DEVELOPMENT AND EVALUATION OF A FERTILIZER BANDING OPENER

BY

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A Thesis
Submitted to the Faculty of Graduate Studies
in Partial Fulfillment of the Requirements
for the Degree of

MASTER OF SCIENCE

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ABSTRACT

Benefits of no-tillage have been widely recognized in reducing soil erosion and improving soil quality. Banding anhydrous ammonia (NH_3) with minimal soil disturbance in no-tillage system can reduce nutrient losses and greenhouse gas emissions. This study focused on developing a low-disturbance and low-cost banding opener for mid row banding NH_3 in no-tillage system. The opener was characterized by double or single disks and a simple but effective leaf spring downforce system. Design parameters of the spring downforce system were selected through an optimisation process in which the opener downforce changes were minimised. The optimal design parameters were further validated through a laboratory test.

The prototype of the leaf spring opener was compared with an existing parallel linkage opener in a field condition. The results showed that the two openers had comparable performance, in terms of the cutting depths and uniformity of the cutting depths. Furthermore, the leaf spring had much lower cost. A field experiment was conducted with the opener prototype in banding NH_3. The field had clay soil and wheat stubble. The treatments were different opener configurations, including two opener disk configurations (single disk and double disks) and two furrow closing wheel configurations (using furrow closing wheel and without using furrow closing wheel). The field measurements included soil surface disturbance, nitrogen trace, and nitrogen concentrations. Under the given field conditions, the double-disk opener without furrow closing wheel had the best performance with the highest soil nitrogen concentration (80.5 μg/g) and the largest area

of NH_3/NH_4^+ trace zone in soil (4607 mm^2). On the contrary, the single-disk opener without furrow closing wheel performed the worst at all aspects, except for the soil surface disturbance.

ACKNOWLEDGMENTS

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Last but not the least, I wish to thank Bereket Assefa and Yanhao Wang, graduate students, for their help on field works. Thanks are given to Gerry Woods, Dale Bourns, and Matt McDonald, the technical support staff of Biosystems Engineering, for their contributions to the project.

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1. INTRODUCTION

In agriculture, the use of fertilizer for crop is one of the two major sources for nitrous oxide emissions (SCCC, 2004). Provincial agriculture departments across Canada have suggested that where possible, fertilizer should be banded rather than broadcasted. Through banding fertilizer, producers can get more value from their fertilizer investment, and at the same time minimise the loss of nitrogen that contributes to greenhouse gas emissions.

With the dramatic improvements in equipment technologies and crop management during past few years, no-tillage is being widely adopted in Western Canada. However, the high soil disturbance and high cost of current fertilizer banding openers become main concerns for no-till producers. Openers with low soil disturbance and low cost for banding fertilizer in no-tillage system are required.

The research undertaken in this study attempted to develop and evaluate a low-disturbance and low-cost fertilizer opener for banding anhydrous ammonia (NH_3). Effects of the banding opener on retention and distribution of NH_3 in soil following banding operations were also investigated in this research. It was expected that such machinery would provide producers a better implement for fertilizer utilisation, soil moisture conservation, and a solution to one-pass direct seeding system. The low-cost banding opener would also encourage the adoption of fertilizer banding method in no-tillage system for those producers, who considered the cost of banding machinery as an issue. This would further enable producers to face the challenge of Canada's overall objectives of soil conservation and reducing greenhouse gas emissions.

2. OBJECTIVES

The objectives of this research were to develop a prototype of a fertilizer banding opener for mid row banding anhydrous ammonia (NH_3) for no-tillage system, to evaluate the opener prototype in laboratory and field conditions, and to study nitrogen retention in soil following NH_3 banding as affected by different opener configurations.

3. LITERATURE REVIEW

3.1 No-till and one-pass direct seeding

No-till farming has been widely recognized as an effective way to reduce the potential for soil erosion due to wind and water (MNZTFA, 1998). No-tillage is a system where crops are grown in narrow slots or tilled strips in previously undisturbed soil defined by ASAE standards (2005). Soil disturbance in no-till system is limited to the requirement for placing seeds and fertilizer, which should be no more than one third of row width.

One-pass low-disturbance direct seeding, a specific planting process and method of no-till farming, applies seeds and fertilizer at one pass without traditional tillage for seedbed preparation prior to planting (Veseth and Karow, 1999). One-pass direct seeding is being widely adopted in Western Canada due to its advantages in saving producing cost, labour cost, and tractor hours (SSCA, 1998). One-pass direct seeded acres in Saskatchewan were increased from 10% in 1990 to 40% in 2002 (PAMI, 2003).

However, with the commonly used fertilizer openers nowadays, one challenge in one-pass direct seeding is that the soil disturbance is often too high, which defeats the purpose of no-till farming (SCCC, 2004). The current banding operation either creates larger furrows for depositing seeds and placing fertilizer sideways (side banding) or opens extra fertilizer furrows for depositing fertilizer at every second seed rows (mid row banding). Therefore, effective low-disturbance fertilizer banding openers are required for successful one-pass direct seeding.

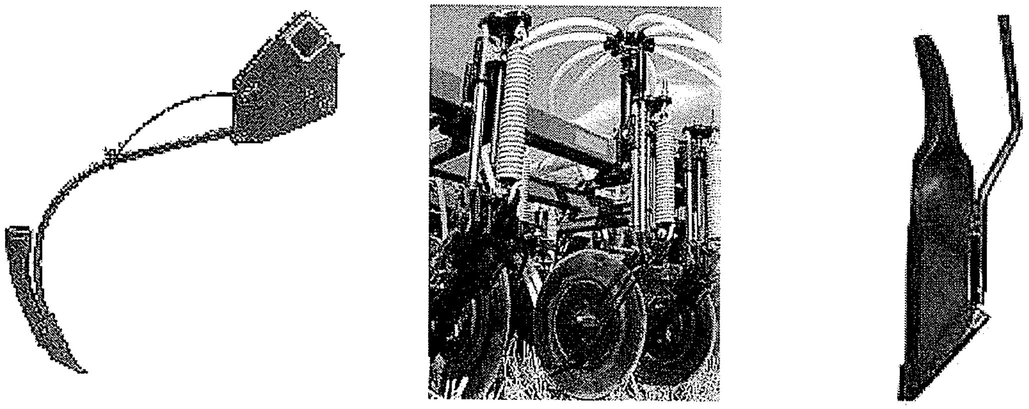
Factors, such as the performance of the banding opener, fertilizer type, and banding method can all affect the performance of one-pass direct seeding system (Veseth and Karow, 1999).

Many studies were conducted on effects of these factors, which are reviewed in the following sections.

3.2 Fertilizer banding opener

3.2.1 General

Furrow opener used for banding fertilizer is a specific soil-engaging device, which is used to slice through soil, create a furrow opening, and deposit fertilizer into the furrows (ASAE standards, 2005). Various types of fertilizer furrow openers are commercially available for producers to choose to fit for their specific tillage methods, soil conditions, and crop types. For no-till system, double-disk, single-disk, and hoe type openers are three dominant types of opener design (Fink and Currence, 1995). Figure 3.1 shows a hoe-type opener, disk-type opener, and conventional knife injector equipped on a chisel plow, which are commonly used to apply NH_3 in both conventional and reduced tillage systems. The general functional requirements of these different openers are reviewed below.



(a) Hoe opener

(b) Disk-type opener

(c) Chisel plow knife opener

Figure 3.1. Various types of fertilizer banding openers; (a) hoe-type opener (John Deere, 2005); (b) disk-type opener (Bourgault, 2006); (c) chisel plow knife opener (V.W. Manufacturing, 2006).

3.2.2 Functional requirements

Three general functional requirements of furrow openers include opening a furrow to the required depth, maintaining uniformity of depth along the furrow and between furrows, and sealing or packing furrows properly. In the case of one-pass direct seeding, other than these general functional requirements, fertilizer banding opener should cut residue effectively, cause minimum soil disturbance, and maintain uniform seed-fertilizer separation (MNZTFA, 2000). To achieve these functions, a typical banding opener should include three necessary components: downforce system, depth control mechanism, packing or furrow closing mechanism. These components are illustrated in figure 3.2.

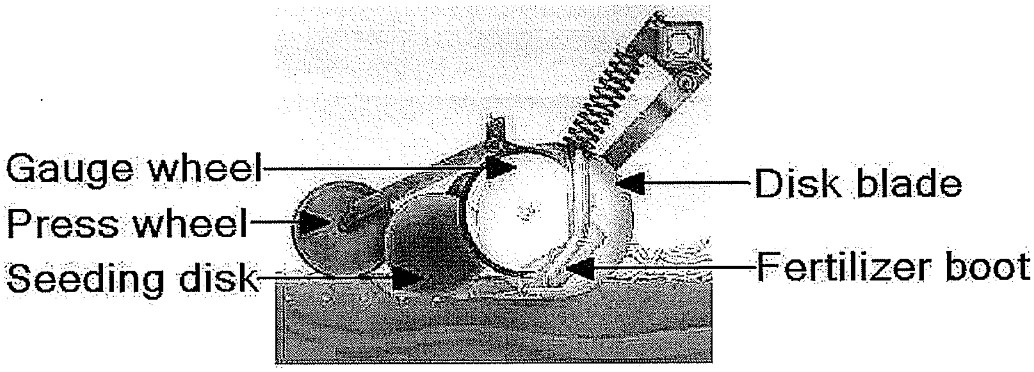


Figure 3.2. Single-disk no-till opener (John Deere, 2005).

3.3 Downforce system

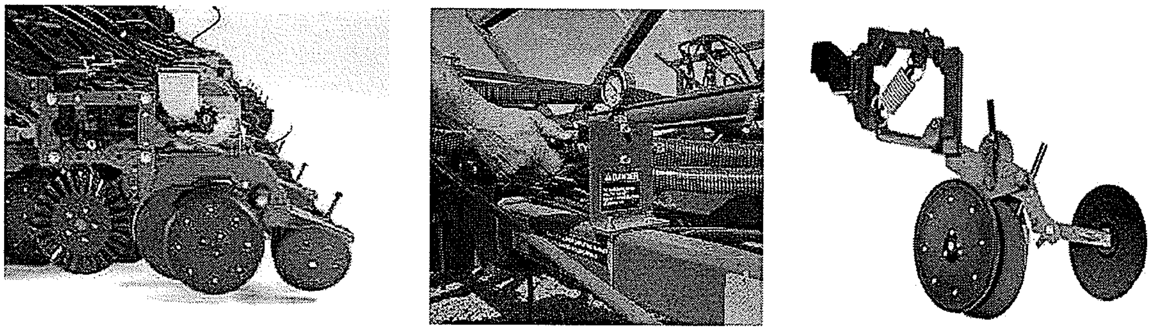
3.3.1 General

For soil penetration and residue cutting, enough vertical force has to be applied onto the soil cutting assembly. This vertical force may be comprised of the weight of the furrow opener assembly, added ballast, and one or more sources of vertical force from a downforce system (Morrison, 1988). Downforce system is usually equipped on various furrow openers as a standard component, and it may also have functions of maintaining even downforce.

Requirement of downforce depends on the soil type, depth of penetration and the amount of residue cover. (Kushwaha et al., 1986; Erbach et al., 1983). Kushwaha et al. (1986) found that the required downforce for single-disk openers ranged from 200 to 800 N. Larger downforce of 700 to 2300 N for soil cutting were needed for double-disk openers as described by Schaaf et al. (1979). They also observed that hoe openers needed less downforce than double-disk openers.

3.3.2 Three common types of downforce systems

Pneumatic, hydraulic, and spring downforce systems are three basic types of downforce system utilized on various seeding and fertilizing machines (fig. 3.3). Spring downforce system is the most commonly used due to its lower cost. Fink and Currence (1995) reported a pneumatic downforce system for no-till seeding, which utilized a pressure regulator to adjust the air pressure inside a pneumatic cylinder and thus changed the downforce. The pneumatic opener was found to be able to hold nearly constant downforce for no-till seeding. Morrison (1988a) designed and tested a hydraulic downforce system which used centralized pressure regulator and valving system to regulate the downforce. This hydraulic downforce system performed adequately in long-term field use and could be converted to other existing planters or drills for no-till system. Gratton et al. (2003) designed a coil spring-loaded downforce system, which used either single linkage or parallel linkage structures. They concluded that the spring-loaded parallel linkage system had comparable or better performance as compared to a hydraulic downforce system.



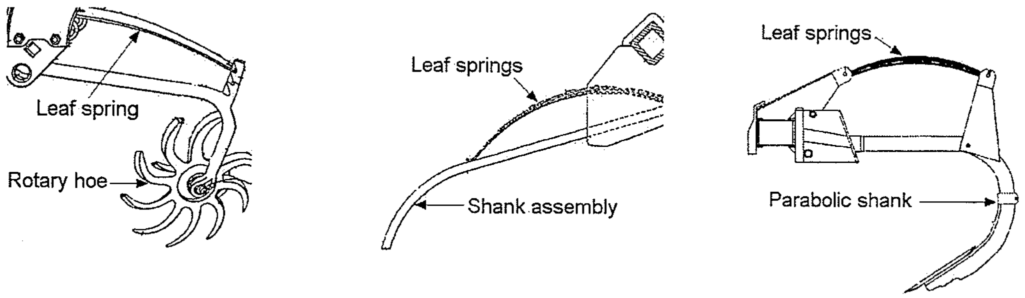
(a) Pneumatic (John deere, 2005)

(b) Hydraulic (John deere, 2005)

(c) Coil spring (Gratton et al., 2003)

Figure 3.3. Three different types of opener downforce system.

However, leaf springs have been seldom used in agricultural machines as downforce mechanism due to the difficulty to control its downforce changes in field environment. Only three commercial tillage products with leaf spring downforce system were found to be used on the rotary hoes (Deere & company, 1976), shank assemblies (Deere & company, 1989), and Tebben deep till (Tebben enterprise, 1991), all of which used the leaf spring as downforce reset mechanism rather than automatic downforce adjustment mechanism (fig. 3.4). Leaf springs have not been used in downforce system for no-till disk openers, where minimised downforce changes are required for both seeding and banding NH_3.



(a) Rotary hoe (Deere & company, 1976)

(b) Compact shank assembly (Deere& company, 1989)

(c) Automatic reset deep till (Tebben enterprise, 1991)

Figure 3.4. Typical applications of leaf springs on tillage tools.

3.3.3 Downforce changes

Higher downforce changes of a pneumatic opener were reported by Fink and Currence (1995), the pressure of which increased about 275 KPa when passing over a block with 76 mm height. They also observed that the downforce changes increased with increasing ground speed and higher initial cylinder pressure. Similarly, Morrison (1988a) found that the downforce changes of hydraulic downforce system were significantly affected by the transmittal distance, field speed, and system pressure when the opener running over simulated soil undulations.

Maintaining uniform downforce regardless of the field surface elevation changes are required for a furrow opener to create an even soil penetration depth, which will not adversely affect the uniformity of the seeding depth and fertilizer placement. Some studies have been conducted to minimise the downforce changes of different opener downforce systems. Gratton et al. (2003) conducted a study to minimise the downforce change of a spring-loaded parallel linkage opener using a mathematical optimization approach, which resulted in a 21% change in downforce changes when the opener ran over 100 mm obstructions. The difficulties of maintaining constant downforces shown in the above studies pose a big challenge for downforce system designs and further studies in this area are needed.

3.4 Depth control mechanism

Gauge wheels are usually equipped on openers to control the soil penetration depth by contacting the soil surface tightly. Some gauge wheels can also interact with the downforce system to adjust the downforce, change the control depth and thus help maintain the soil penetration depth when encountering field surface elevation changes. Generally, the vertical position of gauge wheel should be adjustable to give different soil cutting depths. For individual openers, one or more gauge wheels can be placed either at the front, sides, or rear of the opener units (Morrison and Gerik, 1985). Lawrence and Dyck (1990) compared a double disk opener with an adjustable gauge wheel with a standard double disk opener fitted with depth control bands. They found the former depth control mechanism had superior performance in seeding depths. Morrison (1988b) designed a depth control system, which interacted with the pneumatic downforce system. This interaction system adjusted pneumatic downforce by keeping monitoring the gauge wheel positions. In summary, an effective depth control mechanism is one of the prerequisites for opener design and further for the successful fertilizer banding.

3.5 Comparisons of soil disturbance between openers

Obviously, soil disturbance varies with different opener types. Many studies showed that disk-type openers provided lower soil disturbance than hoe-type openers (Tessier et al., 1991a; Doan et al., 2005). Double-disk openers with cast-iron press wheels were ranked as one of the best choices for no-till system (Morrison, 2002). The benefits of using disk openers for fertilizer banding had been demonstrated in the Peace region of British Columbia in banding NH_3 and had captured producer's interest as using low-disturbance banding openers for applying fertilizer in no-till land while benefiting the environment (SCCC, 2004). Narrow knife, single-disk or double-disk openers only disturbed a narrow strip of soil between openers and retained nearly the entire residue on the surface (Veseth and Karow, 1999). They further found that hoe or sweep openers disturbed more of the soil between openers, though usually not the full row width, and still retaining much of the residue on top. Considering its low-disturbance feature, disk-type opener was selected in this study for banding NH_3 in no-till system.

3.6 Anhydrous ammonia banding

3.6.1 General

Anhydrous ammonia (NH_3), an effective, cost-competitive source of nitrogen fertilizer, is used by many producers in Western Canada. It is normally the lowest priced form of nitrogen fertilizer. The high concentration of nitrogen in NH_3 also cuts transportation costs to a minimum (Anderson, 2005). NH_3 must be injected or banded into the soil to avoid NH_3 loss. Upon banding into the soil, ammonia quickly reacts with water to form ammonium (NH_4^+). In this positively charged form, the ion is not susceptible to gaseous loss because it is temporarily attached to the negative charges on clay and organic matter (Steven, 2005). Some of the ammonia reacts with organic matter to become a part of the soil humus. NH_3 has commonly been used in fall banding, spring banding, or at seeding in one-pass direct seeding system.

3.6.2 Mid row banding and NH_3 placement

Mid row banding involves placing NH_3 between every second seed row or between a paired rows during the one-pass direct seeding operation. This method has good N use efficiency and avoids seed row toxicity if the separation can be maintained under field conditions (CCC, 2005). PAMI (2003) compared the mid row banding with side banding method and reported that NH_3 provided similar yield results with the two systems.

Mid row banding allows the application of high rates of fertilizer without risk of damage to the germinating seedlings and seedbed quality is not affected by this method (SSCA, 2004). However mid row banding does disturb the soil between the rows compared to the single seeding operation. Therefore, the mid row banding opener used in no-till system must be low-disturbance.

