OPEN ACCESS

Spanish Journal of Agricultural Research 23 (1)
January-March, 2025, 20393
ISSN-L 1695-971X, eISSN 2171-9292
https://doi.org/10.5424/sjar/2025231-20393

RESEARCH ARTICLE

Determination of low mass flow rate of wheat in a seed drill using a microwave Doppler sensor

Mustafa G. Boydaş[1]*

[1] *Department of Agricultural Machinery and Technologies Engineering, Faculty of Agriculture, Atatürk University,25240, Erzurum, Turkey.*

*Correspondence should be addressed to Mustafa Gökalp Boydaş: mboydas@atauni.edu.tr

Abstract

Aim of study: to develop a low-cost non-contact measurement system that can be used both in the field and in the laboratory for low volumetric flow.

Area of study: Türkiye.

Material and methods: A measurement system was developed to determine the flow rate of wheat seeds left at different flow rates from the seed metering unit, which has a studded feed roller, with a low-cost microwave sensor. Flow rates were determined for 16 different seed rates, and these flow rates were measured with precision scales. A microwave sensor was mounted on the seed tube. The precision scales and microwave sensors were operated simultaneously.

Main results: The obtained values were subjected to correlation and regression analysis. According to the analysis, it was found that the voltage values obtained from the microwave sensor increased linearly with the increase in the flow rate. There was a significant linear relationship ($R^2 = 0.974$) between the means of mass flow measured from the scales and the means of mass flow measured from the microwave sensor.

Research highlights: It has been determined that the developed microwave sensor measurement system can be used to evaluate the performance of sowing machines in the laboratory and to monitor the amount of seed flow in the field.

Keywords: microwave sensor, seed mass flow, seed metering unit, wheat.

Determinación del bajo caudal másico de trigo en una sembradora utilizando un sensor Doppler de microondas

Resumen

Objetivo del estudio: desarrollar un sistema de medición sin contacto y de bajo coste que pueda utilizarse tanto en el campo como en el laboratorio para bajos caudales volumétricos.

Área de estudio: Türkiye.

Material y métodos: Se desarrolló un sistema de medición para determinar el caudal de semillas de trigo depositadas a diferentes tasas de flujo desde la unidad dosificadora de semillas, que cuenta con un rodillo dosificador con púas, utilizando un sensor de microondas de bajo coste. Se determinaron los caudales para 16 diferentes dosis de siembra y se midieron con balanzas de precisión. Se montó un sensor de microondas en el tubo de semillas. Las balanzas de precisión y el sensor de microondas se operaron simultáneamente.

Principales resultados: Para los valores obtenidos, se realizaron análisis de correlación y regresión. Según el análisis, se encontró que los valores de voltaje obtenidos del sensor de microondas aumentaban linealmente con el incremento del caudal. Se observó una relación lineal significativa ($R^2 = 0.974$) entre los valores medios del caudal másico medidos con las balanzas y los medidos con el sensor de microondas.

Conclusiones: Se determinó que el sistema de medición con sensor de microondas desarrollado puede utilizarse para evaluar el rendimiento de las sembradoras en el laboratorio y para monitorear la cantidad de flujo de semillas en el campo.

Palabras clave: caudal másico de semillas, sensor de microondas, trigo, unidad dosificadora de semillas.

Citation: Boydaş, MG (2025). Determination of low mass flow rate of wheat in a seed drill using a microwave Doppler sensor. Spanish Journal of Agricultural Research, Volume 23, Issue 1, 20393. https://doi.org/10.5424/sjar/2025231-20393.

Received: 09/04/2023. **Accepted:** 15/10/2024. **Published:** 30/04/2025.

Introduction

Agriculture has an important role both in providing food for society and in making an important contribution to the country's economy. At the same time, agriculture is an important source of livelihood in most parts of the world. Grains have been used as the main food source of humans for thousands of years and have contributed greatly to the development of our civilization. Almost all over the world, corn, rice, sorghum, wheat, rye, and millet are important food sources in people's daily lives. In addition to its vital importance, grains are also used in baby foods, confectionery products, processed meats, batters, sweeteners, thickeners, coatings, and beverages such as juice. The three most important food crops in the world are rice, wheat, and maize (Awika, 2011). The main stages of cereal production are tillage, sowing, maintenance, and harvesting.

