms, which are passive and active suspensions. A passive suspension system consists of damper and spring as dissipating element and energy-storing element, respectively. In this model suspension, the characteristics of the components (springs and dampers) are fixed because these characteristics are determined by the designer of the suspension, based on the design goals and the intended application. The active suspension system uses an actuator, power supply, signal processing and proximity transducer, amplifier and feedback components to reduce the amount of external power necessary to achieve the desired performance characteristics. However, the usage of these components leads to a complex system. Since the sprayers are excited by low and high frequency vibrations, a combination of passive and active suspensions is capable to reduce the unwanted motions of sprayers. In general, the conventional controllers, such as proportional (P), Proportional-Integral (PI), Proportional-Derivative (PD), and Proportional-Integral-Derivative (PID) controllers, are employed in the active suspensions to control the system vibration (O'Sullivan, 1988, 1986; Frost and O'Sullivan, 1988).

Finding the mathematical model of the system to design a controller is one of the important characteristics of all conventional controllers although unconventional controllers apply new approaches to the controller design such as neuro or neuro-fuzzy controllers, and fuzzy controller. Previously, a P and PI controllers (O'Sullivan, 1988, 1986; Frost and O'Sullivan, 1988), an active compensator (Ramon and Baerdemaeker, 1996), and a SVD $H^{\infty}$ (Singular value decomposition infinite Hankel matrix) method (Anthonis and Ramon, 1999) were applied to control the vibration of sprayers.

Recently, active suspension systems of vehicles have been implemented by a new method named active force control (AFC) (Mailah & Priyandoko, 2007; Priyandoko *et al.*, 2009a; Alexandru and Alexandru, 2010; Rajeswari, 2010) whereas this idea was firstly introduced by Hewit and Burdess (1981). The aim of the study is an attempt to introduce a new robust control strategy of a suspension system that is based on active torque control (ATC) approach which the concept of that was derived from AFC theory. The purpose of this control scheme is to ensure that a system remains stable and robust even in the occurrence of disturbances. Informally, a controller designed for a particular set of parameters is said to be robust if it would also work well under a different set of assumptions. The original theory of ATC involves direct measurement and estimation of a number of known parameters to forecast its compensation action that is the actuated torque, angular acceleration and estimated mass inertia of the spray boom in this research. As the estimated mass moment of inertia of sprayer boom multiplies to angular acceleration of boom, the main computational part in ATC is estimation of mass moment of inertia. Firstly, usage of artificial intelligent (AI) techniques to estimate the inertia of the system in real time was introduced by Mailah (1998).

## 1.3 Statement of Problem

From the review of reported investigations discussed above, clearly vibration of spray boom affects on the spray distribution pattern and hence the crop yield. Since most of the tractors do not have a chassis suspension system, the vibration is transmitted directly from the chassis to sprayer boom due to unevenness of soil. This induced vibration can produce serious problems in spray distribution pattern such as overdose and underdose. Two types of vibration, namely, low frequency and high frequency, have effects on sprayer boom structures. The suspension systems must have an appropriate response time to the vibration variability. Although many suspensions have been previously devised for sprayer boom structures, it is still an open area of research due to the complex dynamics of flexible structures. Generally, passive suspensions are designed for fixed working conditions, and changing their characteristics is not simple for new condition. In contrast, active suspensions have adaptation potential to change suspension coefficients in real time adequately. The combination of active and passive suspensions is able to create superior performance to control unwanted vibration. Up till now, some conventional controllers were used in active sprayer boom suspensions. Additionally, since sprayer booms are weakly damped flexible structures with large dimensions, it is appropriate to test the sensitivity of the designed feedback systems to unmodeled high frequency modes and parameter variations before implementing them on the physical system.

Lately, AFC approach was considered by many researchers (Hewit and Burdess, 1981; Mailah, 1998; Kwek *et al.*, 2003; Mailah *et al.*, 2005) due to its attributes such as simplicity, robustness, and high accuracy compared with conventional methods in controlling dynamical systems. The suspensions implemented by AFC systems can overcome on disturbances better compared to conventional controllers. Besides, using intelligent methods for predicting mass moment of inertia can enhance the efficiency of this type of controllers.

This study serves to present other alternatives to cope with the vibration control problem of the sprayer structures. Thus, the research should investigate the possibility of improving the sprayer suspension dynamic performance using a robust control strategy including intelligent method. The main works of this study contain the design of the proposed controller based on a number of established control models, choice of the actuator system, AI method and a number of loading conditions.

## 1.4 Objectives of the Study

The main objective of this study is to investigate the suitability of intelligent control scheme in reducing low frequency vibration of the agriculture sprayer boom. To accomplish this objective, the following sub-objectives are defined:

- To present the mathematical model of the sprayer boom dynamical behavior.
- To design and analyze the implementation of artificial neural network (ANN) and iterative learning (IL) techniques for the computation of the estimated inertial parameter in the ATC scheme to improve the performance of the sprayer boom active rolling suspension system by simulation study. Governing
- To evaluate and validate the performance of the ATC- based controller for the active rolling suspension system and passive suspension through experimental study.

