Dynamic analysis for kernel picking up and transporting on a pneumatic precision metering device for wheat

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Abstract: The objective of this study was to theoretically investigate the factors affecting kernels during picking up and transporting stage using a pneumatic precision metering device designed especially for wheat precision seeding and correlates findings with the results from practical testing under laboratory conditions using a test stand with camera system. The results from dynamic analysis were found to be corresponding with that of the laboratory testing. The findings revealed that the performance indices, such as quality of feed index (QFI), multiple index (MULI) and miss index (MISI), were obviously influenced by changing the negative pressure force F_Q and rotating speed ω. The result from test stand highlighted that when the negative pressure increased the QFI increased, MULI increased and MISI decreased, however, the QFI decreased and MISI increased with increasing the rotating speed. The dynamic analysis likewise revealed that increasing the friction index $\tan\alpha_g$ by choosing a suitable material with high friction angle α_g for seed plate as well as enlarging the seed hole diameter could improve the efficiency of the negative pressure force F_Q.

Keywords: wheat, kernel, picking up, transportation, dynamic model, precision metering device

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1 Introduction

The pneumatic technology is widely used in agricultural machinery as in drying, threshing and metering seeds processes.

Among precision metering devices, a pneumatic seeder using either both negative and positive pressure for picking up and releasing seeds respectively, or only the negative pressure for picking up seeds while for releasing process a mechanical device is likely involved in air cutting off is now the industry standard.

Kachman and Smith (1995) reported that the quality of feed index, multiple index, miss index and number of seeds per meter distant have been included to evaluate the performance of the metering device in the present analysis.

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Barut (1996) and D. Karayel et al. (2004) concluded that loss of uniformity of the vacuum seeder was probably a combination of several factors. The pattern efficiency of the vacuum plate differed most at lower or higher vacuum pressures and faster wheel speeds.

Guarella et al. (1996) and Tijskens et al. (2004) stated that the forces acting on seeds during the sucking process were the main factors impacting seeds suction performance. However, the recent performance studies on vacuum precision seeder were still depending largely on the tests.

Laboratory and field experiments on cottonseeds showed that lower miss indices were observed at higher pressures and lower speeds, and lower multiple indices at lower pressure and higher speeds (Singh et al., 2005).

The advantages of the pneumatic precision metering devices are that the seeds do not have to be precisely matched to the hole size, i.e., grading of seed is not an essential requirement, although still preferable for maximum accuracy of metering, also the singulation is more accurate than those of plate type precision meters, in the addition, no seed damage exists with the pneumatic precision seed meters (Murray et al., 2006).

Jin Chen et al. (2010) analyzed seeds motion during the sucking process on vacuum precision seeder; they reported that the seeds single pickup ratio decreased with an increase of rotating speed (ω).

Based on the dynamic analysis of kernel motion during picking up and transporting stages on a pneumatic precision metering device for wheat, a test stand with camera system was used to investigate the effect of negative pressure and rotating speed on performance indices.

