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Prototype twin vacuum disk metering unit for improved seed spacing uniformity performance at high forward speeds*

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Abstract: The objective of this study was to design and develop a prototype twin vacuum disk metering unit so that seeding can be achieved at higher forward speeds while reducing the peripheral speed of the vacuum disk for improved seed spacing uniformity performance and increased field work capacity. In order to meet this objective, a new precision seeding unit with twin vacuum disks, each being a mirrored view of the other and geometrically the same, was designed in animated drafting software and then it was manufactured and used for the laboratory experiments. Three crop seeds were used to determine the performance of the new metering unit in the lab on a sticky belt test stand. Two alternative measures were used to quantify the seed spacing accuracy, and polynomial functions using the principles of response surface methodology were developed to calculate the optimum level of the variables. The tests performed in the laboratory at 2, 3, and 4 ms^{-1} forward speeds resulted in improved seed spacing accuracy values, while the quality of feed index measure went down once the forward speed increased from 2 to 4 ms^{-1}. The quality of feed index with the new metering unit was obtained to be 100% at 2 ms^{-1}, while it was almost 98% for all crop seeds at 3 ms^{-1}. The forward speed of 4 ms^{-1} resulted in quality of feed index values of 92%, 96%, and 96% for cotton, sunflower, and corn seeds, respectively.

Key words: Design, optimization, response surface methodology, precision metering unit, vacuum, hole diameter

1. Introduction

Agricultural machinery-related operations are required to be achieved at the highest field work capacity while the performance is at the desired level. The field work capacity for any operation can be maximized if the operation is achieved at high forward speeds for a machine with a specific operating width. Precision seeding, like many field operations, should be conducted in such a way that the seed spacing accuracy falls into the accepted level. As a result of accurately incorporating seeds into the soil, competition among plants for receiving moisture and nutrient should be avoided.

Previous studies have demonstrated that 3 factors mainly contribute to the performance of a vacuum type metering unit. One of the factors is the peripheral speed of the vacuum disk as it is associated with the forward speed of the planter, while the other 2 factors are the vacuum applied on the vacuum disk and the hole diameter (Yazgi and Degirmencioglu, 2007). Staggenborg et al. (1999) studied the effect of planter speed and seed firmers on corn stand establishment and a randomized complete block experiment was conducted for this purpose. The performance of the planter was evaluated based on the mean plant spacing, standard deviation in spacing, and four indices (miss, multiple, quality of feed, and precision). The main conclusion from their study was that increased corn seeding speed adversely affected plant spacing uniformity performance.

Studies on the performance of precision seeders mostly focused on the vacuum pressure applied to the vacuum disk, the most common metering system in precision seeders. In one study, Singh et al. (2005) studied the effect of the operational speed of the vacuum disk, vacuum pressure, and shape of the entry of seed hole on performance-related measures. These measures were miss index, multiple index, and quality of feed index. They used a vacuum disk with holes at 2.5 mm diameter for cotton seeds and found that the metering system with a speed of 0.42 m s^{-1} and a vacuum pressure of 2 kPa produced superior results with a quality of feed index of 94.7% and a coefficient of variation of 8.6% in seed spacing. In another study, Panning et al. (2000) focused on five seeders that

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* Patent pending (Turkish Patent and Trademark Office, Application Number: 2015/15817)

** Correspondence: adnan.degirmencioglu@ege.edu.tr were different in terms of configuration for seed spacing uniformity, and they carried out experiments at 3 field speeds using a seed location method in the field and a laboratory method involving an optoelectronic sensor system.

Moody et al. (2003) tested the performance of a row crop seeder in the field at 3 seed meter rotational speeds of 0.16, 0.23 and 0.31 rev s^{-1} with corresponding forward speeds of 4.8, 7.2 and 9.7 km h^{-1} using cotton seeds. They concluded that the seed spacing variability increased with increased peripheral speed, while the quality of feed indices ranged between 76.2% and 91.4%.

In order to overcome the reduced seed spacing accuracy at high seeding speeds, as it corresponds with the peripheral speed of the vacuum disk, and achieve desired seed spacing, the peripheral speed of the vacuum disk should be reduced, which can be achieved by either increasing the seed spacing or increasing the number of holes on the vacuum disk. Seed spacing for different row crops varies based on the crop in order to obtain an optimal plant population per unit area. Hence, the most obvious solution to increase the seeding rate and decrease the peripheral speed of the vacuum disk is to increase the number of holes on the vacuum disk. However, the number of holes on a vacuum disk can only be increased to a certain limit before this may result in a vacuum band around the holes, which causes a significant reduction in the seeding performance due to increased multiple seeds held by single holes (Önal et al., 2012). Another option to reduce the peripheral speed of the vacuum disk is to use twin vacuum disks that oppose each other, so that the seeds released by one of the disks are placed in between the ones released by the other one. The addition of a second seed disk reduces the rotational speed of a single seed vacuum disk while increasing the overall per row seeding rate when compared to a single vacuum disk. Therefore, a study was conducted and the objective of this study was to design and develop a prototype precision metering unit with twin vacuum disks, so that seeding could be achieved at higher forward speeds to improve the seed spacing uniformity performance and to increase field work capacity.