There are various techniques for seeding cover crops, including universal seed drills, precision seed drills, and no-till drilling. Each method has its own set of advantages and limitations. The seed drill is a key component in developing successful conservation plantings. It is a complex machine that delivers seeds at a metered rate, places them at a consistent depth in the soil, and produces light compaction to provide good seed to soil contact. One of the most important parts is the seed metering mechanism. The ultimate objective of the seed metering mechanism is to achieve precise seed distribution within the row (Boydas & Turgut, 2007). There are many different seed metering mechanisms. Generally, volumetric seed metering units such as parallel fluted feed rollers, studded feed rollers, and helical fluted feed rollers are used for sowing cereals (Collins et al., 1976). Volumetric flow metering mechanisms send the seeds in a continuous flow in furrows at a uniform rate. The seed rate is varied by adjusting the gear ratio between the seed metering unit and the seed drill ground wheels for a studded feed roller, and adjusting the gate or shifting the fluted wheel sideways for fluted feed type mechanisms. The seed rate does not change with travel speed. However, the mass of the flowing seed can be increased or decreased depending on the ground of the seed drill machine. Seed flowing through the metering mechanism must be monitored for maintaining the recommended plant spacing and population (Nandede et al., 2012). It is easier to determine the spacing of large grain seeds such as corn, bean, and peas and to evaluate the seed metering mechanism according to small seeds such as wheat, rice, and rye in the laboratory and in the field. Because the seed metering systems used in grain seed drills are delivered the seeds into furrow lines in a continuous flow. The difficulty in designing a measuring of the flow of small seeds has been that the seeds flow in clumps (Al-Mallahi & Kataoka, 2016). The seed metering mechanism is evaluated either in the field or in the laboratory. Evaluation done manually in the field is a very tedious process (Nandede et al., 2012). Therefore, researchers are using easier and faster methods to evaluate seed metering mechanisms in the laboratory. Some of the researchers used a sticky belt test stand (Collins et al., 1976; Kelly & Gould, 1995; Liu et al., 2018; Yin et al., 2018), optoelectronic sensor (Griepentrorong, 1994; Kocher et al., 1998; Lan et al., 1999; Panning et al., 2000; Al-Mallahi & Kataoka, 2013), acoustic technique (Karimi et al., 2015), high-speed camera (Karayel et al., 2006; Cakir et al., 2016), digital scale (Boydas & Turgut, 2007; Al-Mallahi & Kataoka, 2013). Each of these measurement methods has advantages and disadvantages. The sticky belt is the most common method used to evaluate seed metering mechanisms. However, it is a labor-intensive procedure. Karayel et al. (2006) used a high-speed camera system to evaluate the spacing uniformity of the wheat and soybean seeds. They measured the distribution uniformity of seeds with 96% accuracy. They stated that the high-speed camera system did not miss any wheat and soybean seeds. But, the high cost of high-speed cameras is a disadvantage. Both seed flow rate and flow evenness of volumetric flow metering mechanisms are effectively measured with a digital scale. Nevertheless, none of these measurement methods are suitable for using in the field. It is very important for tractor operators and researchers to monitor the workability of the metering unit while working in the field. Therefore, studies are carried out on the development of methods to be used both in the field and in the laboratory. Researchers such as Grift et al. (2001), Nandede et al. (2012), and Al-Mallahi & Kataoka (2016) developed measurement systems by using an optoelectronic sensor to evaluate seed metering units both in the field and in the laboratory. Al-Mallahi & Kataoka (2016) stated that the overall error in estimating flow rates for rye seeds at all speeds was 5.3%, and the sensor can be used on the grain drill for estimating seeds at variable sowing rates within certain speed limits. Li et al. (2015) used electrostatic and capacitance sensors to measure the mass flow rate of glass balls. They determined that the measurement error of the mass flow rate of glass beads within the range of 0.13 kg s^{-1}-0.9 kg s^{-1} is -3%-8%.

The aim of this research was to develop a low cost measurement system for a low volumetric flow that could be used both in the field and in the laboratory. The microwave Doppler sensor was used for this. The microwave Doppler sensor appears to have some advantages compared to the other sensors described above. The microwave Doppler sensors have small dimensions, simplicity, low cost, and easy installation (Yan, 1996). So, it will be easier to place and adjust in a planter. In addition, signals reflected from stationary particles do not create the Doppler Effect, and thus measurement errors can be prevented (Pang et al., 2018). Yang et al. (2020) developed a granular fertilizer mass flow measurement system based on the microwave Doppler method. They built a linear regression model of sensor output value and fertilizer mass flow by using the least squares method. They stated that the relative errors of the microwave Doppler method were not more than 5%, and the measurement system can be installed on the fertilizing machine. Pang et al. (2018) used the microwave Doppler measurement method to determine the mass flow rate of quartz sand particles of different diameters. They investigated the relationship between the solid mass flow rate and the output signal of the microwave Doppler measurement system. They stated that the microwave Doppler measurement method can be applied to other solid particles with different sizes, and unsteady solid flow as well as steady solid flow.