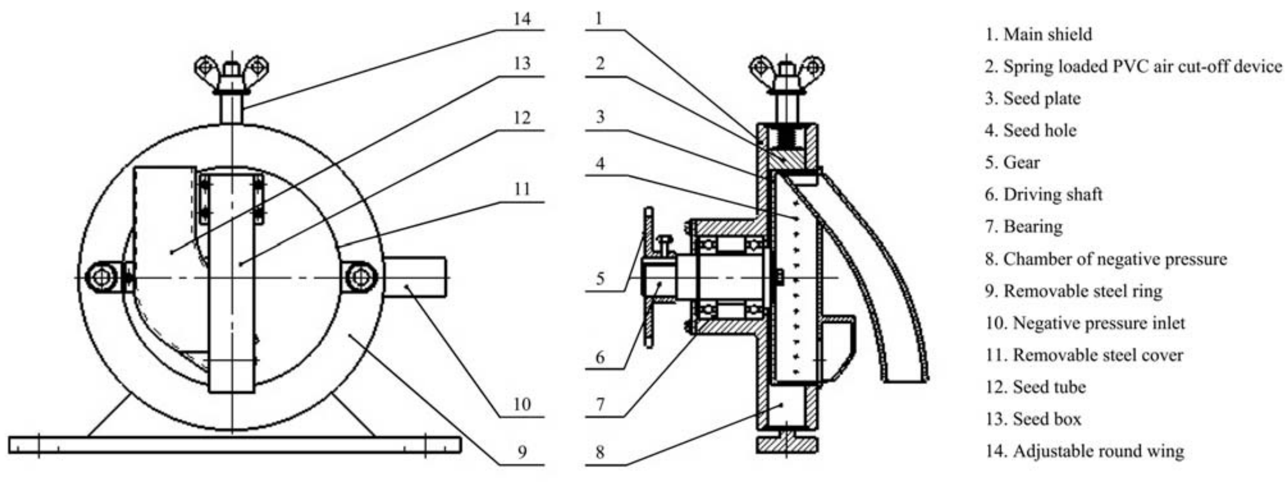
2 Dynamic analysis of seed motion

2.1 Structure and operating principle of the pneumatic precision metering device for wheat

The seed plate was made of aluminium having 140 mm diameter with 30 equidistant cylindrical holes, and the plate has 2 mm thickness and 30 mm width. Because of the non spherical shape of wheat kernels, the plate was made to have a depth of 27 mm to work as seed lot besides metering seeds to insure kernel to seed plate contact. A circular cavity of 35 mm diameter and 1 mm depth was made at the back side of the plate to secure stability when fix and rotate with the driving shaft (Figure 1). The seed plate creates the negative pressure chamber when it fixed to the main shield and covered with adjustable steel ring; the main shield consists of driving shaft and inlet of the negative pressure. Seed box and seed tube are fixed in another removable shield and easy to be joined to the other part of the device.

The main shield of the device was made of steel, with 200 mm outside diameter and 26 mm depth with total width of 73 mm. This part is equipped with the driving shaft.

The kernels enter through the inlet port at the bottom of the seed plate which simultaneously works as a seed lot. The kernels stir according to the movement of the seed plate, then they were picked up by the seed holes, held and transported under the influence of negative pressure. At the top of the metering device the negative pressure drops by spring loaded air cut-off device, the kernels then fall down vertically via the outlet to the seed tube by gravity.



a. Front view of the wheat precision seeder b. Cross section illustrating the internal parts

Figure 1 Schematic diagram of pneumatic precision metering device

2.2 Dynamic analysis of seed motion during pick-up stage

The motion of wheat kernel passes through five stages during its movement from the moment it enters the seed lot to its being released to the seed tube, those are fulfillment stage (flowing to the seed lot), pick-up stage, transporting stage, protecting stage and ejecting or releasing stage, the effect of negative pressure and rotating speed is more clear at pick-up stage and transporting stage, so these two stages will be analyzed in this paper.

In pick-up stage, as is shown in Figure 2, the forces acting on single kernel in this stage can be denoted as gravity force (G), friction force caused by seed plate (F_{fg}), normal force from seed plate (F_{Ng}), the force of the negative pressure (F_Q) and centrifugal force (F_c).

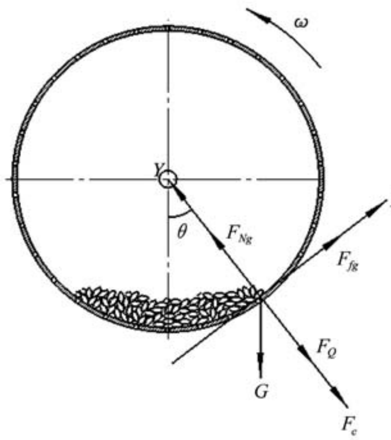


Figure 2 Forces affecting wheat kernels during pick-up stage

$$\begin{cases}\sum F_X = F_{fg} - G\sin\theta = 0 \\ \sum F_Y = F_{Ng} - G\cos\theta - F_Q - F_c = 0\end{cases} \tag{1}$$

The relationship between friction force F_{fg} and supporting force F_{Ng} can be given as:

$$F_{fg} = F_{Ng}\tan\alpha_g \tag{2}$$

Where, α_g is the friction angle between the seed and seed plate.