1.1. Design of a prototype precision metering unit with twin vacuum disks

The vacuum type precision seeder performance in terms of seed incorporation into the soil could be viewed in 2 parts. The first one is the metering unit performance and the second one is the rolling and bouncing of seeds on the soil surface due to forward speed and impact angle of the seed. The metering unit performances are usually determined in the laboratory, while obtaining the overall performance of a seeder requires field tests.

The study conducted in the laboratory by Yazgı and Değirmencioğlu (2016) indicated that an average forward speed of 1 ms^{-1} is the speed at which seed spacing accuracy for corn, cotton, and sunflower can reach a maximum level. Based on this finding, a new approach was realized to reduce the peripheral speed of the vacuum disk while achieving the desired seed spacing. This new approach was assumed to be the solution to the problem, since using twin disks in order to obtain the same theoretical seed spacing would reduce the peripheral meter speed to half as compared to a single vacuum disk with the same number of holes on the disk. Since each disk releases seeds at two times greater spacing than the theoretical seed spacing, it means that seeds from one vacuum disk are placed in between the seeds released by the other vacuum disk. This approach is depicted in Figure 1.

In order to create a twin vacuum disk metering system, a new vacuum type metering system was designed in computer animated drafting software, and then it was manufactured. The technical dimensions (in mm) and the view of the left metering unit only (in the direction of travel) are depicted in Figures 2–5, since the left and right metering units are mirrored versions of each other and geometrically the same. Each metering unit is in a compact form, includes a seed box in it, and has a volume of 412 cm^3. The metering units were made of aluminum and manufactured on a CNC lathe by a private company.

2. Materials and methods

Three different crop seeds (corn, cotton, and sunflower) were used for the laboratory experiments in order to test the performance of the new metering system. The physical properties of the seeds are given in Table 1.

A sticky belt stand was used to evaluate the performance of the seeder for the tests performed in the laboratory. The

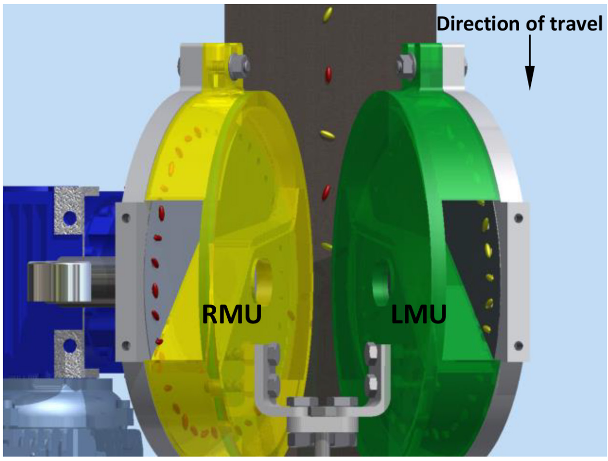

Figure 1. Top view of the twin disk metering unit showing the conceptual approach for dropping seeds intermittently and equidistantly (RMU and LMU: right and left metering unit).