Material and methods

Seeds

The study was conducted with wheat seeds. Some physical properties of wheat seeds are shown in Table 1.

Table 1. Some physical properties of wheat used in the experiment.

Properties	Value
Bulk density (kg m^{-1})	736
Repose Angle (°)	27.45
Thousand kernel weight (g)	42.32
Grain dimensions [a] (mm) Mean value± S.d	
Length	6.4±0.35
Width	3.1±0.18
Thickness	2.8±0.14

[a]Grain dimensions shown are the averages with 100 measurements

Seed metering unit

A standard studded feed roller mechanism was used in the experiment (Figure 1). The Studded feed roller mechanism which is a volumetric flow metering mechanism was commonly used for sowing cereals. This mechanism conveys the seed to seed tube from the hopper by the agitating effect of the studs around the periphery of the roller, and the volumetric flow rate of seeds is regulated by changing the gear ratio between the ground wheels and seed metering unit. However, an AC (Alternating Current) speed control unit was used to change the rotation speed of the seed metering unit. The studded feed roller used in the experiment was two rows of studs, 12 studs in each row, 5.5 mm in stud height, 7 mm in stud width, 32 mm in roller width, and 63 mm in stud outer diameter.

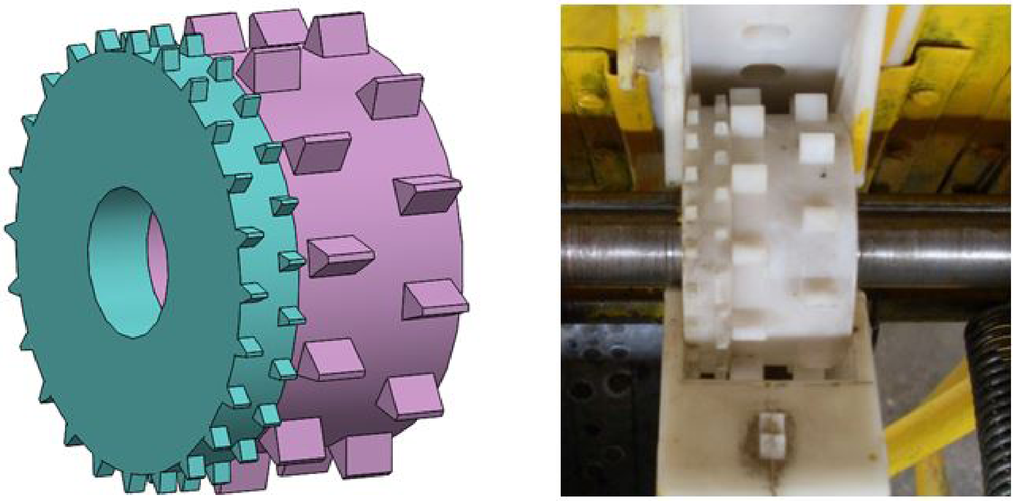

Figure 1. A standard studded feed roller mechanism.

Microwave sensor

In this study, the Crowtail microwave Doppler sensor module (Elecrow, CMS38743C) (Figure 2) was used to determine the flow rate of seeds. The average price of this microwave Doppler sensor was $15. The specifications of this sensor are presented in Table 2. The microwave sensor module applies the Doppler Effect to detect moving objects by using microwaves. The Doppler shift or Doppler effect was named after the Austrian physicist Christian Doppler (1803-1853), who described the phenomenon in 1842. Doppler shift or Doppler effect was defined as the change in frequency or wavelength of a wave relative to an observer moving relative to the wave source (Polivka, 2007; Wikipedia, 2023). The Doppler effect is the basis for the operation of microwave and ultrasonic detectors. Doppler effect device is a true motion detector because it is responsive only to moving targets. Thus, while moving objects are detected by this sensor, stationary objects are not detected (Fraden, 2010). The working principle of the microwave sensor in the test stand is summarized in Figure 3. To detect a moving object according to the Doppler effect, the frequency shift (F) between the signal transmitted and received by the microwave Doppler sensor is proportional to the radial velocity (v) of the object. Accordingly, the Doppler frequency can be found with the help of the following equation (1) (Polivka, 2007; Fraden, 2010; Alimenti et al., 2020).