3.6.3 NH_3 retention and loss

The retention of NH_3 is a critical factor in evaluating and comparing the performance of different banding openers. NH_3 retention was defined by Papendick and Parr (1965) as the summation of all the different mechanisms of sorption and reaction whereby NH_3 was held by soil, including chemically sorbed or exchangeable NH_4^+, fixed NH_4^+, NH_3 that reacts chemically with organic matter, and physically sorbed NH_3.

However, few studies have been conducted to research the effects of banding opener types on NH_3 retention and losses. Hnatowich (1994) observed NH_3 losses applied by six different kinds of openers and found that no particular opener was superior from location to location and big NH_3 losses occurred evidently with all openers. Hanna et al. (2004) reported a single-disk opener resulted in greater NH_3 losses in coarse soil compared to a conventional knife injector. They believed that the potential reason for this was due to the poor sealing performance of the single-disk opener. Anhydrous ammonia losses during the banding operation are affected by the opener types and configurations. Both of Hnatowich (1994) and Matus et al. (1999) emphasized the effect of the openers' packing or press wheels on sealing the fertilizer furrow and reducing the NH_3 losses.

Soil texture is a determining factor for the retention of anhydrous ammonia. Laboratory studies have shown that retention is satisfactory in soils of intermediate texture which have a relatively large sorption capacity. Under these conditions, ammonia would probably be sorbed more efficiently than in lighter, sandy soils with relatively poor sorption capacities (Stanley and Smith, 1956).

3.6.4 NH_3 distribution in soil

Initial NH_3 distribution in soil following banding operations is one of the important indicators of the performance of different banding openers. Papendick and Parr (1966) reported that the initial distribution pattern of anhydrous ammonia NH_3 after application to soil might determine to a considerable extent the ultimate agronomic effectiveness of the applied N. Blue and Eno (1954) reported that studies on NH_3 distribution could also be used to determine the row spacings of banding operations.

Quantitative data on the NH_3 distribution under the field conditions may greatly contribute to the improvement banding opener designs. NH_3 distribution in soil is affected by the application rate, soil moisture, soil reaction, and exchange capacity (Baker et al., 1959). An earlier study on NH_3 distribution showed that NH_3 was concentrated in zones from 51 to 203 mm wide depending on the soil moisture content (Blue and Eno, 1954). They also found that most of the NH_3 was usually concentrated in a zone 76 mm wide at high application rates. However, Stanley and Smith (1956) observed that NH_3 only had a movement of 102 mm from the NH_3 release point eight weeks after injecting.

Several methods were used to detect NH_3 distribution in soil under lab and greenhouse conditions using pH detection methods. A qualitative pH indicator-gypsum spray method was used by Baker et al. (1959) to study the distribution of applied ammonia in the soil.

However, this method was only useful for showing whether application losses occurred by noting the color change of the indicator sprayed on the surfaces of the fertilizer furrow. Papendick and Parr (1966) reported an effective filter paper – pH indicator method to detect the NH_3 distribution patterns around the injection point. It was apparent to find the contrast between the zone of initial retention of high concentration around the NH_3 injection point and the adjacent lesser-affected soil regions. Papendick and Parr (1966) further found that the NH_3 patterns were in close agreement with their corresponding pH contour lines around the injection points.

In summary, the literature review highlights the need for developing a low cost and low disturbance opener for mid row banding NH_3 in no-till system. The literature review also highlights the challenge to evaluate NH_3 losses following NH_3 banding. Most studies focused on the effects of soil conditions, application depth, and application rate on the retention and distribution of NH_3, which were mainly conducted under lab or greenhouse soil conditions. Little work has been done on testing the NH_3 distribution under field conditions and measuring nitrogen concentration quantitatively related to different banding opener configurations.

4. FUNCTIONAL ANALYSIS AND DESIGN PROCEDURE

4.1 Problem description

Most commercial tillage and seeding machines utilize either hydraulic cylinder or coil spring to maintain downforce. The coil spring is usually combined with extra linkages to construct the downforce system, such as the common parallel linkage mode. Hydraulic downforce systems are usually able to generate widely different initial downforces onto tillage machines and may maintain relatively even downforce if self-regulated downforce sensors are equipped. However, this kind of system is usually too expensive for banding fertilizer. The parallel linkage with coil spring, which is the most commonly used combination, is also expensive due to the extra pivots in the linkage. Furthermore, the numerous pivots in parallel linkage subject to wear and may cause unwanted looseness in the system. When designing downforce system for fertilizer banding openers, low cost and uniform downforce with good furrow closing are the first considerations. Therefore, an alternative with leaf springs as the downforce mechanism was investigated as described below.

4.2 General design criteria

Based on the problems and challenges faced on the banding opener design, special considerations were made related to the general design criteria. They are as follows:

- The design should be low-cost in production and convenient in operation. More specifically, it should be simpler in construction and easier to assemble than parallel linkage opener.

- The design must be low-disturbance to meet requirements for no-till operation.
- The design must have adjustable depth control and maintain a substantially constant furrow banding depth even when the soil surface is irregular.

4.3 Design concept of leaf spring

Leaf springs, like coil springs, can absorb and store energy and then release it. Leaf springs also have the advantages of working as an attaching linkage or structural member. Thus, a leaf spring itself can function like the combination of a coil spring and extra linkages.

4.4 Selection of opener type

Ponik opener (Gratton et al., 2003) (fig. 4.1), a disk-type opener with parallel linkage downforce system, was used as a starting point for the development of the opener prototype in this study. Ponik opener was originally designed for no-till seeding equipped on an air seeder. It consisted of two large offset disks. The smaller disk (380 mm diameter) was oriented vertically, whereas the larger disk (460 mm diameter) was angled relative to both the direction of travel and the vertical axis. This orientation helped the disks cut through residue and soil, as well as displace a volume of soil forming a seeding furrow. The adjustable gauge wheel (410 mm diameter by 100 mm wide) for seeding depth control was located beside the small disk and a steel press wheel (360 mm diameter by 13 mm wide) was located behind the disks. A spring-loaded parallel linkage system applied downforce on the opener.

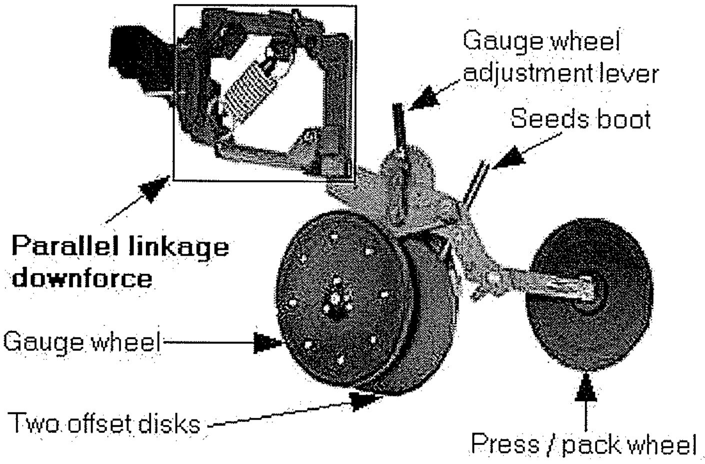


Figure 4.1. Configuration of the Ponik parallel linkage opener.

The design task was to replace the current parallel linkage of the Ponik opener by a simple but effective leaf spring, while keeping the disk configurations. Thus, the fertilizer banding opener to be developed would be an assembly with the newly designed leaf spring downforce system and the disks of the Ponik opener. The leaf spring downforce system would reduce the cost, and it would be designed according to the general design criteria.

4.5 Design procedure

The whole design and improvement of the leaf spring banding opener took almost one year, which basically included the following three steps.

4.5.1 Preliminary design

The first step was to research the configuration of the Ponik opener, study the mechanism of leaf springs, and develop the drawings of a leaf spring downforce system to replace the parallel linkage downforce system for theoretical analysis. The initial design (fig. 4.2) included multiple leaf springs, mounting brackets, opener arm and gauge wheel improved from the Ponic opener. Theoretical analysis and calculation focused on the design parameters of leaf spring, such as the geometry, spring rate, load, stress distribution, strength of spring end. The selection decision between multiple leaf springs and single leaf spring was also investigated. The relationships between the leaf springs shape and the length of the spring shackle, slot position of the mounting bracket were also studied.

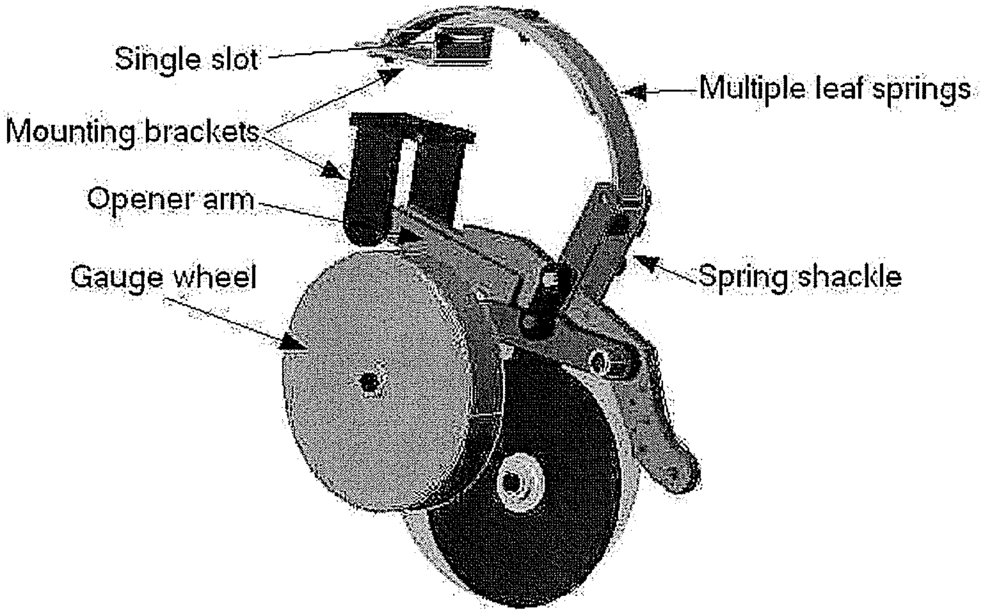


Figure 4.2. Drawings of initial design.

4.5.2 First prototype

The first prototype was designed in the second step of the development based on the theoretical analysis conducted in the first step. The drawing is shown in figure 4.3. Improvements were made from the preliminary design by adding one alternative slot in the upper mounting bracket, two different hole positions in the shackle, and one alternative pivot in the lower mounting bracket. The combinations of these different positions were expected to give different initial deflections, which resulted in different initial downforces for different soil conditions. A single leaf spring was adopted for the first prototype to further simplify the down force system to reduce the cost.

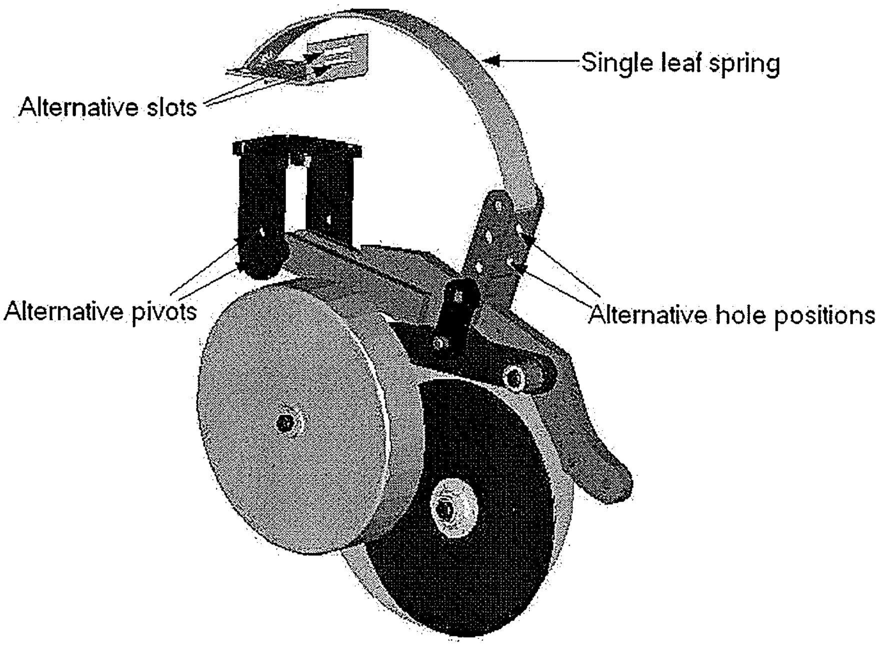


Figure 4.3. Drawings of first prototype.

The single leaf spring selected had a dimension of 11.5 mm thickness, 533 mm length (spring chord), and 137 mm free arch height. The material chosen for the spring was SAE 5160H. The spring chord is defined as the datum line passing through the two ends of the leaf spring. Its ultimate strength and elastic limit were 1450MPa and 1280MPa, respectively. The spring rate, thickness and deflection range were calculated by finding the required total moment of inertia, designed load and Hooke's law. The safety factor for the design was 1.3.

The first prototype (fig. 4.4) was fabricated and tested. The tests were very preliminary with the focus on the functionality of the single leaf spring downforce system. Two opener prototypes were mounted on an air seeder frame (fig. 4.5) which was available at the time of the test. The openers were operated in the fields without using fertilizer, as the objective was to test the cutting function of the opener. Test runs were done for different initial positions of the leaf spring: the combinations of two fixed holes (First and Second) at the spring shackle and two slot positions of the mounting bracket (Upper and Lower). The soil cutting depth of the different combinations were measured for comparisons (fig. 4.6).

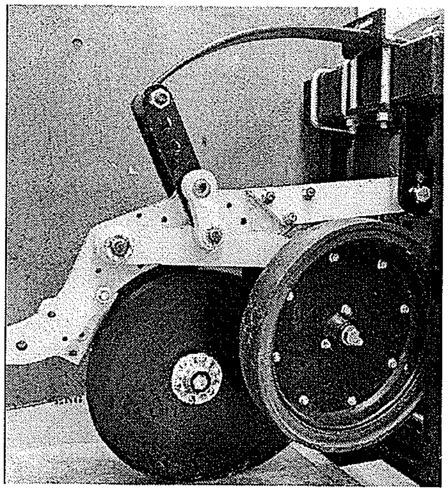


Figure 4.4. Assembly of first prototype mounted on a toolbar.

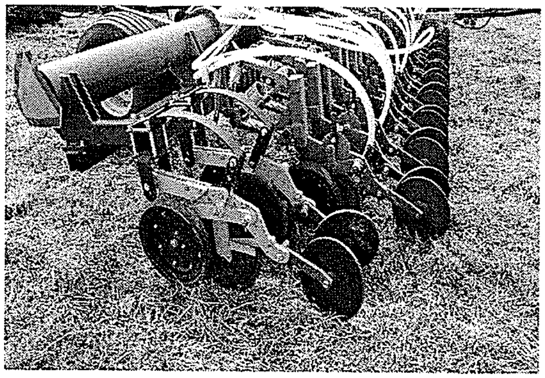


Figure 4.5.Two openers of the first prototype mounted on an air seeder frame.

Figure 4.6. Measurement of furrow depth along the path of the opener prototype.

The results showed that different soil penetration depths (25 mm – 64 mm) could be achieved by changing the combinations of shackle holes position and the slot position of the mounting bracket, which generated different downforce from the leaf spring. The soil cutting depths were satisfactory, although further improvement on the design was required.

4.5.3 Second prototype

The first prototype was sensitive to micro-relief elevation changes of the field surface, and the main reason was due to the high spring rate of the single leaf spring. The function of the shackle was only used to give different initial deflections of the leaf spring. It did not help on minimizing downforce changes of the leaf spring.

In the second prototype, a solution was explored to tackle the above problems by using double leaf springs, longer opener arm, and improved spring shackle (fig. 4.7). The double leaf springs consisted of a main leaf spring and a helper leaf spring. The mechanisms of this prototype are systematically discussed in the following sections.

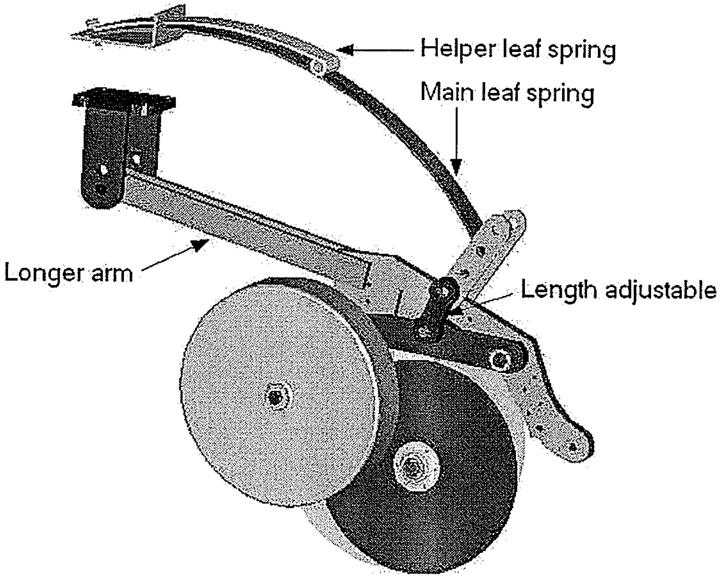


Figure 4.7. Drawings of second prototype.

Adjustable soil cutting depth In order to maintain consistent banding depth, the arm of the rubber gauge wheel needs to be fixed by attaching to both the opener arm and the spring shackle. The depth of the furrow is then substantially determined by the vertical distance that the bottom end of the gauge wheel extends to the bottom of the opener disks. The connection part between the shackle and the gauge wheel arm is length adjustable. Therefore the different initial soil cutting depth can be easily set in this way. The rotation of the spring shackle adjusts the position of the gauge wheel to maintain the bottom of the gauge wheel and the bottom of the furrow opener disks at the same relative vertical distance when the opener is lifted up.

Uniform soil cutting depth The essential factor to determine soil cutting depth is the relationship of the downforce exerted to the opener disks and the soil vertical reaction force, which generally increases with the soil cutting depth and vice versa. When the soil surface elevation changes, the soil vertical reaction force will be changed. To maintain a uniform soil cutting depth, downforce system, which consists of a spring shackle and double leaf springs, has to make corresponding changes.

Spring shackle effects The spring shackle has two main functions on the leaf spring mechanism. As the leaf spring deflects, the length of the spring chord changes and the shackle will swing and change its angle relative to the spring chord. In swinging, the shackle load may lift or lower the eye of the spring and thus increase or decrease the vertical deflection of the spring. This is the first shackle effect. When the shackle is not perpendicular to the spring chord, the shackle load will have a longitudinal component either compressing or stretching the spring between the ends. This second shackle effect will either decrease or increase the effective rate of the spring.