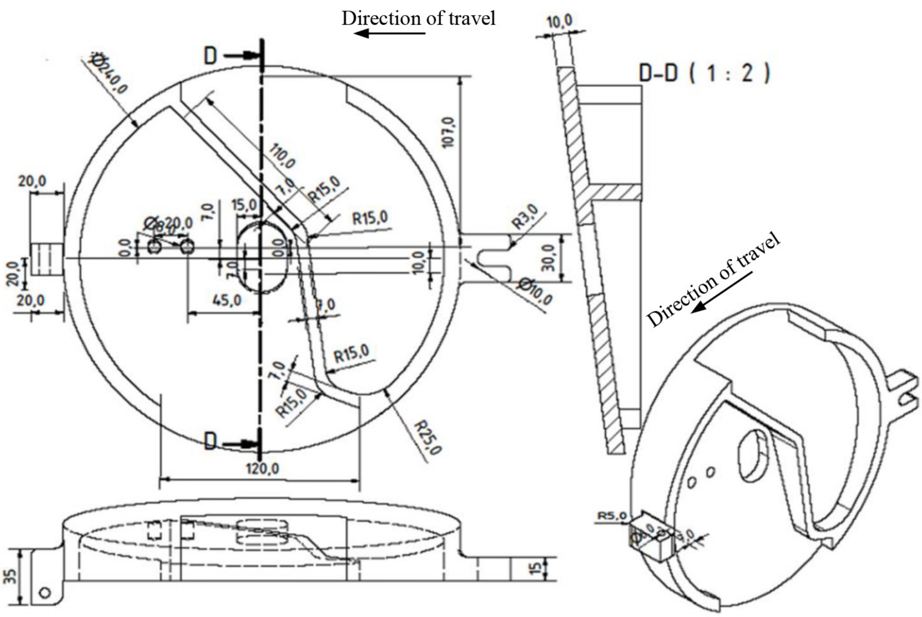

Figure 2. Technical dimensions and view of the right side metering unit in the direction of travel (dimensions are in mm).

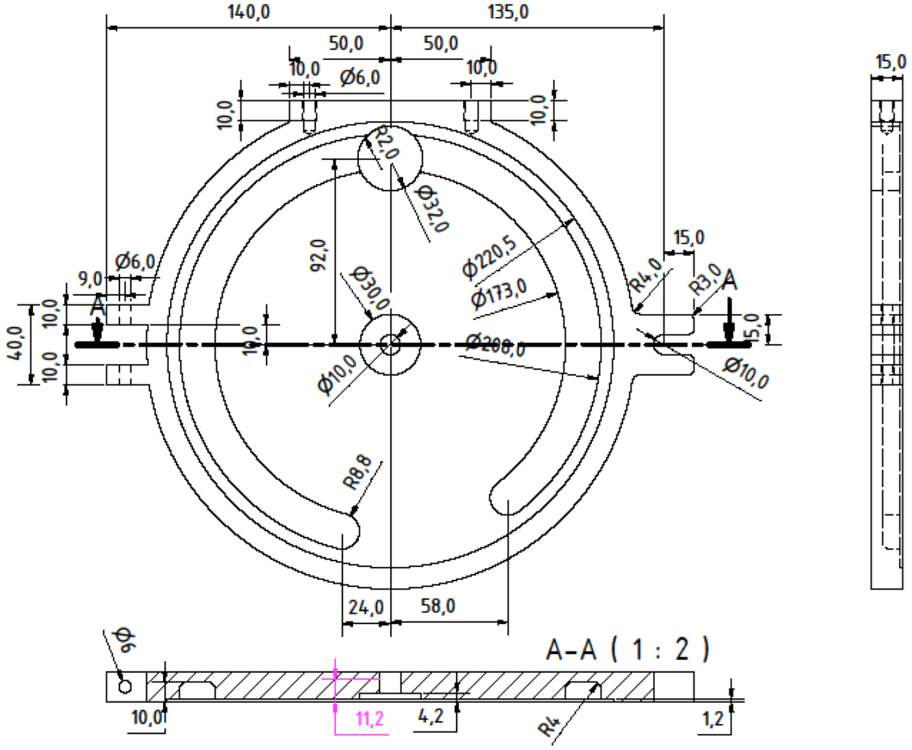

Figure 3. Technical dimensions and view of the lid for right side metering unit (dimensions are in mm).

belt was 15 m long and 14 cm wide. The measurement of the seed distances was carried out at a distance of approximately 10 m. The vacuum type metering unit with twin disks was mounted on a special test stand as shown in Figure 6. Each vacuum disk with 36 holes was rotated about 5° from the vertical direction, so that the seeds

Figure 4. Manufactured view of the right side metering unit in the direction of travel.

Figure 5. Manufactured view of the lid for right side metering unit in the direction of travel.

could be placed in the same line and driven by an electric motor. The disks were coupled by a stiff coupling made of polyurethane in such a way that the holes of one of the vacuum disks were offset by the other disk, so that the seeds released from one disk could be placed in between the seeds released by the other one. The necessary vacuum at different levels was provided by the fan of a separate unit driven by the power take-off of the tractor. The grease belt was driven separately and special care was taken to provide synchronization of the forward speed associated with the peripheral speed of the vacuum disk and belt speed. Prior to each experiment, the seed box was refilled and made full of seeds, even though the seed box volume was more than enough to carry out a certain number of experiments.