Substituting F_{fg} from (2) in (1)

$$\begin{cases}\sum F_X = F_{Ng}\tan\alpha_g - G\sin\theta = 0 \\ \sum F_Y = F_{Ng} - G\cos\theta - F_c - F_Q = 0\end{cases} \tag{3}$$

From Equation (3):

$$F_{Ng} = \frac{G\sin\theta}{\tan\alpha_g} \tag{4}$$

Substituting F_{Ng} from (4) in (3):

$$F_Q = G\frac{\sin\theta}{\tan\alpha_g} - G\cos\theta - F_c \tag{5}$$

The force of the negative pressure F_Q either to be greater than or equal to the other forces to pick up seeds so,

$$F_Q \geq G\frac{\sin\theta}{\tan\alpha_g} - G\cos\theta - F_c \tag{6}$$

or

$$F_Q = G\frac{\cos\alpha_g\sin\theta}{\sin\alpha_g} - G\cos\theta - F_c \tag{7}$$

Thus,

$$F_Q = G\frac{\sin(\theta - \alpha_g)}{\sin\alpha_g} - F_c \tag{8}$$

Theoretical force for kernel's picks-up:

$$F_Q = C_d S\frac{\rho V_0^2}{2} \tag{9}$$

where, C_d is drag coefficient; S is projected area (m^2); ρ is air density (kg/m^3); V_0 is air velocity (m/s).

Air velocity can be calculated from the following equation:

$$V_0 = \frac{Q}{2\pi R^2} \tag{10}$$

$$S = \frac{\pi d_s^2}{4} \tag{11}$$

$$G = \frac{\pi\rho_s g d_s^3}{32} \tag{12}$$

$$\frac{C_d\rho Q^2}{\pi^2\rho_s d_s R^4 g} \geq \frac{\cos(\theta - \alpha_g)}{\sin\alpha_g} - F_c \tag{13}$$

where: α_g is friction angle between seed and seed plate.

From Equation (9) it can be concluded that kernels were affected by kernel parameters (ρ_s, C_d, d_s), remote between kernel and hole (R), friction angle between kernels and seed plate α_g and air characteristics (ρ, Q).

The sucking force is influenced by both seed density and geometric mean, i.e., the sucking force is directly proportional with seed density and geometric mean.

The sucking force is also directly proportional with square air flow rate (Q^2) and inversely proportional with the distance between seed and hole (R).

2.3 Dynamic analysis of seed motion during transporting stage

Figure 3 shows the forces acting on wheat kernels during transporting stage.

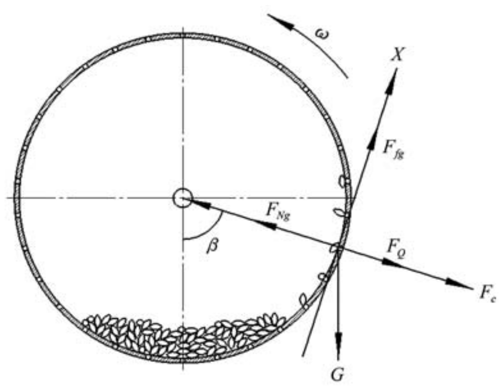


Figure 3 Forces acting on wheat kernels during transporting stage

$$\begin{cases} \sum F_X = F_{fg} - G\sin\beta = 0 \\ \sum F_Y = F_{Ng} - G\cos\beta - F_Q - F_c = 0 \end{cases} \quad (0 < \beta \le 90°) \tag{14}$$

$$\begin{cases} F_{fg} = F_{Ng}\tan\alpha_g \\ F_c = m\,\omega^2 R_c \end{cases} \tag{15}$$

where, F_c is the centrifugal force.