When utilizing leaf spring as opener downforce system, the best-case scenario is that after the leaf springs deflects to a critical position, the further deflection will not affect the downforce or have little effect on the downforce. Therefore, the opener could be able to maintain its target downforce within an acceptable limit when encountering major field surface elevation changes. Theoretically, this can be achieved by utilizing the second shackle effect on the leaf spring under certain configurations. However, for generally assembled leaf springs, either single or multiple ones, the two shackle effects are very difficult to control. Therefore, double leaf springs with special dimensions are used.

Double leaf springs The double leaf springs are comprised of a lower main spring and a upper helper spring, which are stacked and stepped. The main spring is longer and flexible and the helper spring is shorter and stronger. Spring ends of the two leaf springs are fixed on top of the toolbar frame. But only the spring eye of the main spring is connected to the spring shackle. The spring eye of the helper spring is attached on the lower main spring. The functions of the double leaf springs are discussed as follows.

Main spring The chord of the main spring is as long as twice of that of the upper helper spring and thus has a spring rate of only one eighth of the helper spring when the width and thickness of the material for the two springs are the same. The function of the main spring is to rotate the shackle in such a way that it will be more stretched out horizontally by the shackle than being lifted up vertically when the opener encounters obstacles in the field. The displacement trend of the main spring is decided by the magnitude of its flexibility, the shackle angle, the downward force exerted by the helper spring, and the upward shocking load resulting from encountering the field obstacles.

Helper spring The upper helper spring is the main mechanism to exert downforce onto the opener. Due to its high spring rate, less deflection will result in a higher downward force changes onto the lower spring and further transmitted onto the opener disks compared to the main spring. However, the spring eye of the helper spring attaches onto the relatively flat arc of the upper portion of the main spring. This portion can be deflected only within limited extent due to the characteristics of the cantilever spring. Therefore, after presetting the initial downforce of the upper leaf spring, the further raising and lowering of the opener will be balanced by the horizontal deflections of the main spring with the shackle rotation and then little effects will be on the helper spring. The total downforce changes, therefore, can be minimised within a certain level.

Changeable spring rate The combined spring rate of the aforementioned double leaf springs is neither constant nor linear, because the rate of the leaf springs with shackle, also called shackled spring rate, depends on the nominal rate of the spring, the length and the angle of the shackle, the camber and chord of the spring, and the load on the spring (SAE, 1990). To find the best combination of dimensions in terms of minimizing the downforce changes, theoretical calculations, optimization approach, and intensive lab tests on different experimental treatments are required. It is expected that the result from the optimization and the lab tests can find the best curve of load-deflection in vertical direction to meet the design criteria. The mathematical optimization approach and the lab test are described in the next two chapters.

Before the second prototype was fabricated, optimization on the design parameters was performed to determine the dimensions of the double leaf spring downforce system. The purpose of the optimization was to minimise the downforce change of the opener.

5. DESIGN OPTIMISATION

5.1 General requirements

The conceptual downforce system with double leaf springs (main spring and helper spring) stated in the previous chapter was mathematically optimised to guide the development of the second prototype. The specific purposes of conducting the mathematical optimisation were to find the optimal dimensions and positions of the leaf spring and shackle, which firstly enabled the opener to have the target downforce and secondly made the opener maintain minimum downforce changes during field operations.

Effects of field elevation changes on the opener downforce system are demonstrated in figure 5.1. The elevation change, 2ΔH, can be significant. This results in significant changes in the spring deflections, positions of shackle and arm, and consequently significant changes in the opener downforce. After optimisation, these changes in the leaf spring downforce system were expected to be able to respond immediately and effectively to minimise the downforce changes.

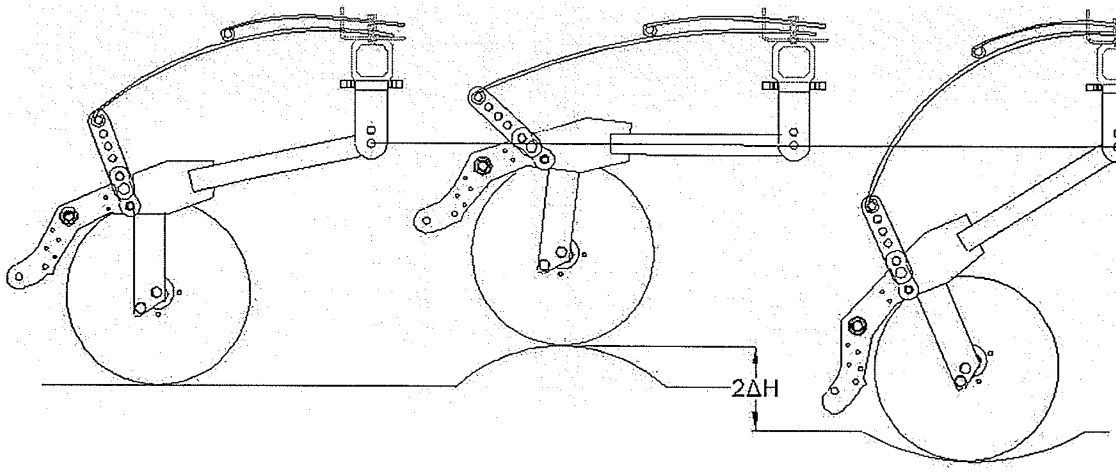


Figure 5.1. Position and dimension changes of the leaf spring downforce system when the opener disk running under normal field elevation, encountering a field obstacle, and entering a field depression; 2ΔH is the total field elevation change.

For the optimisation, the target downforces were set around 1779 N, which is the upper end of 1023 – 1780 N set by Gratton et al. (2003). The downforce system should provide this target force when the opener is at the normal position. Their design criteria for downforce variations were also adopted in the optimisation, which required the opener to maintain the downforce changes no more than ±12% of its normal downforce when the opener encountered field surface elevation changes of ±50 mm. Thus, the total surface elevation changes were set as 100 mm.

5.2 Physical theory of the mathematical optimisation approach

An objective function was developed for the optimisation using the moment equilibrium equation about pivot point O (fig. 5.2). When the opener is operated in a field at a constant speed, the moment created by the vertical and horizontal soil reaction forces, denoted as F_D and F_H, respectively, should be balanced out by the moment created by the resultant force P from the leaf spring downforce system.

Vertical soil reaction force F_D acts at some point in front of or to the right of the disk axle, not directly underneath it. This force can exert an equal and opposite moment about the disk axle to balance the moment by F_H. The location of the centre of the disk is independent of the magnitudes of both F_D and F_H. Therefore, it is legitimate to move the two forces from the interface of the disk and soil to the axle of the disk to simplify the calculation.

The resultant force P consists of P_1 and P_2 resulting from the deflections of the lower main spring and the upper helper spring, respectively. The objective function for the optimisation based on this physical theory is described in the following sections.

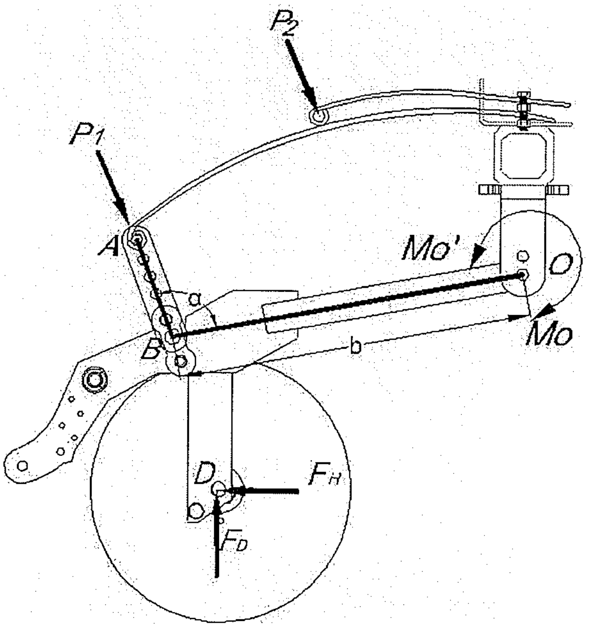


Figure 5.2. Forces applied to the opener and moment created at pivot O.

5.3 Objective function development

The moment M_O about pivot O, created by soil reaction forces F_D and F_H, can be described as follows (fig. 5.3a):

$$f_1 = M_O = F_D \cdot L \cdot \cos\theta + F_H \cdot L \cdot \sin\theta \tag{5.1}$$

where

M_O = moment created by soil reaction forces about pivot O (N·mm)

F_D = soil vertical reaction force (N)

L = distance between pivot O to disk centre D (mm)

θ = angle of line OD relative to horizontal plane (degrees)

F_H = soil horizontal reaction force (N).

The moment created by the double leaf springs, shown in figure 5.3b, can be expressed in the following equation:

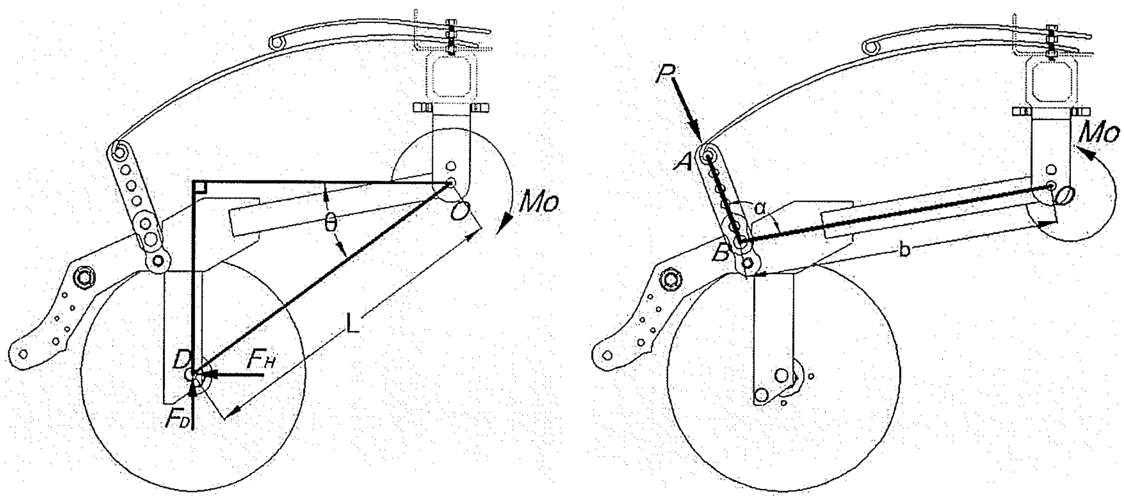
$$f_2 = M_O = P \cdot b \cdot \cos(\alpha - \frac{\pi}{2}) = P \cdot b \cdot \sin\alpha \tag{5.2}$$

where

P = resultant force of P_1 and P_2 applied to the shackle by the leaf springs (N)

b = length of opener arm OB from pivot O to the shackle base point B (mm)

α = angle of the spring shackle AB relative to the opener arm OB (degree).



(a) (b)

Figure 5.3. Moment created by (a) soil reaction forces and by (b) leaf springs P.

5.3.1 Dependent variables isolation

The target dependent variable of the objective function is the opener downforce change, which is required to be minimised. The opener downforce change is equal to the changes of the soil vertical reaction force in magnitude, but opposite in direction. Thus the dependent variable can be considered as dF_D. The horizontal soil reaction force F_H is assumed as a constant when the opener is operated at a given travel speed and set at a predetermined soil penetration depth (Gratton et al., 2003). Assuming that ΔH of 50 mm is sufficiently small, taking the first derivative of equation 5.1, a new function showing the change in M_O is given by:

$$df_1 = dM_O = \frac{\partial M_O}{\partial(\theta)} d\theta + \frac{\partial M_O}{\partial(F_D)} dF_D = (-F_D \cdot L \cdot \sin\theta + F_H \cdot L \cdot \cos\theta) \cdot d\theta + L \cdot \cos\theta \cdot dF_D \quad (5.3)$$

Using the geometrical relationship between incremental change in dθ and incremental change in vertical position ΔH of the opener disk, it is easily arrived at:

$$d\theta = \frac{\Delta H}{L \cdot \cos\theta} \quad (5.4)$$

Substitution of equation 5.4 into equation 5.3 results in an equation relating an incremental change in M_O to an incremental change in ΔH and the target dependent variable dF_D:

$$df_1 = dM_O = (-F_D \cdot L \cdot \sin\theta + F_H \cdot L \cdot \cos\theta) \cdot \frac{\Delta H}{L \cdot \cos\theta} + L \cdot \cos\theta \cdot dF_D \quad (5.5)$$

Likewise, after taking the first derivative of equation 5.2, the following equation is formed and evaluated as:

$$df_2 = dM_O = \frac{\partial f_2}{\partial P} dP + \frac{\partial f_2}{\partial \alpha} d\alpha = b \cdot \sin\alpha \cdot dP + P \cdot \cos\alpha \cdot b \cdot d\alpha \quad (5.6)$$

where

dα = incremental change of α (degrees)

α = angle of spring shackle relative to opener arm (degrees)

dP = incremental change of P (N).

A new function f_3 can be formed:

$$f_3 = df_1 - df_2 = dM_0 - dM_0 = 0 \tag{5.7}$$

Substitution of equation 5.5 and equation 5.6 into equation 5.7 results in the final objective function shown below:

$$dF_D = \frac{b \cdot \sin\alpha \cdot dP + P \cdot \cos\alpha \cdot b \cdot d\alpha - (F_H \cdot L \cdot \cos\theta - F_D \cdot L \cdot \sin\theta) \cdot d\theta}{L \cdot \cos\theta} \tag{5.8}$$

The incremental changes, dP, dα, and dθ, are all related to ΔH as described in the following sections. It is reasonably assumed that the ΔH of 50 mm is sufficiently small and thus equation 5.8 is sufficiently accurate to represent the geometry of the system when depth of the opener has changed by 50 mm.

5.3.2 Relationship between dα and ΔH

The spring ends of the double leaf springs are defined as the spring fixture ends between the two slots of the mounting bracket and the fixture bolt F (fig. 5.4). A tangent-chord angle β of the main spring end is introduced to track the dimension and position changes of the two springs. It is assumed that the spring ends are parallel to the surface of the upper mounting bracket. It is further assumed that the change of tangent-chord angle of the helper spring is proportional to that of the main spring, dβ, within the deflection limit of the two springs. This ratio is determined by the length of the two spring chords l_1 and l_2. These assumptions are reasonable according to characteristics the cantilever springs.

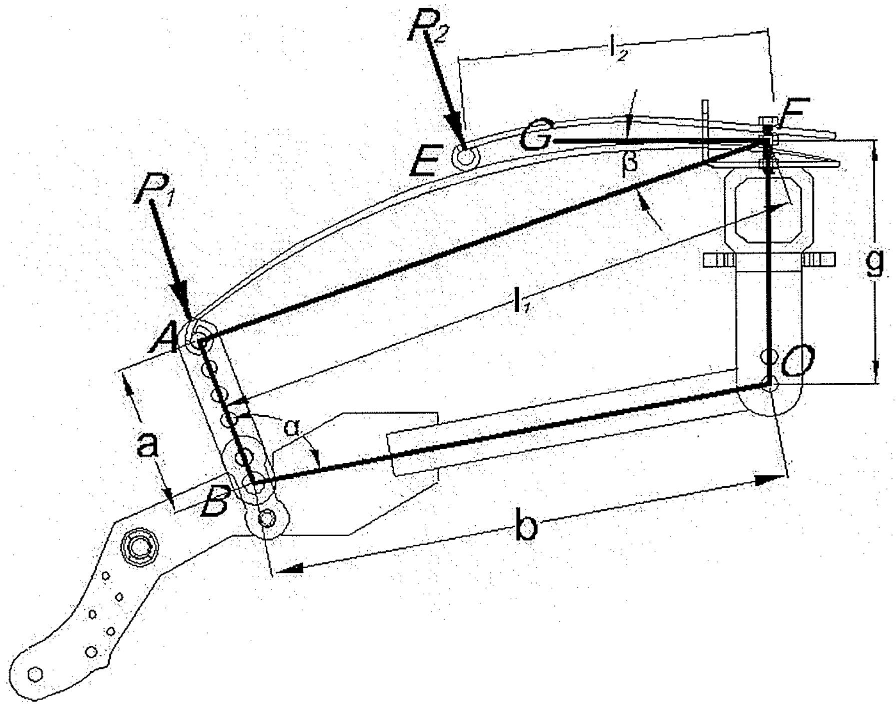


Figure 5.4. Dimension of the leaf spring system.

When the opener is lifted up due to obstacles during field operations, the spring shackle will move upwardly and backwardly, which results in the increase of the angle α. The upward movement of shackle will raise the main spring eye A and the helper spring eye E in different extents. The springs are then deflected in vertical direction.

The backward movement of the shackle has a longitude component to stretch the main spring at the point A. This results in the point A moving backwards. The helper spring is also affected due to the stretching of the main spring. Furthermore, the point E of helper spring may move either upwards or keep its position without any displacement depending on the position changes of the contact point between the main spring and the helper spring.

The following equation is found using the law of cosines in ΔABO and ΔAFO:

$$\overline{AO} = a^2 + b^2 - 2ab \cdot \cos\alpha = l_1^2 + g^2 - 2l_1 g \cdot \cos\angle AFO = l_1^2 + g^2 - 2l_1 g \cdot \cos(\frac{\pi}{2} - \beta) \quad (5.9)$$

All the angles and reference lines in equation 5.9 are shown in figure 5.4. Equation 5.9 is further reduced to equations 5.10 and 5.11, where variables α and dα are expressed with the variable β:

$$2l_1 g \cdot \sin\beta = l_1^2 + g^2 - a^2 - b^2 + 2ab\cos\alpha \quad (5.10)$$

$$d\alpha = \frac{l_1 \cdot dl_1 - g \cdot \sin\beta \cdot dl_1 - l_1 g \cdot \cos\beta \cdot d\beta}{ab \cdot \sin\alpha} \quad (5.11)$$

where

l_1 = length of the main spring chord AF (mm)

g = distance between pivot O and leaf spring fixture point F (mm)

β = tangent-chord angle of the main leaf spring chord AF (degree)

dβ = incremental change of β (degree)

a = length of the spring shackle (mm).