Each vacuum disk was set to provide a seed spacing of 23.6 cm so that the desired theoretical seed spacing (Z_t) of 11.8 cm could be achieved for all of the seeds used in the study. In order to facilitate this study, the seed spacing measurements and evaluations were performed using a computerized measurement system on a sticky belt test stand (Önal and Önal, 2009). In order to determine how the prototype metering unit would perform under different seeding conditions in the laboratory, different measures of accuracy in seed spacing were considered and evaluated based on different indices in this study. One of the indices is the one defined by Kachman and Smith (1995). Three different seed spacing groups according to Z_t are classified, and these 3 indices are defined as:

I. The quality of feed index (I_{qf}) indicates the percentages of single seed drops in the range of $>0.5\ Z_t$ to $\leq 1.5\ Z_t$.

II. The multiple index (I_{mult}) indicates the percentage of multiple seed drops (0 to $\leq 0.5\ Z_t$).

III. The miss index (I_{miss}) indicates the percentage of missed seed locations or "skips" ($>1.5\ Z_t$).

Another performance measure was the one called root-mean-square deviation (E_{rms}) from the theoretical seed spacing as proposed by Yazgi and Degirmencioglu (2007). The functions to be developed based on this criterion are considered to be penalty functions, since any deviation from the theoretical seed spacing is penalized. This definition is given below.

$$E_{rms} = \sqrt{\frac{\sum_{i=1}^{N} (Z - Z_t)^2}{N}} \tag{1}$$

Table 1. Physical properties of the seeds used in the study.

Seed	Length (a; mm)	Width (b; mm)	Thickness (c; mm)	Sphericity$^{£}$ (%)	Thousand-seed mass (g)	Bulk density (kg m^{-3})
Corn	11.3 (0.46)	6.9 (0.43)	3.8 (0.32)	59.0 (2.00)	251.3 (2.55)	805.9 (4.7)
Cotton	8.7 (0.52)	4.8 (0.32)	4.24 (0.28)	65.0 (3.00)	91.9 (0.25)	593.6 (5.6)
Sunflower	11.9 (0.48)	6.2 (0.44)	5.9 (0.27)	54.0 (2.00)	83.2 (1.01)	424.1 (1.3)

Numbers in parentheses are the standard deviations. Sphericity was calculated as $£ = (abc)^{1/3}/a$.

Here, Z_t is the theoretical seed spacing, Z is the measured seed spacing, and N is the number of measurements.

The performance criterion as indicated in ISO 7256/1-1984(E), namely "precision", was also evaluated along with the abovementioned indices in this study (ISO, 1984). The precision is the coefficient of variation of the seed spacings measured as singles.

As a statistical and mathematical technique, response surface methodology (RSM) was employed in this study as it was used by Yazgi and Degirmencioglu (2007) in order to develop the performance functions and to optimize the constructional-related variable (hole diameter) and the operating-related variables (peripheral speed of the vacuum disk and vacuum pressure) for each seed separately.

Central composite design, one of the designs in RSM, was selected to study the abovementioned variables, and based on this design 5 levels for each independent variable were considered. These levels were coded as −1.682, −1, 0 (center point), +1, and +1.682, respectively (Box and Draper, 1987).

The coded and uncoded levels of the variables are given in Tables 2–4, while the experimental designs for corn, cotton, and sunflower seeds are tabulated in Tables 5–7, respectively. A total of 20 experiments for each seed were carried out as seen from the tables. Each experiment (run) was triplicated and each replication included a total of approximately 60 seed spacings.

3. Results and discussion

The results obtained from the experiments are given in Tables 8–10, for corn, cotton, and sunflower seeds, respectively.

Once the results of the experiments are examined from the point of view of performance indices, it can be stated that the performance indices at the center of the central composite design resulted in the highest quality of feed index values for all crop seeds, except in two cases for cotton. The quality of feed index for corn ranged between 88.9% and 100% while precision (%) and E_{rms} (cm) values showed parallel changes with the quality of feed index. The practical upper limit of precision is 29% (Kachman and Smith, 1995) and, as seen from Table 8, the precision values are mostly at

Table 2. Coded and uncoded levels of the peripheral speed (X_1) of the vacuum disk for all seeds.

Seed	Step value (ms^{-1})	Coded level of the peripheral speed (X_1)				
		−1.682	−1	0	1	1.682
For all seeds	0.028	0.036 (0.52)	0.056 (0.8)	0.084 (1.2)	0.112 (1.6)	0.131 (1.87)

Numbers in parentheses are the forward speeds (ms^{-1}) corresponding to the peripheral speed of the vacuum disk (ms^{-1}).

Table 3. Coded and uncoded levels of the hole diameter (X_2) used in the study.

Seed	Step value (mm)	Coded level of hole diameter (X_2)				
		−1.682	−1	0	1	1.682
Corn	1.0	2.318	3.0	4.0	5.0	5.682
Cotton	0.5	1.660	2.0	2.5	3.0	3.340
Sunflower	0.5	1.159	1.5	2.0	2.5	2.841

Table 4. Coded and uncoded levels of the vacuum (X_3) for all seeds used in the study.