## 1.5 Scope of the Study

The scope of research consists of the following:

- A tractor mounted sprayer boom is considered to operate using a suspension, and it is assumed that the chassis of the sprayer boom can move in vertical direction.
- Initially, the optimal vertical passive suspension parameters for sprayer boom structure was determined.
- The spray boom is considered as a rigid body component and revolves around a longitudinal axis because it is pivoted at the center point. The effect of the dynamics due to the masses of the nozzles located along the boom was neglected because the nozzle mass is very small compared to the spray boom mass. Also, as the nozzles are assumed to be arranged symmetrically on the boom, the thrust forces were neglected assuming a well balanced system.
- The source of vibration in tractor and sprayer boom is the unevenness surface of field.
- The theoretical framework includes the study of different principles related to the ATC-based methods, proportional-integral-derivative (PID) control, the neural network (NN) and the iterative learning (IL) techniques.
- The performance of the passive suspension system exposed to various field surfaces or farmland terrains will be evaluated based on vertical sprayer acceleration. Moreover, the performance of active rolling suspension will be studied based on rotational sprayer boom acceleration. Results shall be presented and analyzed both in time and frequency domains.
- The physical structure of the test rig need to be constructed in laboratory scale and mechanical characteristics which are required for suspension design and simulation shall be considered from the developed test rig.

- In the experimental works, only ATCAIL scheme is considered for the validation.

## 1.6 Contributions of the Research

The main research contributions from this research are as follows:

1. Two new robust ATC-based control schemes have been proposed, designed and implemented for the control of a sprayer boom suspension using ATCANN and ATCAIL.
2. Novel approximation techniques using ANN and IL methods were employed to compute adaptively and continuously the suitable estimated mass moment of inertia of the dynamic system in the ATC loop for the control of the active rolling suspension to improve the performance.
3. A fully instrumented sprayer boom experimental test rig was developed in the laboratory for the experimental validation of the theoretical component.

## 1.7 Organization of the Thesis

This thesis is organized into six chapters. A brief outline of contents of the thesis is given as follows:

Chapter 1 describes an overview of the context of crop protection and sprayer boom vibration. It involves the statement of problem and objectives of this research too.

In chapter 2, a comprehensive survey of the theoretical and experimental works related to the proposed research is described. Some brief explanation on suspension systems and isolators and reviews on recently published articles related to application of the active force control strategy are also highlighted.

Chapter 3 is devoted to the methodology of the research. Basically, there are two main research activities to be achieved, the theoretical modeling and design of the passive suspension system based on experimental data and the experimental implementation of the identified approaches for evaluation purpose.

Chapter 4 focuses firstly on the basic concepts and fundamental theories of the ATC scheme, ANN, and IL methods. Subsequently, the simulation study of the new proposed schemes, i.e., ATCANN and ATCAIL is presented. The general proposed ATC-based system basically comprises two feedback control loops, namely, innermost loop for the compensation of the disturbances using ATC strategy and an outermost loop for the computation of the desired torque for the actuator applying a PID controller. Performance of the suspension system is evaluated based on the desired sprayer boom angular position, both in time and frequency domains. The results of the proposed schemes are also shown and compared.

Chapter 5 presents the mechatronic design and development of the experimental sprayer boom structure test rig that incorporates the proposed ATCAIL scheme. An electromagnet shaker is used to excite the structure. The specifications of the active rolling suspension system, PC-based control system and its instrumentation system are expressed in detail in this chapter. The performance of the control approach is validated via experimental measurements in which the ATCAIL scheme result is compared to the PID controller. The experimental results are depicted both in time and frequency domains and they were compared to the simulation work findings.

Chapter 6 sums up the study project. The directions and recommendations for future works are also listed. Some experimental results, instrumentation specification and list of publications related to this research are enclosed in the appendices.

rolling suspension of spray boom was built up based on mechatronic design approach. A precision servomotor was used as an actuator controlled by pulse frequency technique. The computer control involving the programming of the data acquisition (DAQ) system using LabVIEW software was carried out to command the actuator in relation to the needed task via the proposed ATCAIL control scheme. The test rig was experimented in laboratory environment by simulated terrain profiles produced via shaker. The results of active rolling suspension implemented by ATCAIL and ATC-PID, and PID control systems were acquired and compared together. The findings reveal that applying ATCAIL scheme can cause vibration cancelation improvement in both time and frequency domains, thus guaranteed a more uniform spray deposit on a bumpy field. Finally, the experimental study outcomes have a good agreement with simulation work results.

## 6.2 Recommendations for Future Works

A number of suggestions proposed for further works that may improve the distribution pattern uniformity of sprayers during field operation are outlined as follows:

- Several numbers of frequencies, other various external disturbances, and other terrain profiles especially random signal should be tried to investigate the system performance in wake of horizontal vibration.
- An experimental research can be performed by shaking the tractor-sprayer boom in laboratory to analyze the movements of spray boom via developed suspension.
- The performance of current active suspension can be measured in outdoor test, and finally it should be tried to employ on real size sprayer.

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