The angle of opener arm OB relative to the horizontal line is denoted as φ and is assumed that OB should always below the horizontal plane during field operations. Assuming the system is located in a coordinate system with pivot O as the origin (fig. 5.5). R_1 and R_2 are two horizontal reference lines passing through origin O and shackle base point B, respectively. The coordinate of B is located at (-b·cosφ, -b·sinφ) and the coordinate of A is located at ($-l_1$·cosβ, g - l_1·sinβ). Therefore, the following relationship can be found in ΔABC:

$$\cos\angle ABC = \frac{BC}{AB} = \frac{l_1 \cdot \cos\beta - b\cos\phi}{a} \tag{5.12}$$

It is obvious to notice that $\angle ABC = \angle OKB$. In ΔOBK, α, φ, and $\angle OKB$ all make incremental changes as the opener disk moving up and down. The summation of all three incremental changes is equal to zero. Therefore, the following relationship is found:

$$d\phi - d\alpha = \angle OKB \tag{5.13}$$

Using geometry, equation 5.13 can be further changed to the following equations:

$$d\angle OKB = d\angle ABC = \frac{d(l \cdot \cos\beta - b\cos\phi)}{a} = \frac{\cos\beta \cdot dl_1 - l_1 \cdot \sin\beta \cdot d\beta + b \cdot \sin\phi \cdot d\phi}{a} \tag{5.14}$$

$$d\phi = \frac{\Delta H}{b \cdot \cos\phi} \tag{5.15}$$

Substitution of equation 5.14 and 5.15 into equation 5.13 results in the function which relates the dβ to ΔH:

$$\cos\beta \cdot dl_1 - l_1 \cdot \sin\beta \cdot d\beta + a \cdot d\alpha = (a - b \cdot \sin\phi) \cdot d\phi \tag{5.16}$$

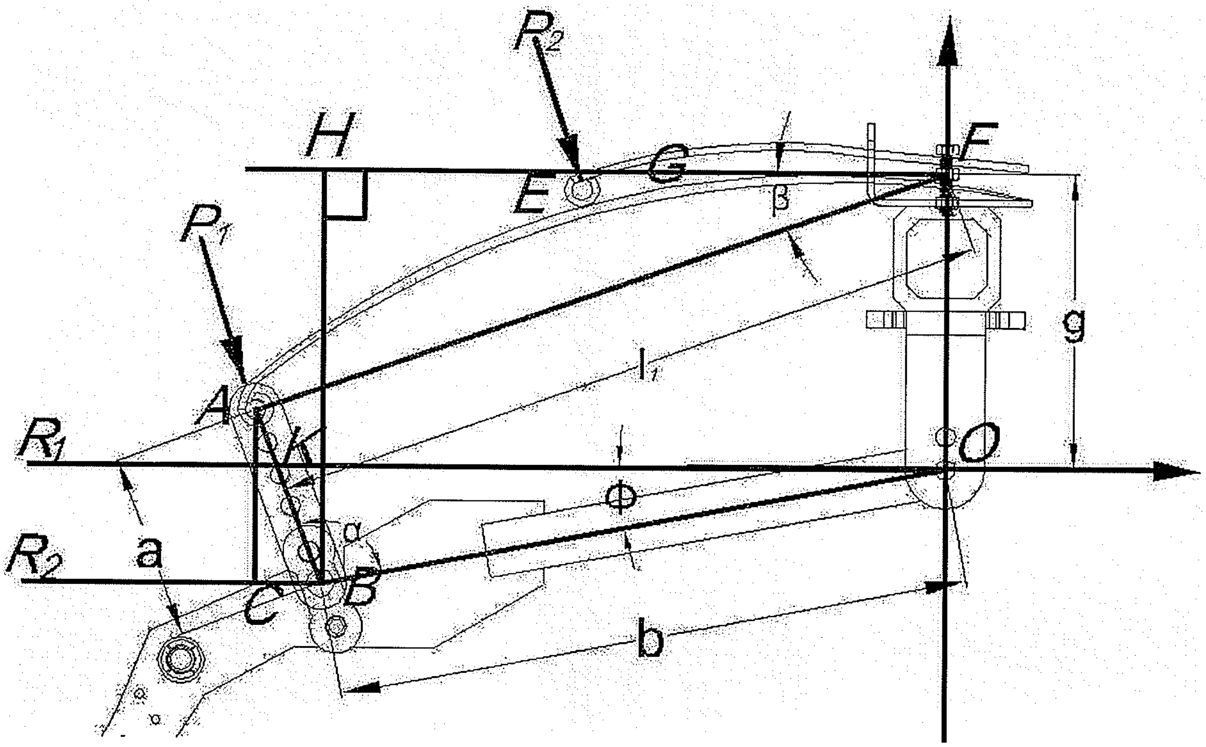


Figure 5.5. Coordinate system with O as the origin; φ= angle of OB relative to R_1; R_1 and R_2 = horizontal reference lines through O and B, respectively; K = intersection of R_1 and line AB; AC = vertical reference line to R_1 and R_2.

The vertical distance BH between the shackle pivot B and horizontal line HF can be expressed by the following equation:

$$BH = g + b \cdot \sin\phi \tag{5.17}$$

The vertical distance BH can also be described in another equation:

$$BH = l_1 \cdot \sin\beta + a \cdot \sin(\alpha + \phi) \tag{5.18}$$

After combining equation 5.17 and 5.18 and taking the first derivation:

$$l_1 \cdot \cos\beta \cdot d\beta + \sin\beta \cdot dl_1 + a \cdot \sin\alpha = (a - b \cdot \sin\phi) \cdot d\phi \tag{5.19}$$

5.3.3 Relationship between dP and ΔH

Incremental changes in total spring force dP were combined by force changes of main spring dP_1 and helper spring dP_2. Only the spring deflection perpendicular to the spring chord is considered and the spring deflection parallel to the spring chord is neglected. The following three equations are found according to Hooker's law:

$$dP = dP_1 + dP_2 \tag{5.20}$$

$$dP_1 = k_1 \cdot df_1 \tag{5.21 a}$$

$$dP_2 = k_2 \cdot df_2 \tag{5.21 b}$$

where

dP_1 = incremental change of main spring force (N)

k_1 = spring rate of main spring (N/mm)

df_1 = incremental change of main spring deflection perpendicular to the spring cord (mm)

dP_2 = incremental change of main spring force (N)

k_2 = spring rate of helper spring (N/mm)

df_2 = incremental change of helper spring deflection perpendicular to the spring cord (mm).

As the spring ends of the two springs are parallel, the tangents of arc EF and arc AF are also parallel with the common tangent point F (fig. 5.5). The spring eye E of the helper spring presses on the main spring tightly. Therefore, it is reasonable to assume that the incremental changes of their respective tangent-chord angles are proportional and have the following relationships:

$$df_1 = l_1 \cdot \tan d\beta \quad (\tan d\beta \simeq d\beta \text{ for small angle}) \tag{5.22 a}$$

$$df_2 = \frac{l_2}{l_1} \cdot \tan \frac{l_2 \cdot d\beta}{l_1} \quad (\tan \frac{l_2 \cdot d\beta}{l_1} \simeq \frac{l_2 \cdot d\beta}{l_1} \text{ for small angle}) \tag{5.22 b}$$

$$dP = k_1 \cdot l_1 \cdot d\beta + k_2 \cdot \left(\frac{l_2}{l_1} \right)^2 \cdot d\beta = (k_1 \cdot l_1 + 2k_1) \cdot d\beta \tag{5.23}$$

5.4 Optimization process

5.4.1 Parameters optimised

Many parameters are involved in the above objective function (eq. 5.8). For optimization, only the parameters, highly sensitive to the dependent variable, need to be found for the optimal values. These parameters include the spring rates of the double leaf springs k_1 and k_2, chord lengths of the double leaf springs l_1 and l_2, and the length of the spring shackle, a. These parameters have the most significant effects on the function of the downforce system.

When choosing the spring material for optimization, spring steel with the same uniform cross section (constant width and constant thickness) was selected for the double leaf springs as such springs are cheap to produce without any special machining. It is assumed that the double springs can be treated as cantilever springs. For the cantilever leaf spring with uniform section, the spring rate is given as follows:

$$k = \frac{3 \cdot E \cdot \sum I}{l^3} \tag{5.24}$$

where:

k = spring rate (N/mm)

E = modulus of elasticity (for steel: 200000 MPa)

$\sum I$ = total moment of inertia. (mm^4)

l = spring length (mm).

The constant width w and thickness t selected were 63 mm and 10 mm, respectively, according to the requirement of the spring strength and the limitation of the shackle dimension. Thus, the total moment of inertia $\sum I$ of the main and helper springs was fixed as 5250 mm^4. If the ratio of chord length l_1 and l_2 was set as constant, i.e. $l_2/l_1 = 1/2$, according to equation 5.21, the ratio of the spring rate will be $k_1/k_2 = 1/8$. Thus only l_1 and k_1 need to be optimised. Variables l_2 and k_2 can be calculated from l_1 and k_1. The parameters to be optimised are reduced to shackle length a, the chord length l_1 and the spring rate k_1 of the main spring. The upper and lower bound values of the design variables are given in table 5.1.

Table 5.1. Design variables for optimization.

Symbol	**Description**	**Units**	**Lower/Upper Bounds**
a	Length of spring shackle	mm	$100 <= a <= 300$
l_1	Chord length of main spring	mm	$700 <= l_1 <= 1000$
k_1	Spring rate of main spring	N/mm	$3 <= k_1 <= 7$

5.4.2 Fixed parameters and constraints

Some parameters are often relatively fixed due to the geometries of the opener configuration or limitations of the resources. Fixed parameters are usually set as the constants in the objective function. The fixed parameters in this study include the opener arm b, the opener arm angle φ, the tangent-chord angel β, the spring width and thickness, and some others. The horizontal soil reaction force F_H can be assumed as constant when the depth control of the opener functions normally (Gratton, 2003). The constant values of these fixed parameters are given in table 5.2.

Table 5.2. Fixed parameters for optimisation

Symbol	Description	Units	Value
b	Length of opener arm OB	mm	700
θ	The angle of OD relative to horizontal line (fig.5.3 a)	radian	0.52
L	The length of OD (fig.5.3 a)	mm	750
Initial α	Initial shackle angle	radian	2.09
Initial P	Initial force generated from the leaf springs deflection	N	2405
Initial Φ	Initial angle between the opener arm OB and horizontal line	radian	0.21
Initial β	Tangent-chord angle of the main spring chord	radian	0.52
F_H	Horizontal reaction for on the opener	N	667
w	Width of the springs	mm	63
t	Thickness of the springs	mm	10
l_1/l_2	Ratio of the chord length of the two springs	dimensionless	2
k_1/k_2	Ratio of the spring rate of the two springs	dimensionless	1/8

After placing the values of the fixed parameters into the equation 5.8, the objective function is reduced to:

$$dF_D = 0.93(k_1 \cdot l_1 + 2k_1) \cdot d\beta - 1295 d\alpha + 280 d\theta \qquad (5.25)$$

From the above equations 5.4, 5.11, 5.15, 5.16, 5.19, the relationship between dα, dβ, dl_1, and

ΔH are found in the following equations:

$$dl_1 = \frac{0.27a + 163}{500 - 2.26 \cdot l_1} \cdot \Delta H \tag{5.26}$$

$$d\alpha = \left[\frac{(0.27a + 163) \cdot l_1}{(233 - l_1) \cdot a} - \frac{1}{306 \cdot a} \right] \cdot \frac{\Delta H}{685} \tag{5.27}$$

$$d\beta = (\frac{30.6 \cdot a + 18360}{306 l_1 - 1.37 l_1^2} - \frac{846 - 2 \cdot a}{1.37 \cdot l_1}) \cdot \frac{\Delta H}{685} \tag{5.28}$$

When the leaf spring opener encounters micro-relief changes ΔH in the field, the vertical deflection of the leaf springs and the shackle angle will make corresponding changes. The first constraint is set on the incremental changes of the tangent-chord angle, namely dβ. The spring eye can not be raised up to a level higher than the spring fixture ends. The marginal scenario is that the spring eye will be leveled with spring fixture end when the opener encounter the highest obstacle ΔH in the field. The second constraint is set on the changes of shackle angle, dα, which can not exceed 30°. The third constraint is the constant total moment of inertia of the main spring. These three constraints are set as follows:

$$d\beta = (\frac{30.6 \cdot a + 18360}{306 l_1 - 1.37 l_1^2} - \frac{846 - 2 \cdot a}{1.37 \cdot l_1}) \cdot \frac{\Delta H}{685}$$

$$\sum I = \frac{k_1 \cdot l_1^3}{3 \cdot E}$$

$$d\alpha = \left[\frac{(0.27a+163)\cdot l_1}{(233-l_1)\cdot a} - \frac{1}{306\cdot a} \right] \cdot \frac{\Delta H}{685}$$

The upper and lower bound values of constraints for the above three equations are set as:

$0^\circ < d\beta < 15^\circ$, $0^\circ < d\alpha < 30^\circ$, and $\sum I = 5250\ \text{mm}^4$.

5.4.3 Optimisation results

The above objective function (eq. 5.22) was minimised in Matlab (The MathWorks., Natick, MA) using genetic algorithms (GA). GA has the advantage of searching the result for global optimum rather than local optimum. When setting ΔH = -50 mm and applying the GA, the objective function converged after 7 generations. The optimization result given was -233 N, which meant the percent of downforce change was about -13% compared to the normal downforce 1780 N. The corresponding optimum values for a, l_l and k_l were 100 mm, 874 mm, and 6 N/mm, respectively (Fig. 5.6).

When ΔH was set as 50 mm, after 24 generations, the optimization result from the GA was 90 N, which meant the percent of downforce change was about 5% (Fig. 5.7). The optimum values for a, l_l and k_l were 300 mm, 954 mm and 3.6 N/mm, respectively. Therefore, the average downforce changes given by this optimization approach was around 9%. The optimisation results are summarized in table 5.3.

Table 5.3. Optimisation result and design variables.

Optimisation result			Design variables				
ΔH (mm)	dF_D (N)	dF_D (%)	k_l (N/mm)	l_l (mm)	k_2 (N/mm)	l_2(mm)	a (mm)
-50	-233	-13%	6	874	48	437	100
50	90	5%	3.6	954	29	477	300

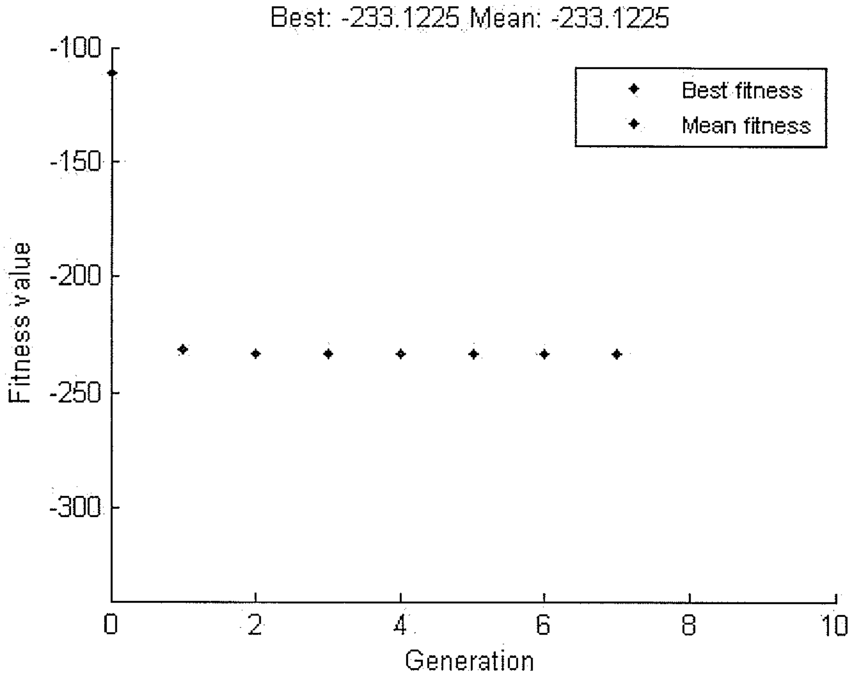


Figure 5.6. Optimisation result achieved by Genetic Algorithm when ΔH = -50 mm.

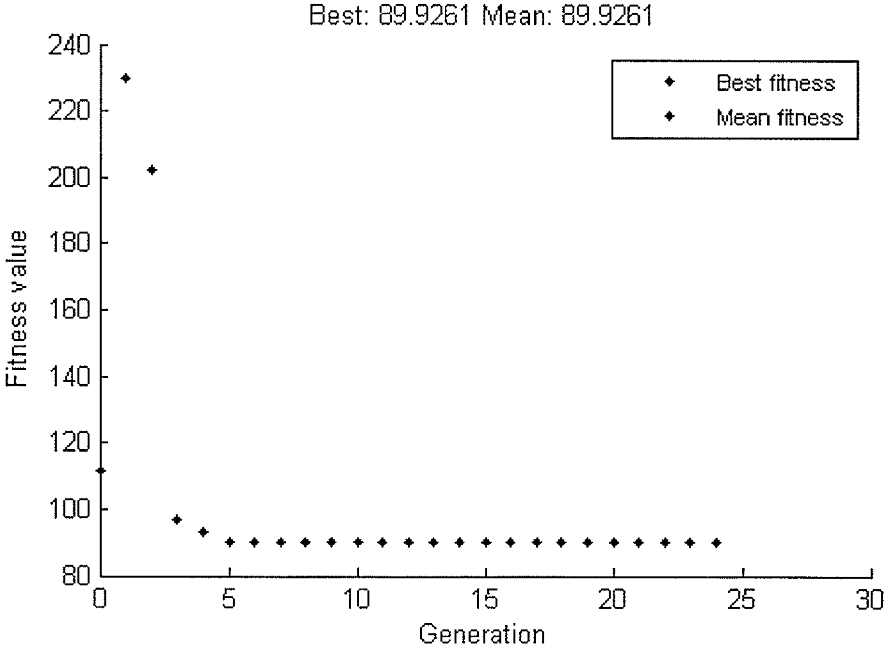


Figure 5.7. Optimisation result achieved by Genetic Algorithm when ΔH = 50 mm.

Based on the optimisation result, the leaf springs of the second prototype (fig. 5.8) were fabricated with the spring rate 4.5 N/mm for the main spring and 36 N/mm for the helper leaf spring, which were in the range of the recommending values of the optimisation results. The dimensions of the leaf spring length and the shackle length were fabricated as length adjustable. The optimal dimensions for these length adjustable parts were further tested in a laboratory static downforce test to validate the effectiveness of this mathematical optimisation method. The lab test is described in the next chapter.