Seed	Step value (kPa)	Coded level of vacuum (X_3)				
		−1.682	−1	0	1	1.682
For all seeds	2.0	2.64	4.0	6.0	8.0	9.36

acceptable levels and lower than 29% for corn. The quality of feed index for cotton ranged between 75.8% and 100%, while the range was between 70% and 100% for sunflower. The E_{rms} values should be considered as penalty values only, and in ideal seed distribution it should be zero. The E_{rms} values at the center of the design (from run number 15 through 20), as tabulated in Tables 8–10, were the lowest for cotton as compared to the other 2 crop seeds.

In order to build performance functions in coded form of the 3 dependent (performance-related) variables, the following transformation (Rawlings, 1988) was made for all the performance indices except E_{rms}, so that the predictions from the developed functions should not exceed 100%.

$$y = \arcsin\left(\sqrt{\frac{I_{qf}}{100}}\right) \tag{2}$$

No significant model for any of the performance indices was developed for corn seeds. Hence, the verification tests


Figure 6. Assembled view of the metering unit with twin vacuum disks.

Table 5. RSM design used for seeding corn seeds.

Run number	Independent variables					
	Peripheral speed (X_1)		Hole diameter (X_2)		Vacuum (X_3)	
	Coded	Uncoded (ms^{-1})	Coded	Uncoded (mm)	Coded	Uncoded (kPa)
1	–1	0.08	–1	3	–1	4
2	–1	0.08	1	5	–1	4
3	1	0.16	–1	3	–1	4
4	1	0.16	1	5	–1	4
5	–1	0.08	–1	3	1	8
6	–1	0.08	1	5	1	8
7	1	0.16	–1	3	1	8
8	1	0.16	1	5	1	8
9	–1.682	0.052	0	4	0	6
10	1.682	0.187	0	4	0	6
11	0	0.12	–1.682	2.318	0	6
12	0	0.12	1.682	5.682	0	6
13	0	0.12	0	4	–1.682	2.64
14	0	0.12	0	4	1.682	9.36
15	0	0.12	0	4	0	6
16	0	0.12	0	4	0	6
17	0	0.12	0	4	0	6
18	0	0.12	0	4	0	6
19	0	0.12	0	4	0	6
20	0	0.12	0	4	0	6

Table 6. RSM design used for seeding cotton seeds.

Run number	Independent variables					
	Peripheral speed (X_1)		Hole diameter (X_2)		Vacuum (X_3)	
	Coded	Uncoded (ms^{-1})	Coded	Uncoded (mm)	Coded	Uncoded (kPa)
1	–1	0.08	–1	2	–1	4
2	–1	0.08	1	3	–1	4
3	1	0.16	–1	2	–1	4
4	1	0.16	1	3	–1	4
5	–1	0.08	–1	2	1	8
6	–1	0.08	1	3	1	8
7	1	0.16	–1	2	1	8
8	1	0.16	1	3	1	8
9	–1.682	0.052	0	2.5	0	6
10	1.682	0.187	0	2.5	0	6
11	0	0.12	–1.682	1.66	0	6
12	0	0.12	1.682	3.34	0	6
13	0	0.12	0	2.5	–1.682	2.64
14	0	0.12	0	2.5	1.682	9.36
15	0	0.12	0	2.5	0	6
16	0	0.12	0	2.5	0	6
17	0	0.12	0	2.5	0	6
18	0	0.12	0	2.5	0	6
19	0	0.12	0	2.5	0	6
20	0	0.12	0	2.5	0	6

for the corn seeds were achieved based on the results obtained from the experiments.

The performance model with an R^2 of 0.604 was the only model developed for the cotton seeds. The quality of feed index model given below for cotton seeds (YCI_{qf}) resulted from the stepwise regression analysis at a probability level of 95%, even though all 3 variables were defined in a quadratic form.

$$YCI_{qf} = 1.51 - 0.095\,X_2^2 + 0.087\,X_2 - 0.082\,X_3^2\ (R^2 = 0.604) \quad (3)$$

This model may be considered to have a low coefficient of determination, but once the raw data are examined, it is seen that the I_{qf} performance varies in a narrow range and this may be the consequence of the model with low R^2. The optimum level of the variables in the model given above was found with the software to be 0.457 and 0 for variables X_2 and X_3, respectively. On the other hand, the original level of the variables can be calculated as follows:

$$\frac{X_2 - 2.5}{0.5} = 0.457 \Rightarrow X_2 = 2.72\,mm \quad (4)$$

$$\frac{X_3 - 6}{2} = 0 \Rightarrow X_3 = 6.0\,kPa \quad (5)$$

For sunflower seeds, only the quality of feed index (YSI_{qf}) and miss index (YS_{miss}) models were developed. The quality of feed index model and the optimum level of the variables were found to be 0.504 and 0.17 for the hole diameter and vacuum in coded form, respectively, and their levels in the original units of these variables are given below.