Thus,

$$F_{Ng} = G\frac{\sin\beta}{\tan\alpha_g} \tag{16}$$

Substituting F_{Ng} in Equation (14)

$$G\frac{\sin\beta}{\tan\alpha_g} - G\cos\beta - F_c = F_Q \tag{17}$$

Put $F_c = m\,\omega^2 R_c$

$$F_Q \ge -m\,\omega^2 R_c + G\left(\frac{\sin\beta}{\tan\alpha_g} - \cos\beta\right) \tag{18}$$

or

$$F_Q = -m\,\omega^2 R_c + G\left(\frac{\sin\beta\cos\alpha_g - \cos\beta\sin\alpha_g}{\sin\alpha}\right) \tag{19}$$

Put $\beta = 90°$

$$F_Q = G\frac{\cos\alpha_g}{\sin\alpha_g} - m\,\omega^2 R_c = m\left(\frac{g}{\tan\alpha_g} - \omega^2 R_c\right) \tag{20}$$

The force of the negative pressure can also be given by the following equation:

$$F_Q = PS = P\frac{\pi d_s^2}{4} \ge m\left(\frac{g}{\tan\alpha_g} - \omega^2 R_c\right) \tag{21}$$

where, $\tan\alpha_g$ is the friction index for the friction force F_{fg}.

This indicates that as the wheat kernel picked up and transports with the seed plate, it was influenced by many factors such as hole diameter, mass of the kernel m, the rotating speed ω, the radius of the seed plate R_c, the negative pressure P and the friction index $\tan\alpha_g$.

2.4 Results and discussion

In this design the pick-up process starts at the bottom of the seed plate (seed lot), and the kernels which are ready for picking up will be always close to the seed hole influenced by the movement and weight of the other kernels, therefore, the magnitude of R is very small. When the air flow rate (Q) increased and the distance between seed and hole (R) decreased, the efficiency of sucking will increase. When the friction angle between seeds and seed plate increased, the seeds will be easily sucked to the seed hole. Enlarging the seed hole and increasing the negative pressure and friction index should improve the efficiency of picking up kernels, exaggeration in these factors; however, it will lead to high values of multiple index. Considering the gravity acceleration g, the radius of the seed plate R_c and friction index $\tan\alpha_g$ are constants, the force of the negative pressure will increase when the rotating speed decreases.

Changing the material of seed plate to a suitable one with high friction may increase the friction index.

3 Experimental study

3.1 Experimental design

The new device was designed to have one plate made of aluminium with 30 holes of 1.8 mm diameter each.

A test stand with camera system was used to find out the effect of rotating speed and negative pressure on seed performance indices described as quality of feed index (QFI), multiple index (MULI), and miss index (MISI)

A 5×5 RCB statistical design was applied with five levels of the rotational speed (19, 24, 29, 34 and 39 r min^{-1}) and five levels of the negative pressure (2.5, 3.0, 3.5, 4.0 and 4.5 kPa). Each test was repeated five times and the average was measured. The belt speed was constant at 2 km h^{-1}.

The seed spacing on the greased belt were measured manually over 30 m length, every 10 m represents one replication. The quality of feed index (QFI), multiple index (MUTI) and miss index (MISI) were then determined based on the following formulas:

Miss index: the miss index I_{miss} is the percentage of spacing greater than 1.5 times the set planting distance S in mm.

$$I_{miss} = n_1 / N \tag{22}$$

where, n_1 is number of spacing, more than 1.5 S; and N is total number of measured spacing.

Multiple index: the multiple index I_{mult} is the percentage of spacing that are less than or equal to half of the set plant distance S in mm.

$$I_{mult} = {n_2}/{N} \tag{23}$$

where, n_2 is number of spacing, less than 0.5 S.

Quality of feed index: the quality of feed index I_q is the percentage of spacing that are more than half but not more than 1.5 times the set planting distance S in mm. The quality of feed index is an alternate way of presenting the performance of misses and multiples.

$$I_{fq} = 100 - (I_{miss} + I_{mult}) \tag{24}$$

3.2 Results and discussion of laboratory testing

Using a Chinese local variety of wheat (*hua mai 13*), the experiments were conducted under laboratory conditions, and the results of the impact of rotating speed and negative pressure on performance indices are shown in Tables 1 and 2, and Figures 4 and 5.