5.5 Cost estimation

The production cost of the leaf spring downforce system is estimated as about $150 including the double leaf springs, the spring shackle, and the mounting bracket (fig. 5.6). Other parts of the opener, such as the disks, are not included. The leaf springs do not need special machining as they are the same as those commonly used in the vehicle suspension system. The steel consumption of the leaf spring downforce system is 26% of that of the parallel linkage system. The machining time of the former system is 30% of that of the latter system. Attributing 0.5 of weighing factor to the steel consumption and machining time, the total cost of leaf spring downforce system is only about 28% of the parallel linkage downforce system based on the number of the parts required and the consumption of the steel material (Table 5.4). 70% of cost reduction of leaf spring downforce system was calculated by attributing 0.5 of weighing factor to the steel consumption and machining time, which represent the material cost and labour cost, respectively. Therefore, the simple structure of the leaf spring downforce system has a significant cost advantage compared to the complicated parallel linkage downforce system, which mainly includes two parallel arms, two linkages, four pivots, one heavy coil spring and some other parts.

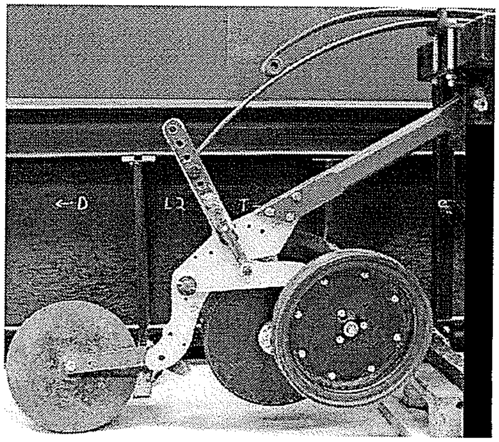


Figure 5.8. The second prototype of the fertilizer banding opener.

Table 5.4. Cost comparison between parallel linkage downforce system and leaf spring downforce system.

	Structure		Material and labour	
Downforce system	Number of Parts	Number of Pivots	Steel consumption (kg)	Machining time (hr)
Parallel linkage	13	4	57	5
Leaf spring	7	2	15	1.5

6. LABORATORY TEST OF THE SECOND PROTOTYPE

Static measurements on the downforce of the second prototype were performed to investigate relationships between the design variables of the leaf spring downforce system and the corresponding downforce changes when the opener was simulated to encounter obstructions in field. Data from the lab test were also used to validate the design concepts and optimization results obtained in the previous chapters.

6.1 Material and methods

6.1.1 Equipment

The second prototype was tested in a laboratory condition. The prototype was mounted onto a 102 mm x 102 mm toolbar frame which was fixed on the floor. The toolbar frame was set in the same way as it was running in a field. A hydraulic hand pallet truck, weighing scale, magnetic digital protractors were used in the tests as the measuring tools.

6.1.2 Experimental design

The experiment was designed to examine effects of different shackle lengths (a) and main spring chord length (l) on the opener downforce. The experiment also examined effects of the shackle angle α, as the variables, a and l, change the magnitude of α. As discussed in the optimization process, all α, a, and l affect the downforce changes of the opener.

The treatments used were the combinations of four different main spring chord lengths and four different shackle lengths. Four different main spring lengths were 755, 810, 865, and 920 mm, denoted as l755, l810, l865, and l920. Four shackle lengths were 100, 140, 180, and 220 mm, denoted as a100, a140, a180, and a220. Each treatment was corresponding to a shackle angle to be measured in the experiment. Some treatment combinations were not tested due to the dimension limitations of the spring and opener arm. Each treatment was replicated twice.

6.1.3 Simulation of ground elevation changes

The opener was lifted up by the hydraulic pallet truck to simulate field elevation changes (fig. 6.1). The weighing scale was placed on top of the pallet truck. The opener disks pressed on the surface of the scale measuring area. Thus the opener disk and the scale would move together by the pallet truck. The static downforce was read off the scale at a certain ground elevation. This force included the gravity force of the opener assembly and the spring vertical force.

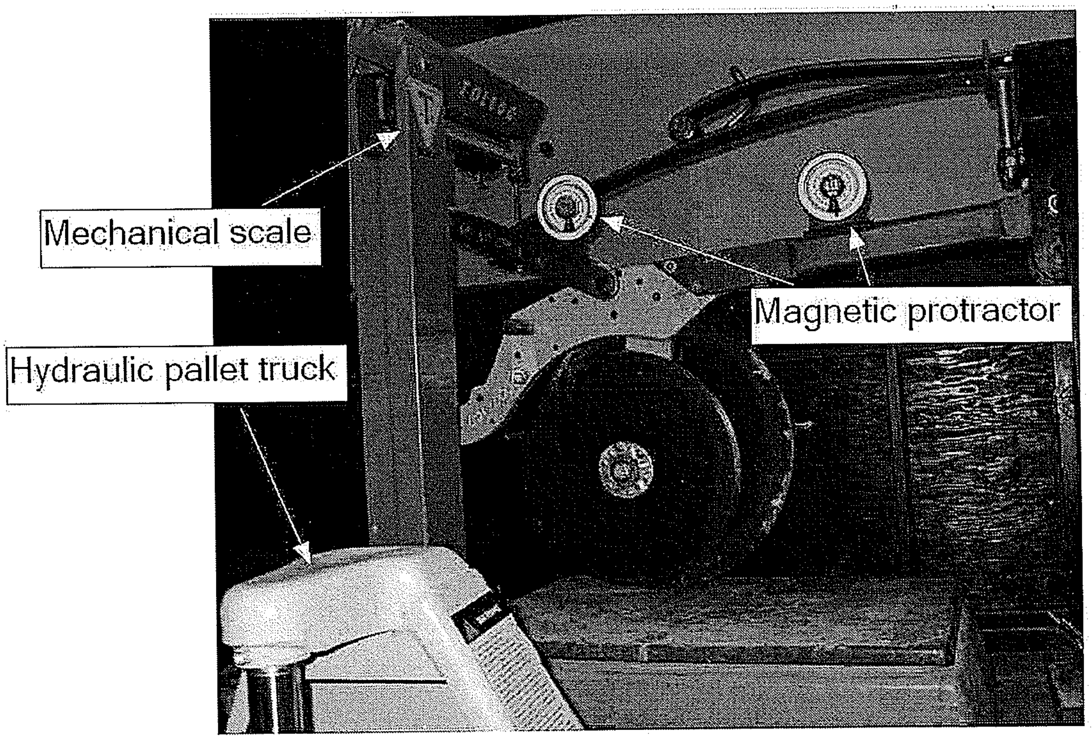


Figure 6.1. Tools and opener used in conducting the lab test.

6.1.4 Measurements of downforce

During the procedure of raising the opener by the hydraulic pallet truck, the normal working position of the opener was identified, at which the downforce shown on the scale was 1779 N. Then the lifting range of the opener was set as 50 mm above and below the normal position.

For measurements, the opener was set with the desired combination of l x a. The corresponding shackle angle α was measured using two magnetic protractors. One protractor was set on the opener arm and the other was set on the shackle (fig. 6.1). The shackle angle was calculated using the readings from these two protractors. Then different ground elevations were created by raising the opener for 7 or 8 mm each time. Approximately 13 – 15 elevations were tested for each l x a combination or α. At each elevation (ΔH), the static downforce indicated by the scale was recorded.

6.2 Results and discussion

The results showed that downforce of the opener varied with the treatments. In all cases, the target downforce of 1779 N could be easily achieved by the leaf spring downforce system of the prototype. The maximum downforce observed in the tests reached to approximately 3118 N. The following discusses effects of the treatments on the downforces. Percentage of downforce change is also presented as it was crucial for the opener design. The percentage of down force change was referred to the downforce at the normal position.

6.2.1 Effects of spring chord length

Spring chord length had a significant effect on the downforce change (fig. 6.2). The downforce change was linearly decreased approximately linearly as the spring chord length was increased. Decreasing the spring length from 920 to 755 mm, the down from change varied from approximately 10% to 50%. The longer leaf spring chord length would compromise more vertical deflections during the vertical movement of the opener. However, the length of the spring chord could not be increased without limit.

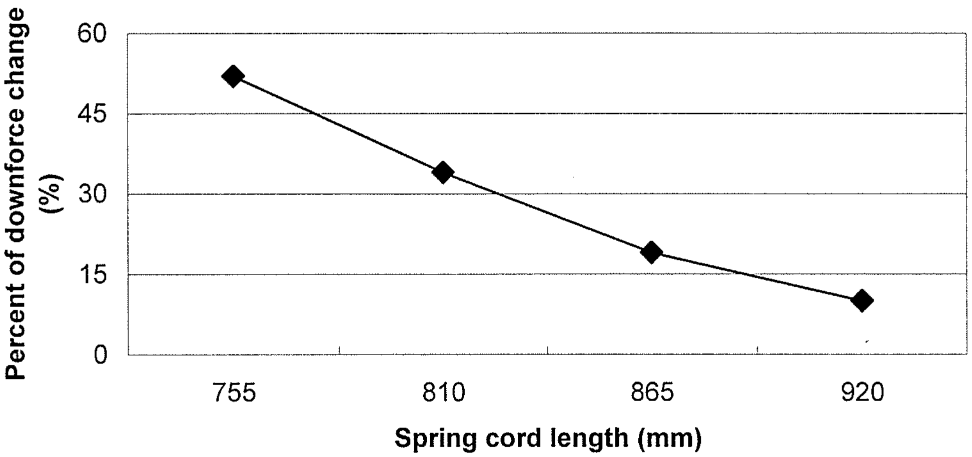


Figure 6.2. Percentage of downforce changes as affected by the spring chord length, regardless of the shackle length.

6.2.2 Effects of shackle length

Effects of shackle length on the downfoce changes were not linear (fig. 6.3). The 140 mm length caused the highest percentage of downforce change, when compared to shorter and longer ones.

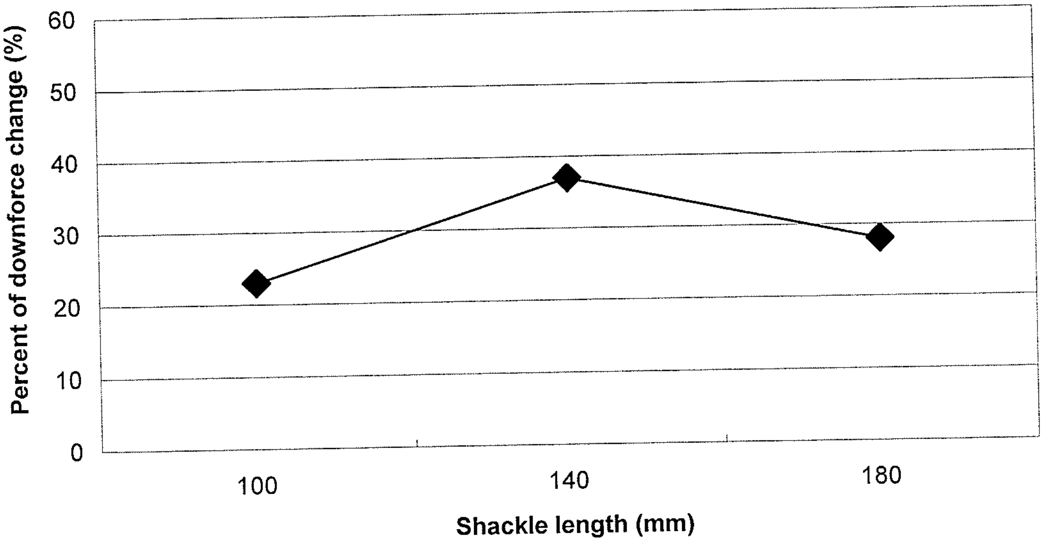


Figure 6.3. Percentage of downforce changes as affected by the shackle length, regardless of the spring chord length.

Further studies found that effects of the shackle length could not tell the real performance of the downforce system because this factor interacted with the other factor, the spring chord length. This interaction is demonstrated by figure 6.4. The trends of shackle length effects were completely different with the one shown in figure 6.3. Figure 6.4 shows that the 140 mm shackle length did not necessarily cause the highest downforce change, depending on the spring chord length. Thus, the downforce changes may be better reflected by the effects of the combinations of these two factors or different shackle angels.

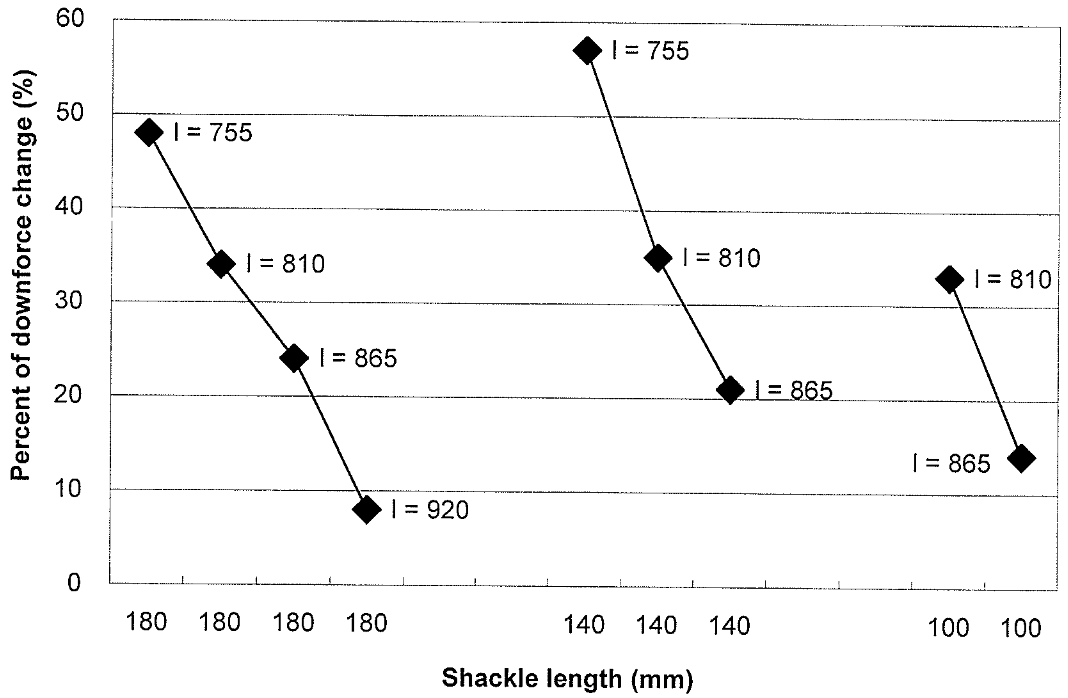


Figure 6.4. Percentage of downforce changes as affected by both shackle length and spring chord length; data points at each shackle length represent different spring chord lengths.

6.2.3 Effects of treatment combination (shackle angle)

Significantly different ranges of downforce changes were found among treatments and they varied from 2% to -72%. The worst treatment combination, in terms of the variations in downforce, was *l*755 x a140, which had the downfoce change from 41% and -72% near ±50 mm ground elevations (fig. 6.5). The average downforce change of this treatment was as high as 57%. The best treatment combination was the *l*920 x a180, which resulted in a low downforce of 2% near +50 mm ground elevation and -14% near -50 mm ground elevation (fig. 6.6). The average downforce change of this treatment was only 8%, which was acceptable according to the preset criteria of 12%.

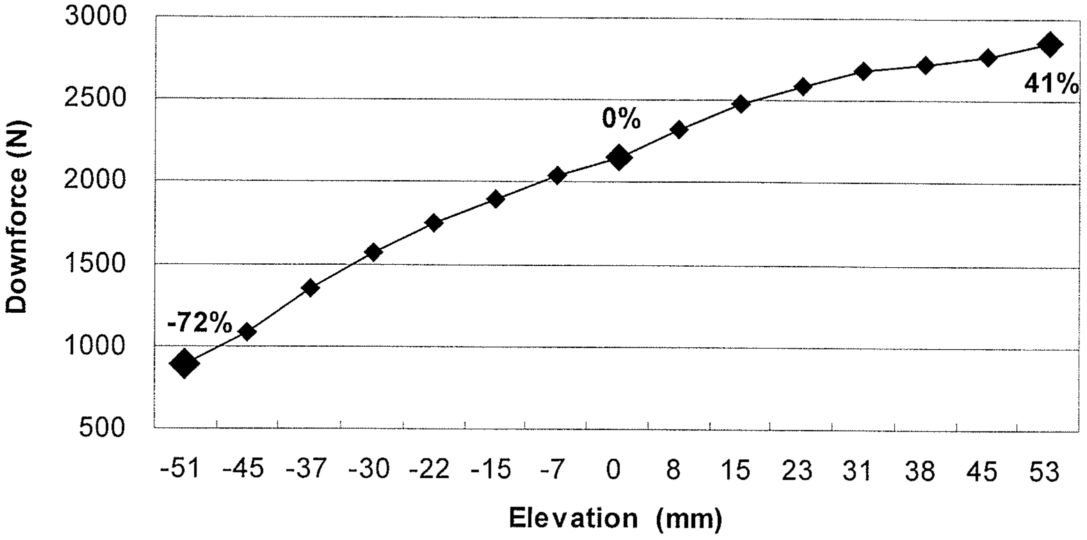


Figure 6.5. Downforces and downforce changes of the treatment *l*755 x a140.

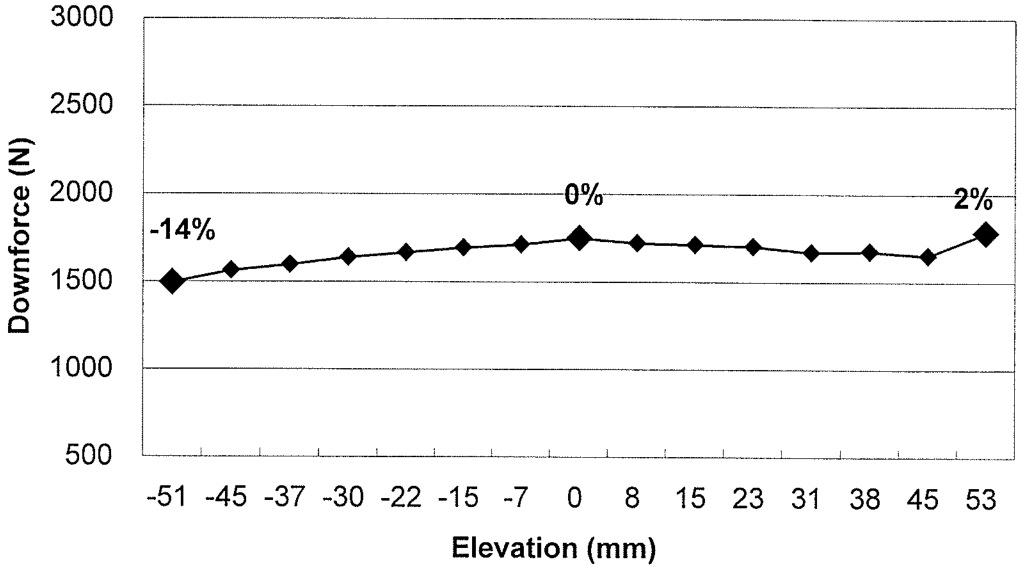


Figure 6.6. Downforces and downforce changes of the treatment *l*920 x a180.