$$YSI_{qf} = 1.556 - 0.122X_3^2 + 0.102X_3 + 0. - 0.12X_2X_3 - 0.072X_2^2\ (R^2 = 0.785) \quad (6)$$

$$\frac{X_2 - 2}{0.5} = 0.504 \Rightarrow X_2 = 2.25\,mm \quad (7)$$

$$\frac{X_3 - 60}{2} = 0.17 \Rightarrow X_3 = 6.34\,kPa \quad (8)$$

The miss index model for sunflower seeds was in the following form, while the optimum level of the variables in coded form was found to be 1.07 and 0.17 for the hole diameter and vacuum, respectively.

Table 7. RSM design used for seeding sunflower seeds.

Run number	Independent variables					
	Peripheral speed (X_1)		Hole diameter (X_2)		Vacuum (X_3)	
	Coded	Uncoded (ms^{-1})	Coded	Uncoded (mm)	Coded	Uncoded (kPa)
1	–1	0.08	–1	1.5	–1	4
2	–1	0.08	1	2.5	–1	4
3	1	0.16	–1	1.5	–1	4
4	1	0.16	1	2.5	–1	4
5	–1	0.08	–1	1.5	1	8
6	–1	0.08	1	2.5	1	8
7	1	0.16	–1	1.5	1	8
8	1	0.16	1	2.5	1	8
9	–1.682	0.052	0	2	0	6
10	1.682	0.187	0	2	0	6
11	0	0.12	–1.682	1.159	0	6
12	0	0.12	1.682	2.841	0	6
13	0	0.12	0	2	–1.682	2.64
14	0	0.12	0	2	1.682	9.36
15	0	0.12	0	2	0	6
16	0	0.12	0	2	0	6
17	0	0.12	0	2	0	6
18	0	0.12	0	2	0	6
19	0	0.12	0	2	0	6
20	0	0.12	0	2	0	6

$$YS_{miss} = 7.9x10^{-05} – 0.125X_2 – 0.117X_3 + 0.102X_3^2 + 0.077X_2X_3 + 0.052X_2^2 \ (R^2 = 0.878\%) \qquad (9)$$

The level of the variables in original units, as calculated below, was found to be 2.54 mm for the hole diameter and 6.34 kPa for the vacuum level.

$$\frac{X_2 - 2}{0.5} = 1.07 \Rightarrow X_2 = 2.54\,mm \qquad (10)$$

$$\frac{X_3 - 60}{2} = 0.17 \Rightarrow X_3 = 6.34\,kPa \qquad (11)$$

The optimum levels of the variables as calculated from the models given above for sunflower seeds are similar and verify each other; in particular, the vacuum levels from both models are the same.

The common point of the developed models given above and the raw data is that the performance functions are free of the peripheral speed of the vacuum disk. This finding proves the hypothesis that the use of twin disks can reduce the peripheral speed so that the seed capture and holding characteristics are improved within a certain range between 0.036 and 0.131 ms^{-1}. Hence, precision seeding can be achieved at higher forward speeds once the optimum levels for the hole diameter and vacuum are set to the correct level for each seed.

In addition to the above models, we tried to build polynomial functions by using the data tabulated in Tables 8–10 for performance indices, namely precision and E_{rms}, but no model was developed for any of the crops at a probability level of 95%.

Some verification tests were conducted in the laboratory on a sticky belt test stand in order to test whether the precision seeding performance could be maximized at high seeding speeds. In these tests, the planter forward speed was set to 2, 3, and 4 ms^{-1}. However, the tests at 3 and 4 ms^{-1} were achieved with twin vacuum disks, each with 72 holes, while the tests at 2 ms^{-1} were conducted by the use of a 36-hole vacuum disk. The peripheral speed of the vacuum disk remained unchanged by the use of a 36-hole vacuum disk at 2 ms^{-1} and 72-hole vacuum disk at 3 and 4 ms^{-1} to obtain the theoretical seed spacing of 11.8 cm.

The results of the verification tests conducted in the laboratory on the sticky belt test stand are given in Table 11. As seen from the table, the quality of feed index was

Table 8. Performance results obtained from the RSM based experiments for corn seeds.