Table 1 Influence of negative pressure on performance indices

Negative pressure	Means		
	QFI	MULI	MISI
2.5	83.59	3.64	12.77
3.0	83.84	6.26	10.56
3.5	85.41	9.12	5.46
4.0	87.42	9.99	2.60
4.5	87.51	10.04	2.38

Table 2 Influence of rotating speed on performance indices

Rotating speed	Means		
	QFI	MULI	MISI
19	89.10	8.72	2.19
24	85.55	8.38	6.27
29	84.94	8.30	6.69
34	84.93	7.34	7.72
39	83.26	6.32	10.89

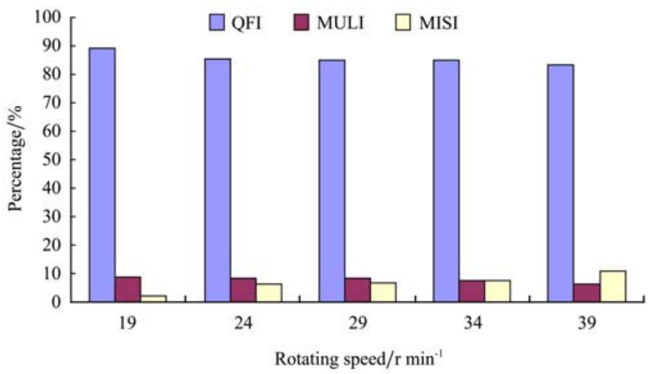


Figure 4 Effect of rotating speed on performance idices

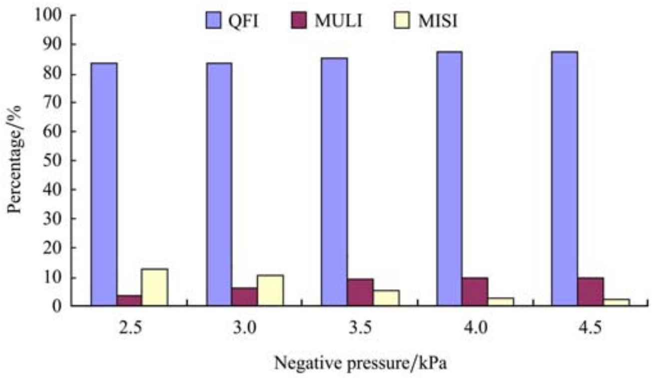


Figure 5 Effect negative pressure on performance idices

The results revealed that when the negative pressure increased the QFI increased as well (Table 1), which indicates that the efficiency of the negative pressure is increased with increasing the flow rate Q.

The MULI is also increased with increasing the negative pressure, whereas, the MISI decreased, and this is in agreement with the findings from dynamic analysis.

The results also exposed that even in the lowest level of negative pressure (2.5 kPa) the QFI is within the reasonable percentage; this may attributed to the small magnitude of R due to the close position of the kernels to the seed hole because of the movement and weight of other kernels and the point in which the picking up starts at the bottom of the seed plate.

Another consistency between the results from dynamic analysis and the laboratory testing is that the QFI decreased and the MISI increased with increasing the rotating speed (Table 2). As is concluded from dynamic analysis, when the rotating speed increases the force of the negative pressure decreases and become insufficient to pick up and transport kernels particularly under low levels of negative pressures which in turn lead the MISI to increase.

4 Conclusions

The dynamic analysis of kernels during pick-up and transporting stages on the pneumatic precision metering device designed especially for wheat was established to determine the factors affecting the sucking force. A laboratory test was also conducted to investigate the impact of different levels of rotating speed and negative pressure on performance indices. The findings from laboratory testing were in agreement with those of the dynamic analysis.

The results revealed that the QFI increased with increasing the force of the negative pressure F_Q and decreased with increasing the rotating speed ω.

The dynamic analysis also showed that increasing the friction index by choosing a suitable material of high friction angle for seed plate and enlarging the seed hole as well may improve the efficiency of sucking force.

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