These results from the best and worst treatments and the other treatments are summarized in table 6.1. Effects of the shackle angle (at the normal position) on the downforce change are further shown in figure 6.7. The angle of 138° seemed to give the lowest downforce change.

This confirmed that the best treatment was *l*920 x a180. It is suggested to use these dimensions of the spring chord length and shackle length when commercialising this opener.

Table 6.1. Summary of the results of downforce changes and corresponding shackle angles from different treatments.

Treatment[a]	Shackle angle (°)	Downforce change (%)		
		50 mm	-50 mm	Average[b]
*l*755 x a140	76	41	-72	57
*l*755 x a180	80	34	-62	48
*l*810 x a180	99	20	-48	34
*l*810 x a140	100	22	-47	35
*l*810 x a100	101	20	-46	33
*l*865 x a180	118	15	-32	24
*l*865 x a140	134	11	-30	21
*l*865 x a100	138	-3	-24	14
l 920 x a180	138	2	-14	8
*l*920 x a220	145	4	-19	12

[a] *l*755 x a140 stands for the treatment with 755 mm spring chord length and 140 mm shackle length.

[b] Average is the average of the absolute values of downforce changes when ΔH = ± 50 mm.

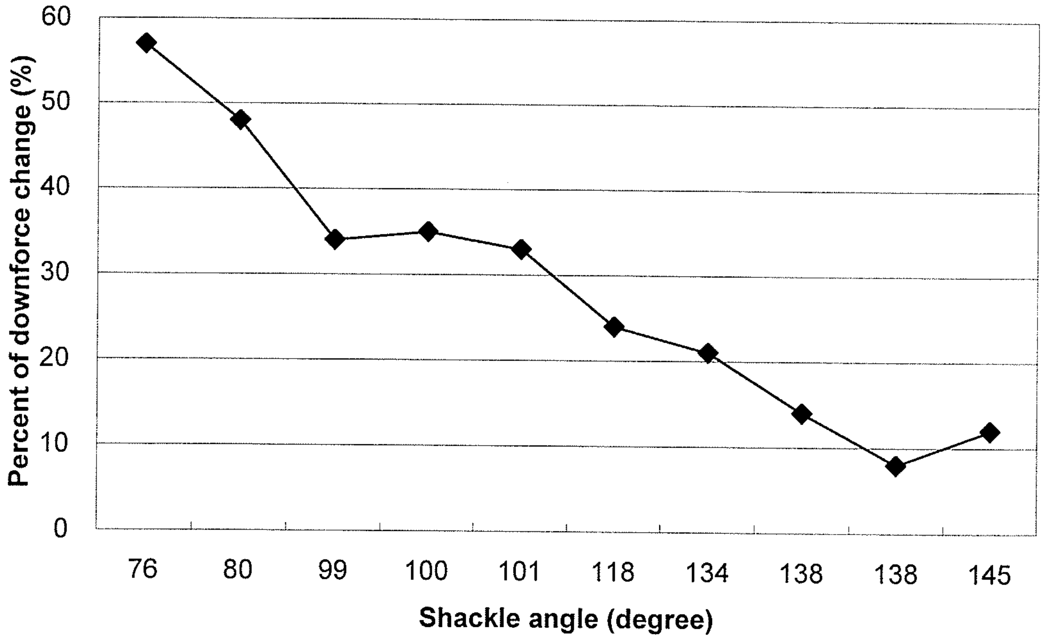


Figure 6.7. Downforce changes as affected by the shackle angles.

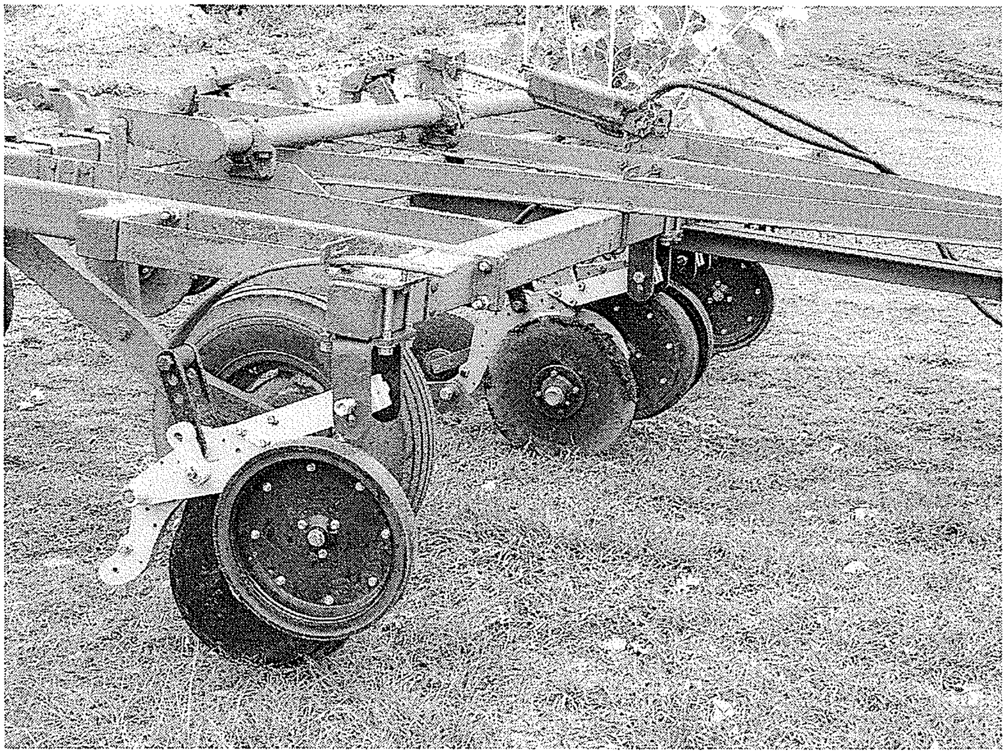
7. FIELD TEST FOR BANDING ANHYDROUS AMMONIA

It would be better, if the second prototype of the opener was used for the field test. However, at the time of the field test, the second prototype had not been fully developed. The field test had to be completed in 2006 as required by the project timeline. Thus, the first prototype was used for the field test. The main purposes of the field test were not only to evaluate the performance of the prototype opener for banding anhydrous ammonia (NH_3), but also to investigate nitrogen retention under different opener configurations. Thus, the use of the first prototype for the field test was not a major concern.

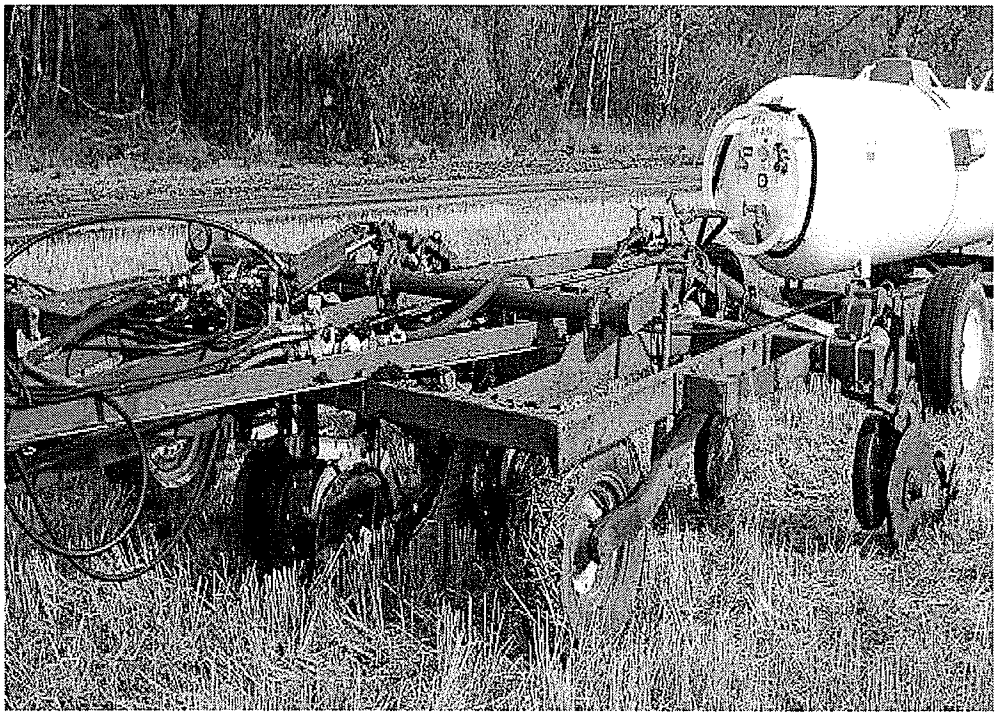
7.1 Material and methods

7.1.1 Construction of fertilizer banding applicator

For banding anhydrous ammonia (NH_3), four of the prototype opener units were fabricated. Those four prototype openers (referred as to leaf spring opener) were mounted in a 4.3-m toolbar (fig. 7.1a) with a tool spacing of 0.4 m. To compare the uniformity of furrow depth of the prototype opener with the Ponik opener, four parallel linkage downforce systems (referred as to parallel linkage opener) were also mounted on the same toolbar. With a fertilizer tank, flow controller, manifold, hoses, and tubes, a field applicator was constructed (fig. 7.1b). A manifold with 16 outlets was used and it was the one with the least number of outlets commercially available. As only eight openers were on the toolbar, the every second outlet of the manifold was blocked for the test. Ammonia was supplied to the openers from the manifold by flexible hoses and 12-mm diameter steel tubes at the delivery end. The ammonia release point was set to 51 mm below the soil surface for all openers.



(a)



(b)

Figure 7.1 The fertilizer applicator; (a) toolbar with the leaf spring openers; (b) toolbar with openers (the first prototype) and fertilizer tank.

7.1.2 Field site description

Field tests were conducted in a farm 35 km north of Oakville, Manitoba, Canada in October 2006. The field had clay soil (clay 43%, silt 50%, and sand 7%) and wheat stubble. The soil was quite wet at the time of field trial. This can be seen from the depth of the rut resulting from the wheel tracks of the applicator (fig. 7.2).

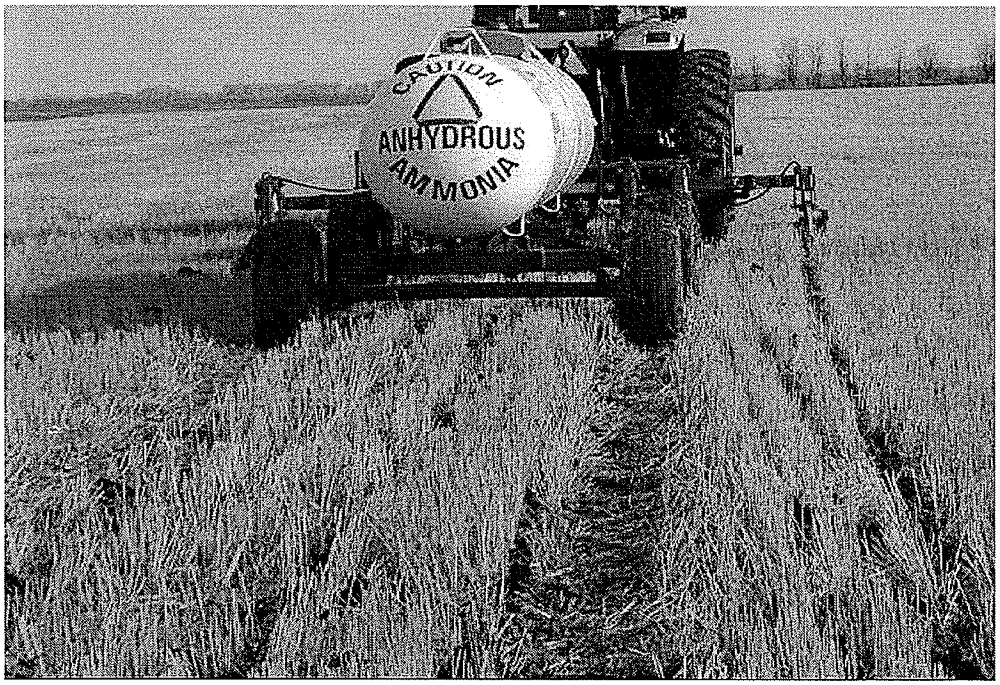


Figure 7.2. Photo showing the fertilizer applicator and field condition at the time of fertilizer banding test.

7.1.3 Experimental design

One purpose of the experiment was to compare the uniformity of the furrow depths between the existing parallel linkage opener and the leaf spring opener. This was achieved through mounting four openers for each type of the two openers on the same tool-bar. Another purpose was to investigate the effects of different opener configurations on the nitrogen retention in soil following the banding operations. This was achieved by a 2x2 factorial experimental design with two disc configurations and two closing wheel configurations. Only the four leaf spring openers were used for this purpose and they had the following configurations:

- single disk with furrow closing wheel (S-W)
- single disc without furrow closing wheel (S-Wt)
- double disk with furrow closing wheel (D-W)
- double disc without furrow closing wheel (D-Wt)

Plots were laid by passing the applicator in the field. Each pass of the applicator created four furrows, representing four treatments. The plot was 152 m long. Each treatment was replicated seven times (i.e. seven passes of the applicator were made). Each furrow was treated as one plot. Plots (treatments) could be randomised by changing the openers' position on the toolbar and changing the NH_3 distribution route from the NH_3 manifold to each opener for every pass. However, for security reasons, this was not done in the field experiment to decrease the chances of contacting with NH_3 when assembling and disassembling the openers and the connection tubes between the manifold and openers. Thus, treatments were not completely randomised. The tractor travel speed (8 km/h) and ammonia application rate (112 kg N/ha) were kept constant for all passes.

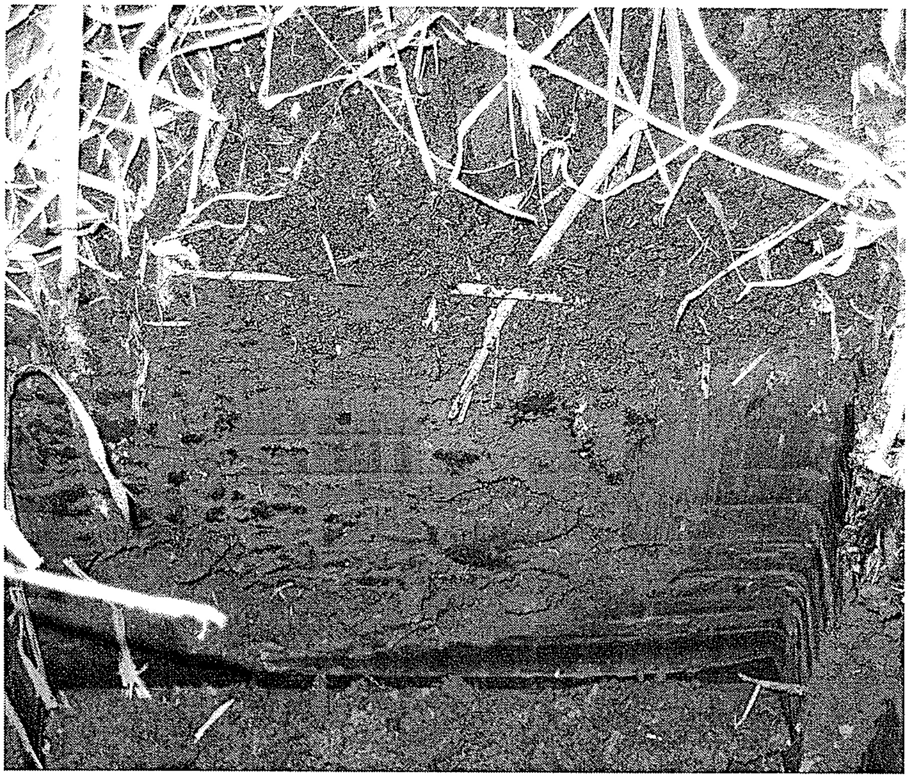
7.1.4 Measurements

Initial soil conditions Before the field fertilizer banding trial, soil cores (50 mm diameter) were taken at six random locations over the entire field at two depth intervals: 0-50 mm and 50-100 mm. Soil samples were weighed, oven-dried at 105 °C for 24 h, and weighed again to determine the soil moisture content and dry bulk density. Soil penetration resistances (cone index) were also measured in these two depth intervals, at six random locations using a Rimik soil cone penetrometer (Model CP 20, Agridy Rimik Pty. Ltd., Australia). The surface residue was collected with a quadrant of one m^2. The quadrant was placed on the soil surface at six random locations in the field. The standing and flat residues confined in the quadrant were collected separately. Residues collected were taken to the laboratory, oven-dried at 60° for 72 h and weighed to determine the dry matter per hectare.

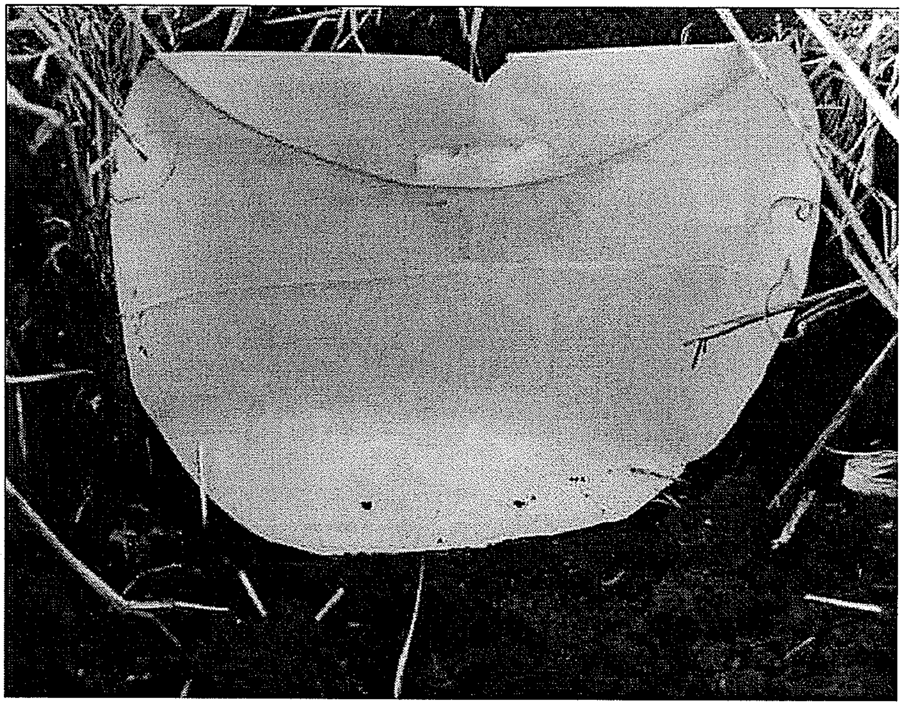
Furrow depth Furrow depths were measured immediately following the banding application. The surface layer of soil accumulated along the furrow edges was removed. A straight edge was laid on the soil surface across the furrow. Approximately 14 measurements were performed along each furrow.