Run number	Coded independent variables			Performance indices				
	Peripheral speed (X_1)	Hole diameter (X_2)	Vacuum (X_3)	I_{qf} (%)	I_{mult} (%)	I_{miss} (%)	Precision (%)	E_{rms} (cm)
1	−1	−1	−1	100	0	0	11.2	3.9
2	−1	1	−1	96.7	3.3	0	16.7	4.1
3	1	−1	−1	88.9	3.7	7.4	36.3	8.4
4	1	1	−1	100	0	0	10.0	2.6
5	−1	−1	1	92.6	3.7	3.7	19.9	4.8
6	−1	1	1	96.7	3.3	0	14.3	3.5
7	1	−1	1	89.7	6.9	3.5	28.0	6.5
8	1	1	1	92.9	3.6	3.6	37.1	8.6
9	−1.682	0	0	100	0	0	6.8	2.1
10	1.682	0	0	100	0	0	11.1	2.9
11	0	−1.682	0	96	0	4	23.4	5.5
12	0	1.682	0	100	0	0	10.6	2.5
13	0	0	−1.682	96.2	0	3.9	31.8	10.0
14	0	0	1.682	100	0	0	4.4	1.5
15	0	0	0	100	0	0	6.5	1.5
16	0	0	0	100	0	0	10.2	2.6
17	0	0	0	100	0	0	5.1	1.5
18	0	0	0	100	0	0	9.8	2.6
19	0	0	0	100	0	0	5.2	1.5
20	0	0	0	100	0	0	10.4	2.6

100%, while very low E_{rms} values were obtained in the tests conducted at 2 ms^{-1} for all crops and the same index declined as the speed increased. On the other hand, the miss index increased with the increase in forward speed and no multiples occurred in any of the tests. The increase in miss index with the increase in forward speed could be attributed to the fact that the vacuum need may change at higher forward speeds. The centrifugal forces at forward speed of 3 and 4 ms^{-1} may overcome the forces so that the seeds are sucked into the hole by the vacuum, as determined at a forward speed ranging between 0.52 and 1.87 ms^{-1}.

E_{rms} increased with the increase in forward speed, but all of the E_{rms} values were considerably low as compared to an ideal E_{rms} value of zero that represents perfect seed spacing accuracy. The same trend is also valid for the precision values at 2, 3, and 4 ms^{-1} forward speeds. An increase the in forward speed deteriorated the precision values (%) for all crops used in this study, but none of the precision values were higher than the practical upper limit of 29%.

The performance indices obtained in some previous studies using a conventional single vacuum type metering unit can be classified in 2 groups and comparisons can be made with the twin disk metering unit developed in this study.

The first group of studies comprises those in which the forward speed was kept constant at a certain level and the performance of the vacuum type metering unit was studied. One of these studies was conducted by Karayel et al. (2004). The vacuum type precision seeder was operated at 1 ms^{-1} and the vacuum level was changed for different crop seeds. The highest quality of feed index was found to be 92.2% for cotton when 3 kPa of vacuum was applied for an assumed hole diameter of 3.5 mm. On the other hand, the highest quality of feed index of 94.5% and 95.9% for 2 different corn varieties was obtained at 4.0 kPa vacuum level and the hole diameter was chosen to be 3.5 mm.

The second group of studies used different forward speeds and studied the effects of different forward speeds on seed spacing accuracy. Karayel and Özmerzi (2001) used 3 different forward speeds of 1, 1.5, and 2.0 ms^{-1} in

Table 9. Performance results obtained from the RSM based experiments for cotton seeds.

Run number	Coded independent variables			Performance indices				
	Peripheral speed (X_1)	Hole diameter (X_2)	Vacuum (X_3)	I_{qf} (%)	I_{mult} (%)	I_{miss} (%)	Precision (%)	E_{rms} (cm)
1	–1	–1	–1	83.3	0	16.7	23.2	10.2
2	–1	1	–1	96.9	3.1	0	16.3	2.4
3	1	–1	–1	75.8	8.2	16	38.3	14.1
4	1	1	–1	100	0	0	9.1	2.5
5	–1	–1	1	92.3	0	7.7	21.2	10.0
6	–1	1	1	97.4	2.6	0	17.1	4.8
7	1	–1	1	79.3	0	21.7	38.8	10.0
8	1	1	1	96.2	0	3.8	22.5	5.9
9	–1.682	0	0	100	0	0	10.3	2.3
10	1.682	0	0	100	0	0	9.5	2.7
11	0	–1.682	0	92.3	0	7.7	23.8	5.9
12	0	1.682	0	93.4	3.3	3.3	23.1	5.3
13	0	0	–1.682	92.6	0	7.4	24.8	6.3
14	0	0	1.682	96.3	3.7	0	20.2	1.8
15	0	0	0	96.3	0	3.7	18.9	4.7
16	0	0	0	100	0	0	9.2	1.5
17	0	0	0	100	0	0	8.1	1.8
18	0	0	0	100	0	0	8.6	1.7
19	0	0	0	96.3	0	3.7	14.4	1.7
20	0	0	0	100	0	0	9.6	1.7