Nitrogen concentration A composite soil sample was made from three monoliths (monolith size: 150 mm deep, 200 mm wide and 50 mm thick) taken from each plot along the centre of the furrow, giving a total of 28 composite samples. Samples were taken approximately six hours after the banding applications. The samples were kept on ice and shipped to the laboratory for analysis. Both NH_3/NH_4^+ and NO_3^- nitrogen concentrations were analyzed as transformation of NH_4^+ to NO_3^- might occur within a short period of time.

NH_3 trace in soil The tracer method used to trace the NH_3 initial distribution zone was based on a previous study by Papendick and Parr (1966). They reported that the distribution patterns of NH_3 in green house pots of moist and air-dry soil after fertilizer injection were well correlated with the resulting pH contour lines. The NH_3 tracing for all treatments was conducted around six hours after banding operations. After taking a soil monolith from the furrow, a smooth vertical wall (200 mm wide and 150 mm high) was left within the soil cross section (fig. 7.3a). A filter paper (220 mm diameter) impregnated with phenol red solution, a pH indicator, was placed on the vertical wall (fig. 7.3b) and kept contact with the soil furrow cross section for about three minutes. A temporary pink area then appeared on the filter paper due to the high pH, indicating that NH_3 had come in the soil solution and reacted to form NH_4^+ ion. To quantify the pink trace, the digital image of the filter paper was quickly taken.



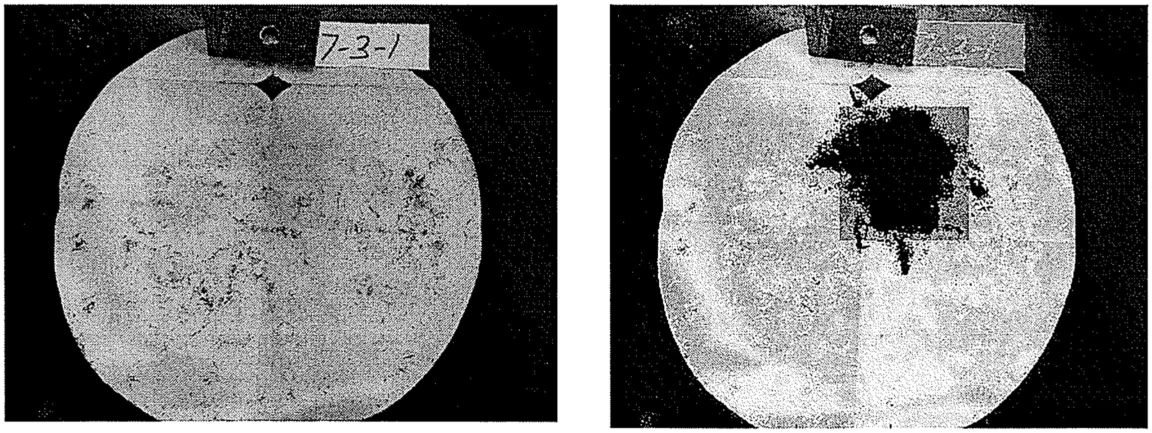
(a)



(b)

Figure.7.3. Ammonia trace measurement; (a) smooth furrow vertical wall after removing soil monolith; (b) filter paper attached onto the soil furrow vertical wall.

The digital images of the filter paper were analyzed and processed using an interactive program written in Matlab R2006 (The Mathworks, Inc., Natick, MA) to extract the NH_3 distribution characteristics. Within the Matlab, each filter paper image (fig. 7.4a) was analyzed first to find the differences between the pink area and other yellow area in terms of the pixel intensity values. A threshold value of pixel intensity was then found and used to isolate and highlight the pink area (fig 7.4b). A rectangular bounding area of the pink trace and its centroid position were calculated by the program. The rectangle was also used to determine the height and width of the NH_3 trace. Width was the horizontal distance measured from the left most edge to the right most edge of the rectangle. Similarly, height was defined as the vertical distance from the top most edge to the down most edge. These characteristics were the useful information reflecting distribution patterns of ammonia under different banding opener configurations.



(a)

(b)

Figure.7.4. Imaging analysis; (a) digital image of the filter paper after tracing; (b) image highlighting the bounding area.

Soil surface disturbance To quantitatively analyze the soil surface disturbance after banding operations, digital pictures (fig.7.5) of the furrows, created by openers with different configurations, were taken. To achieve the soil disturbance information, the same method as analyzing the filter paper digital image was used to find the pixel intensity differences between the soil and the residue within the quadrate area. The surface disturbance was quantified as the percentage of the soil pixels relative to the total pixels. This method may result in higher value than the actual soil disturbance, as residue cover was not 100% before the furrow was created. The soil not covered by residue outside the furrow was also counted in the image analysis.

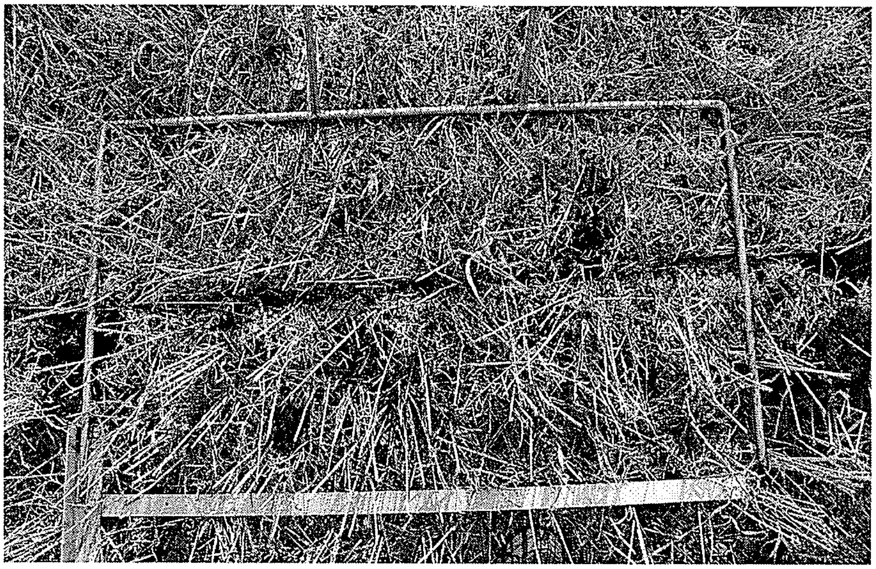


Figure 7.5 Digital image taken for furrow surface disturbance analysis.

7.1.5 Data analysis

Analyses of variance were performed on the data to examine the significance of main effects of experimental factors and their interaction effects. It was found that interaction effects were significant in most cases. Thus, the simple effects were presented in the following sections. Duncan's multiple range tests were used to detect differences among means. A significance level of 0.05 was applied to all data analysis.

7.2 Results and discussion

7.2.1 Field conditions

Both the standing residue (915 kg/ha) and flat residue (807 kg/ha) were heavy. At the time of the fertilizer banding test, the soil had a moisture content of 33% in a dry basis, which was wet for field operations. Although the field had not been tilled at the time of the test, the soil was quite loose, indicated by its dry bulk density (0.9 Mg/m^3) and cone index (1.5 MPa).

7.2.2 Comparisons of the leaf spring and parallel linkage openers

A large number of measurements on furrow depth were made during the field test. A total of 393 data points were taken for the cutting depth of the leaf spring opener and a total of 245 were taken for the parallel linkage opener. The average cutting depth of the leaf spring openers was 65 mm with a standard deviation of 15 mm, and that of the parallel arm linkage openers was 63 mm with a standard deviation of 14 mm. These values indicate that two openers were operated at similar depths. The standard deviation of seeding depth was more interesting to the opener design as it reflects the downforce change while working in field conditions. The standard deviation data indicated that the two openers performed similarly, in terms of maintaining the uniformity of cutting depth.

7.2.3 Comparisons of opener configurations on banding performance

Soil surface disturbance In general, the soil surface disturbance was very low for all opener configurations as shown in figure 7.6, although the soil was wet. The data from the image analysis showed that the single disc without closing wheel (S-Wt) caused the least soil disturbance (5.6%) (fig. 7.7), and the other treatments caused over 10% soil disturbance. The double-disk opener configurations, in general, gave higher soil disturbance than the single-disk ones. However, there were no significant differences in soil disturbance among the opener configurations.

Figure 7.6. Photo showing surface disturbance after application.

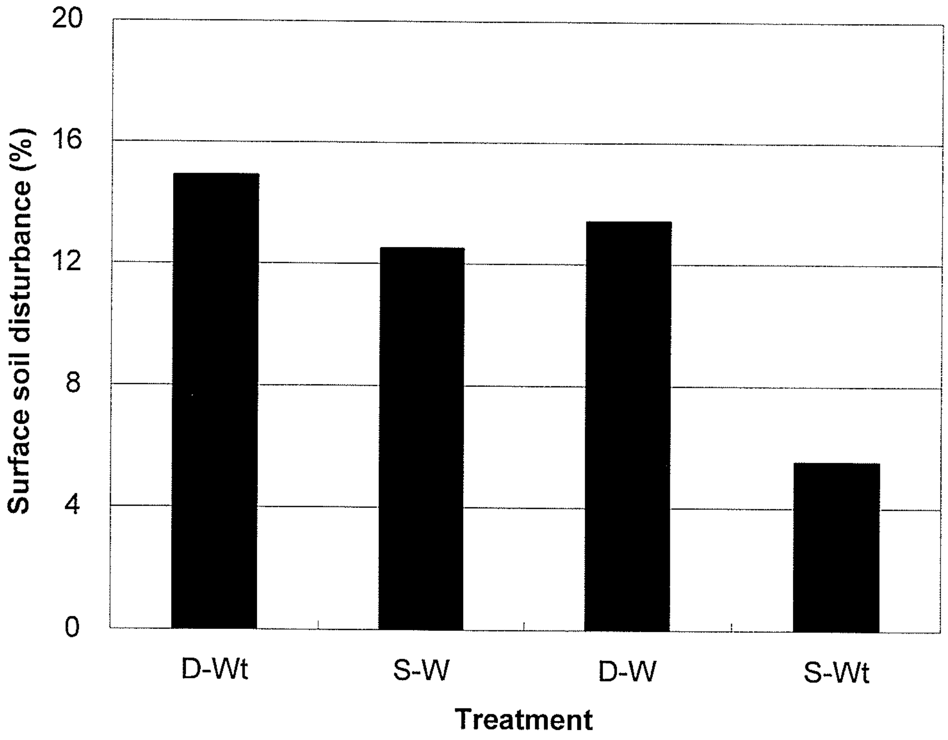


Figure. 7.7. Soil surface disturbance from different opener configurations; S-W = single disk with furrow closing wheel; S-Wt = single disc without furrow closing wheel; D-W = double disk with furrow closing wheel; D-Wt = double disc without furrow closing wheel.

Nitrogen concentration Significant differences in all forms of nitrogen concentrations were found among the treatments (fig. 7.8). The double-disk opener without press wheel (D-Wt) had the highest total nitrogen concentration (80.5 μg/g). On the contrary, the single-disk opener without press wheel (S-Wt) had the lowest total nitrogen concentration (49.3 μg/g). The other two treatments were intermediate. The similar trends were true for the treatment effects on ammonium nitrogen and nitrate nitrogen. The best performance of the D-Wt treatment could be attributable to a number of facts that the double-disk opener created more micro soil pores, which helped the NH_3/NH_4^+ retention and distribution; that the NH_3 release point between the double disks was well protected from being exposed to the faster air flow outside the disks, which reduced the NH_3 losses during the banding; Without having furrow closing wheel had advantages in the wet soil condition.

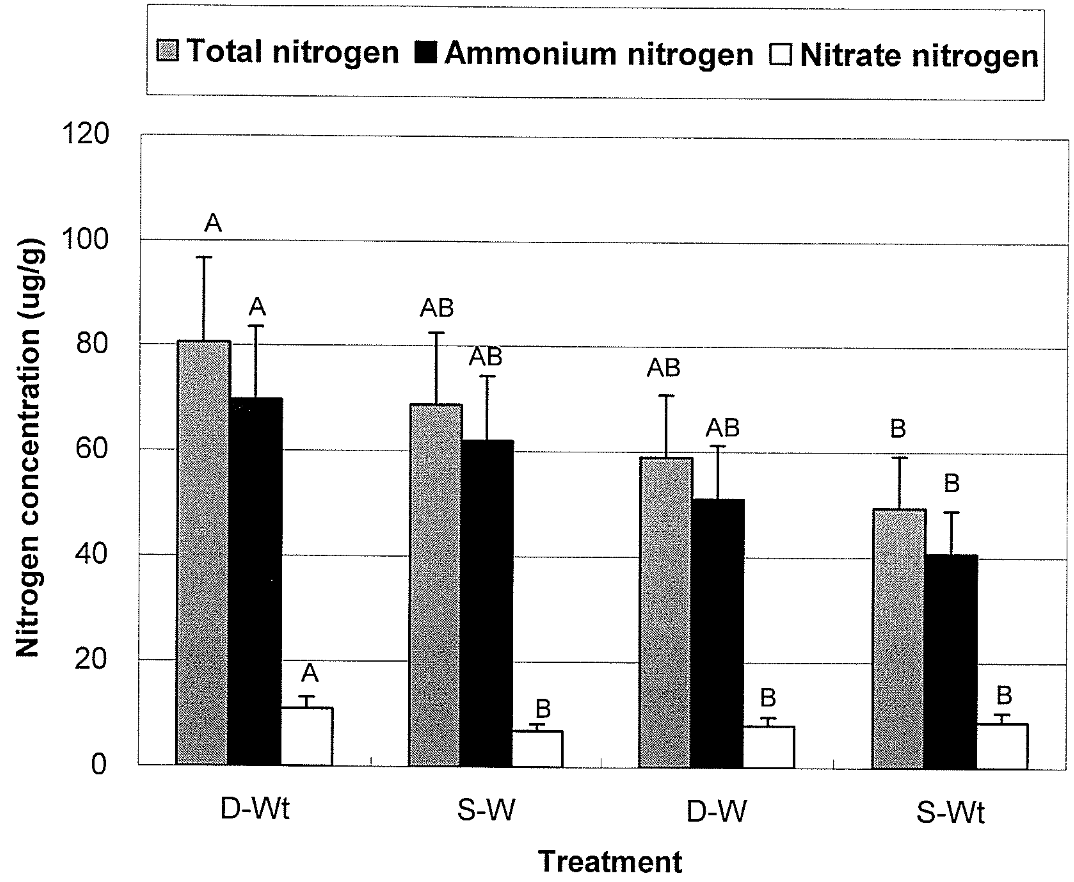


Fig. 7.8. Total-N, ammonium-N, nitrate-N comparisons for four treatments; S-W = single disk with furrow closing wheel; S-Wt = single disc without furrow closing wheel; D-W = double disk with furrow closing wheel; D-Wt = double disc without furrow closing wheel. Bars followed by the same letter are not statistically different within each form of nitrogen.

$NH_3/NH4^+$ trace Significant differences in the area of NH_3/NH_4^+ trace (fig. 7.9). The treatment of single-disk opener without furrow closing wheel (S-Wt) had the significantly lower values than the other treatments. The greatest area (4607 mm^2) was found for the double-disk without press wheel (D-Wt) treatment. However, this value was not statistically different from those of the S-W and D-W treatments.

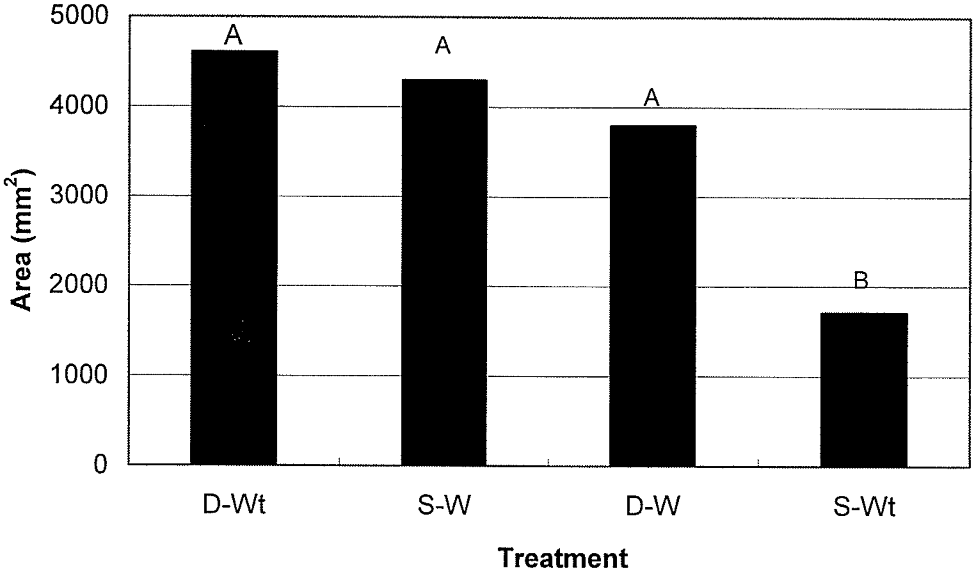


Fig. 7.9. Area of NH_3/NH_4^+ trace in soil for four treatments; S-W = single disk with furrow closing wheel; S-Wt = single disk without furrow closing wheel; D-W = double disk with furrow closing wheel; D-Wt = double disk without furrow closing wheel. Bars followed by the same letter are not statistically different.

Similar to the results of the area, the S-Wt resulted in the smaller height and width of NH_3/NH_4^+ trace than the other treatments (fig. 7.10). Ammonia spread in soil over height up to 100 mm, which was beyond the furrow depths. The width of NH_3/NH_4^+ trace in soil can be used to assess the uniformity of nitrogen distribution in soil and to make decisions on the selection of opener spacing on the toolbar.

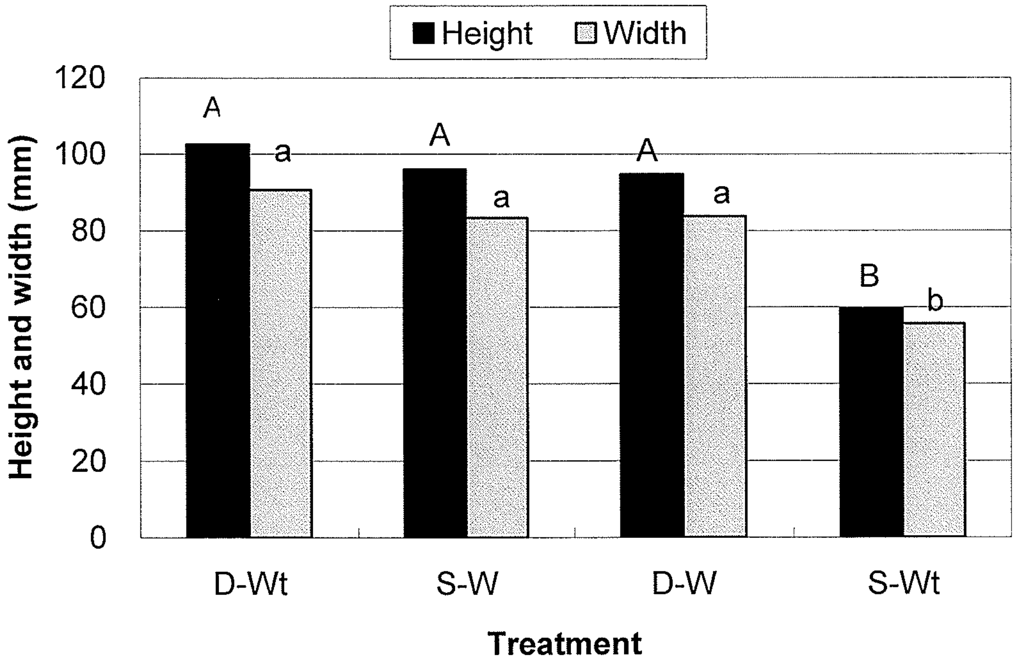


Figure 7.10. Width and height of the NH_3/NH_4^+ trace in soil for four treatments; S-W = single disk with furrow closing wheel; S-Wt = single disk without furrow closing wheel; D-W = double disk with furrow closing wheel; D-Wt = double disk without furrow closing wheel. Bars followed by the same letter are not statistically different within each variable measured.

As the vertical position of the centroid of NH_3/NH_4^+ trace zone is relative to the centre of the furrow surface, it could be presumed that NH_3 distributed radially outwards from the centroid. This information has implication to one-pass side banding system. Seeds and NH_3 should be kept at a proper distance to avoid the toxicity and at the same time to ensure enough fertilizer supply.

The D-Wt and S-W treatments (fig. 7.11) had an average centroid point of 52 mm, which was closer to the NH_3 release point (51 mm below furrow for all treatments). The main reasons for the relatively low centroid position of the other two treatments might be related to the average furrow depths (fig. 7.12), which were 57 mm and 62 mm, respectively. The other two treatments had greater banding depths (71 mm and 70 mm). Therefore, it is reasonable to believe that the centroid of NH_3/NH_4^+ trace zone was related to the furrow depth when other conditions, such as NH_3 release point, NH_3 application rate and soil conditions, were very similar.

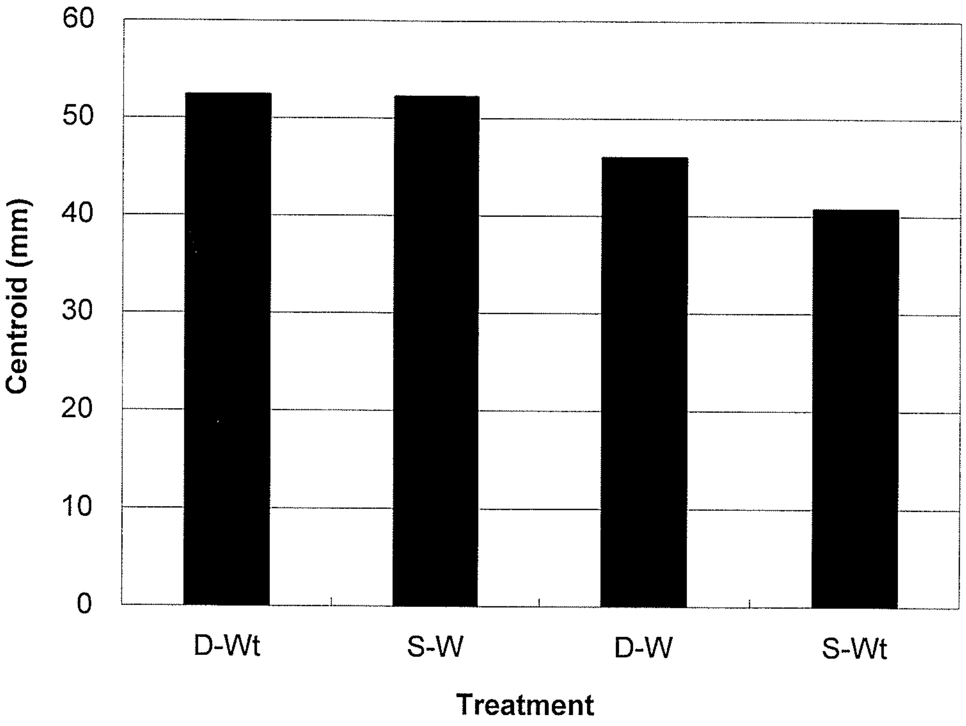


Figure. 7.11. Vertical position of the centroid of NH_3/NH_4^+ trace zone for different opener configurations; S-W = single disk with furrow closing wheel; S-Wt = single disc without furrow closing wheel; D-W = double disk with furrow closing wheel; D-Wt = double disc without furrow closing wheel.

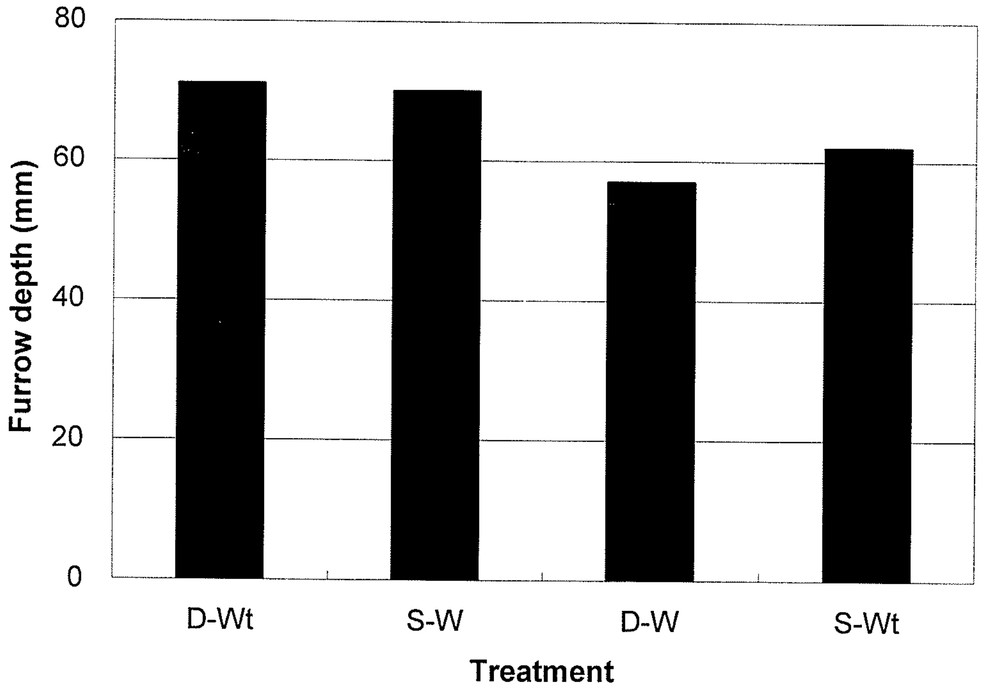


Figure. 7.12. Furrow depths from different opener configurations; S-W = single disk with furrow closing wheel; S-Wt = single disk without furrow closing wheel; D-W = double disk with furrow closing wheel; D-Wt = double disk without furrow closing wheel.

Correlations between NH_3/NH_4^+ trace and NH_3/NH_4^+ concentration

Data of NH_3/NH_4^+ nitrogen concentration and NH_3/NH_4^+ distribution area were highly correlated (correlation coefficient: 0.92). This showed that the tracer method was feasible to assess nitrogen retention in soil. However, it is more of a qualitative indicator of nitrogen in soil. For quantitative assessment, soil nitrogen concentration is a better indicator.

8. CONCLUSIONS

The development of the low-disturbance and low-cost fertilizer banding opener was successful. The double leaf spring downforce system could reduce the cost significantly as compared to the existing parallel linkage downforce system. The leaf spring downforce system worked as effective as the parallel linkage downforce system in terms of average soil cutting depth (65 mm vs.63 mm) and furrow depth variations (15 mm vs. 14 mm).

Through the optimisation, the major factors affecting the downforce changes were optimised, including the spring rate, spring chord length, and the shackle length. The lab test results showed that the interaction effect of the spring chord length and the shackle length was significant. The best combination with the spring chord length (920 mm) and the shackle length (180 mm) had downforce change of only 8% when simulating the field surface elevation change of 50 mm above or below the normal field surface. This best combination was corresponding to the biggest shackle angle. The lab test results were in agreement with the optimization results. The method used to optimise the leaf spring downforce system was feasible.

Soil surface disturbance (varying from 5.6% to 14.9%) in the field experiment was very low for all the opener configurations. The double-disk opener without furrow closing wheel resulted in the highest total nitrogen concentration (80.5 μg/g). The trace area, width, and height of NH_3/NH_4^+ in soil for the single-disk opener without closing wheel were smaller than the other opener configurations. Close correlation ($R^2 = 0.92$) was found between the NH_3/NH_4^+ nitrogen concentration and the NH_3/NH_4^+ trace area, which showed that the NH_3 tracing method was effective in qualifying the NH_3/NH_4^+ initial distribution pattern following banding operations.

The field results imply that that if the double-disk opener is used then the furrow closing wheel may not be necessary. If the single-disk is utilized for banding NH_3, the furrow closing wheel should be equipped. The total cost for the two opener configurations would be similar. The conclusions from this study were from only one field test and may be applicable only for the specific soil conditions similar to those of this research. Also, treatments were not completely randomised in the field experiment. Further field tests are needed to confirm the results. Therefore, care should be given when using the results.

Recommendations for future research

Static measurements on opener downforce change have certain limitations since the opener travel speed during field operations also has effects on the downforce changes. To better simulate the opener downforce changes during field operations, further dynamic tests on the leaf spring downforce system of the second opener prototype is recommended. Transducers embedded into soil could be used to monitor downforce changes and the response efficiency of the leaf spring downforce systems.

The function of the gauge wheel was usually described qualitatively in the past. Further improvement on the leaf spring downforce system could be conducted on the interaction mechanism with the depth control gauge wheel. The quantitative study on the soil reaction forces on the gauge wheel is necessary and the result of which can help further improve the leaf spring downforce system.

For leaf spring downforce system, stop mechanism should used in the shackle to avoid the deflection of the leaf spring exceeding its elastic limitations. Although the bigger shackle angle gave lower downforce changes, shackle angle has to be set with enough space for its rotation before stop mechanism contacting with the opener arm, which will make the shackle's function useless.

To achieve a better understanding of the accurate relationship between the opener configurations and the initial NH_3 retention and distribution following banding operations, additional field research under various soil conditions is required. Different soil conditions will allow most of the ammonia losses resulting from soil properties to occur and then the losses related to the banding opener configurations will be found. Furrow closing wheels have a significant effect on NH_3 fertilizer banding result. Further research on different types of closing wheels is required.

The tracer method used to trace the initial distribution zone of NH_3/NH_4^+ is recommended to be used in mid row banding operation, the result of which can verify the row spacing settings, the seed fertilizer separation, and the nutrient availability to seeds. This method will be more effective if the tracing measurement can be conducted at a consecutive period after seeding since the distribution of the NH_3/NH_4^+ and the seed-fertilizer relative placement are changing with time. This is possible because the filter paper used in the tracing method can be reused many times, which can save the research costs significantly.

9. REFERENCES

Anderson et al. 2005. Investigation into placement of anhydrous ammonia and urea with seed. Available at: http://www1.agric.gov.ab.ca/$Department/deptdocs.nsf/all/eng9950. Accessed on 5 April 2007.

ASAE Standards. 2005. Ep 291.3. Terminology and definitions for soil tillage and soil-tool relationships. Approved Feb. 2005. St. Joseph, Mich.: ASAE.

Baker, J.H., M. Peech, and R.B. Musgrave. 1959. Determination of application losses of anhydrous ammonia. *Agron.J.* 51(6): 361-362.

Blue, W.G., and C.F. Eno. 1954. Distribution and retention of anhydrous ammonia in sandy soils. *Soil Sci. Soc. Am. Proc.* 18(4): 420-424.

CCC (Canola Council of Canada). 2005. Nitrogen fertilizer management for canola. Available at: www.canola-council.org/nitromgmt.aspx Accessed on 13 April 2007.

Deep till automatic reset. Why deep tilling works? Available at: www.tebbenenterprises.com. Accessed on 5 April 2007.

Doan, V., Y. Chen and B. Irvine. 2005. Seeding performance of no-till openers: Part 1 – Various residue types. *Canadian Biosystems Engineering* 47: 2.29-2.35.

Erbach, D.C., J.E. Morrison, Jr., and D.Wilkins. 1983. Equipment modification and innovation for conservation tillage. *J.Soil Water Conser*v. 38(3): 182-185.

Fink, J.T. and H.D. Currence. 1995. No-till drill adjustable seed furrow openers. *Applied Engineering in Agriculture* 11(6): 811-816.

Gratton, J., Y. Chen and S. Tessier. 2003. Design of a spring loaded downforce system for a no-till seed opener. *Canadian Biosystems Engineering* 45: 2.29-2.35.

Hanna, H.M., P.M. Boyd, J.L. Baker, and T.S. Colvin. 2004. Anhydrous ammonia application losses using single-disc and knife fertilizer injectors. *Applied Eng. in Agric.* 21(4): 573-578.

Hnatowich, G.L. 1994. Anhydrous ammonia and seeding in a single pass system, SSCC, Saskatchewan Soil Conservation Association. Availabe at: www.sscc.ca. Accessed on 9 June 2006.

Hoeft, R.G. and T.R. Peck. 1991. Soil testing and fertility. Illinois Agronomy Hanbook, Circular 1311, University of Illinois, Urbana-Champaign, IL, USA.

Kushwaha, R.L., A.S. Vaishnav and G.C.Zoerb. 1986. Soil bin evaluation of disc coulters under no-till crop residue conditions. *Transactions of the ASAE* 29 (1): 40-44.

Lawrence, T. and F.B. Dyck. 1990. A comparison of two furrow opener-depth control assemblies for seeding forage grasses. *Journal of Range Management* 43(1): 82-83.

Matus, A., F. Walley, G. Hnatowich, C. Kessel and J.D. Knight, 1999. Use of anhydrous ammonia in single-pass seeding operations of spring wheat at varied landscape positions. *Agron.J.* 91: 969-974.

MNZTFA (Manitoba-North Dakota Zero Tillage Farmers Association). 1998. *Zero tillage.* Brandon, Manitoba, Canada: Leech Printing Ltd.

MNZTFA (Manitoba-North Dakota Zero Tillage Farmers Association). 2000. *Zero tillage.* Brandon, Manitoba, Canada: Leech Printing Ltd.

Morrison, J.E. 1988a. Interactive planter depth control and pneumatic downpressure system. *Transactions of the ASAE* 31(1): 14-18.

Morrison, J.E. 1988b. Hydraulic downpressure system performance for conservation planting machines. *Transactions of the ASAE* 31(1): 19-23.

PAMI (Prairie Agriculture Machinery Institute). 2003. An agronomic comparison of mid row banding and side banding systems. Evaluation report 761. Prairie Agricultural Machinery Institute. P.O. Box 1060, Portage la Prairie, MB, Canada.

Papendick, R.I., and J.F. Parr. 1965. Retention of anhydrous ammonia by soil: I. Methodology and experimental considerations. *Soil Sci.* 100(3): 182-191.

Parr, J.F., and R.I. Papendick. 1966a. Retention of anhydrous ammonia by soil. II. Effect of ammonia concentration and soil moisture. *Soil Sci.* 101(2): 109-119.

Papendick, R.I., and J.F. Parr. 1966b. Retention of anhydrous ammonia by soil. III. Dispensing apparatus and resulting ammonia distribution. *Soil Sci.* 102(3): 193-201.

Rettig V., R. Steilen and J. Postal. 1989. Compact shank assembly with leaf spring: Canadian Patent No.1304976. U.S. Patent No. 4800964.

SAE (Society of Automotive Engineers).1990. *Spring design manual.* Warrendale, PA:.Society of Automotive Engineers, Inc.

SCCC. 2004. Disc-type applicator gives producers another fertilizer option, Soil

Conservation Council Council of Canada. Available at: www.soilcc.ca. Accessed on15 June, 2006.

Schaaf, D.E., S. Hann and B. Rogers. 1979. The development of performance data on seed drill furrow openers. ASAE Paper No. 791016. St. Joseph, MI: ASAE.

Siekmeier D. 1976. Independent and biased cultivator support: Canadian Patent No.1002807.

SSCA (Saskatchewan Soil Conservation Association). 2005. Seeding factors in direct seeding. Available at: www.ssca.ca/agronomics/equipment/index.html. Accessed on 25 February 2007.

SSCA (Saskatchewan Soil Conservation Association). 2007. Economics of Direct Seeding. Available at: www.ssca.ca/agronomics/economics/index.html. Accessed on 25 February 2007.

Stanley, F. A. and G. E. Smith. 1956. Effect of soil moisture and depth of application on retention of anhydrous ammonia. *Soil Sci. Soc. Am. Proc.* 20(4): 557-561.

Tessier, S., K.E. Saxton, R.I. Papendick and G.M. Hyde. 1991a. Zero tillage furrow opener effects on seed environment and wheat emergence. *Soil and Tillage Research* 21(3-4): 347-360.

Veseth, R.J. and R.S. Karow. 1999. Direct seeding or no-till – What's the difference? Pacific Northwest Conservation Tillage Handbook Series No. 23, Chapter 2. Available at: www.pnwsteep.wsu.edu/. Accessed on 5 May 2007.