their study and found that the variability in seed spacing with a precision vacuum seeder increased with increasing forward speed. Among 3 forward speeds, they concluded that a forward speed of 1 ms^{-1} resulted in a better seed pattern than the other forward speeds. Siemens and Gayler (2016) focused on lettuce seeding and used vacuum and belt type precision seeders, and they concluded that acceptable levels of performances could be obtained at speeds below 0.55 ms^{-1} (2 km h^{-1}), while higher speeds decreased the seed spacing accuracy.

In general, it can be stated that the forward speed in the previous studies limited the performance at 1 ms^{-1} or below, but a quality of feed index value of above 97% for all crop seeds was obtained at a forward speed of 3 ms^{-1}. The same index at a forward speed of 4 ms^{-1} was obtained to be around 96% for corn and sunflower, but 92% for cotton. One of the important issues for future work is that field testing with this prototype metering unit is required, since the soil dynamics during seeding may affect the seed distribution and performance indices may go down.

The following points were concluded from the conducted study:

- The twin disk metering unit as developed in this study eliminated the effects of the peripheral speed that deteriorate the seed spacing accuracy within a certain range.
- A new design of a metering unit with twin vacuum disks was able to provide acceptable levels of seed spacing accuracy for 3 different crop seeds.
- The quality of feed index with the new metering unit was obtained to be 100% at 2 ms^{-1} while it was almost 98% for all crop seeds at 3 ms^{-1}. The forward speed of 4 ms^{-1} resulted in quality of feed index values of 92%, 96%, and 96% for cotton, sunflower, and corn seeds, respectively.
- The new metering unit is applicable for use with conventional row crop seeders, as well as disk type seeders.
- The performance of the disk type seeders equipped with seed tubes may be increased by the use of this new design since seeds are dropped into the seed tube at a lower speed as compared to the conventional precision seeders with single vacuum disk.

Table 10. Performance results obtained from the RSM based experiments for sunflower seeds.

Run number	Coded independent variables			Performance indices				
	Peripheral speed (X_1)	Hole diameter (X_2)	Vacuum (X_3)	I_{qf} (%)	I_{mult} (%)	I_{miss} (%)	Precision (%)	E_{rms} (cm)
1	−1	−1	−1	78.3	4.4	17.4	37.5	11.1
2	−1	1	−1	100	0	0	13.0	4.8
3	1	−1	−1	71.4	7.1	21.4	44.2	37.0
4	1	1	−1	96.4	3.6	0	24.1	5.6
5	−1	−1	1	100	0	0	10.3	2.4
6	−1	1	1	96.3	3.7	0	17.6	4.2
7	1	−1	1	87.5	4.2	8.3	26.7	6.4
8	1	1	1	93.1	6.9	0	24.2	5.7
9	−1.682	0	0	100	0	0	10.1	2.6
10	1.682	0	0	100	0	0	11.2	2.9
11	0	−1.682	0	91.3	0	8.7	36.3	11.3
12	0	1.682	0	100	0	0	13.9	3.2
13	0	0	−1.682	70	0	30	39.2	11.5
14	0	0	1.682	100	0	0	13.1	3.4
15	0	0	0	100	0	0	9.2	2.6
16	0	0	0	100	0	0	11.1	2.9
17	0	0	0	100	0	0	10.5	2.8
18	0	0	0	100	0	0	11.6	2.9
19	0	0	0	100	0	0	10.4	2.8
20	0	0	0	100	0	0	9.8	2.6

Table 11. Results of the verification tests achieved at higher forward speeds.

Seed	Hole diameter (mm)	Vacuum (kPa)	Forward speed (ms^{-1})	Performance indices			
				I_{qf} (%)	I_{miss} (%)	Precision (%)	E_{rms} (cm)
Corn	4	6	2.0 3.0 4.0	100 97.9 95.6	- 2.1 4.4	14.2 17.4 22.7	1.6 2.4 2.7
Cotton	2.5	6	2.0 3.0 4.0	100 97.7 92.2	- 2.3 7.8	10.6 17.4 19.8	1.8 2.0 3.1
Sunflower	2.5	6	2.0 3.0 4.0	100 97.8 96.4	- 2.2 3.6	8.3 18.9 19.0	2.1 2.3 2.6

· The polynomial models developed in this study can be used to determine the performance measures for different plant densities that require different theoretical seed spacings.

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