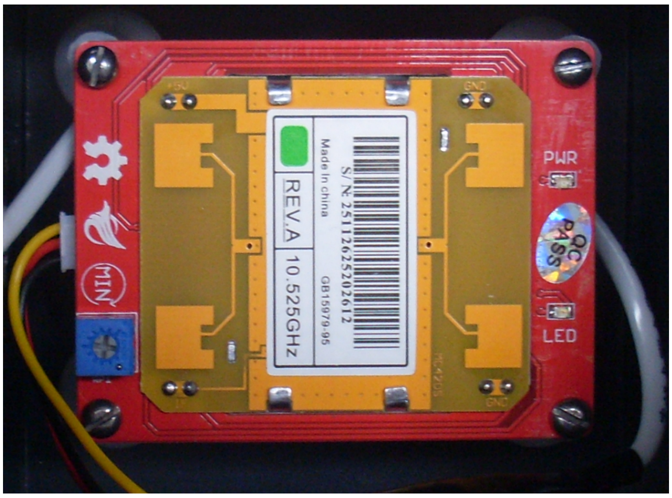

Figure 2. Crowtail microwave Doppler sensor module.

Table 2. Some specifications of Crowtail microwave Doppler sensor.

Properties	Value
Working voltage (V)	5 ± 5%
Working current (mA)	< 30
Center frequency (MHz)	10525
Sensing distance (m)	4
Frequency setting accuracy (MHz)	3
Output frequency (Hz)	3 to 80

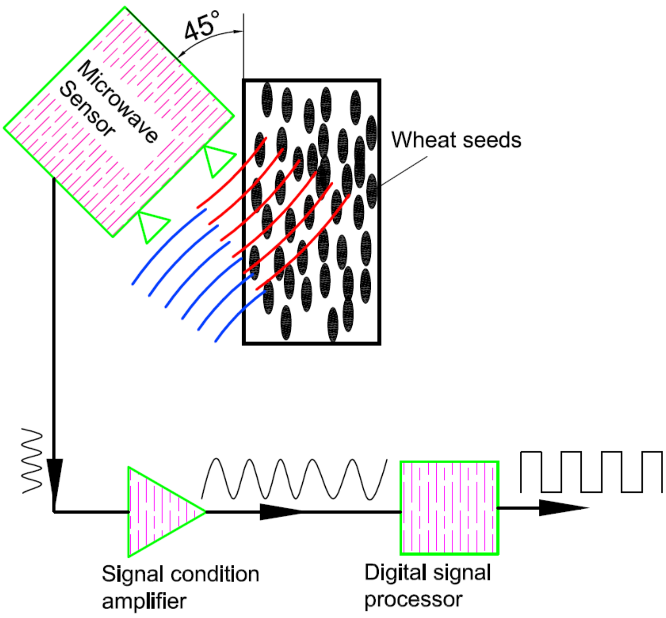

Figure 3. The working principle of the microwave Doppler sensor.

$$F = \frac{2vf}{c} cos\alpha \qquad 1$$

where, F is the frequency shift, f is the original frequency of the transmitted signal. This signal is 10525 MHz for Elecrow, CMS38743C, v is the radial velocity (m s^{-1}), and c is the speed of light (m s^{-1}). α is the angle formed by the microwave Doppler sensor axis with the flow direction of wheat seeds. The solid mass flow rate (kg s^{-1}) in a pipe can be found with the help of the following equation (2).

$$Q = \rho . A . v \qquad 2$$

where, Q is the solid mass flow rate (kg s^{-1}), ρ is the apparent wheat seeds density in the pipe (kg m^{-3}), $\underline{A}$ is the cross-section area of the seed tube (m^2), and v is the average velocity of wheat seeds (m s^{-1}). Zheng & Liu (2011), Pang et al. (2018), Zou et al. (2018) and Guo & Zhang (2018) stated that the power of the received signal is related to the concentration of solids particles in the pipe. Zou et al. (2018) and Guo & Zhang (2018) showed that mass flow rate can be determined with the help of the following equation (3).

$$Q(t) = v(t)\beta(t)A\rho \qquad 3$$

Where, $Q(t)$ is the solid mass flow rate (kg s^{-1}), $v(t)$ is the average velocity of wheat seeds (m s^{-1}), β(t) is concentration value, A is the cross-section area of the seed tube (m^2), ρ is the apparent wheat seeds density in the pipe (kg m^{-3}). Zou et al. (2018) named this equation as the 'velocity-concentration' method. They showed that changes in particle concentration and velocity lead to changes in the sensor output frequency.

It can be seen that the frequency of the microwave Doppler sensor changes depending on both the change in average velocity and concentration of wheat seeds. The signals reflected from the flowing seed were received as square waves (0 and 1) from the output of the microwave Doppler sensor. The frequency of this square wave varied with the velocity and concentration of the seed. In order to make these variable frequencies meaningful, an electronic card was designed using an LM2917 integrated circuit manufactured by Texas Instruments that converts frequency to voltage (Figure 4). This card was connected to the microwave sensor outlet. The output of this card was connected to the data logger. The relationship between voltage and frequency is shown in Figure 5.

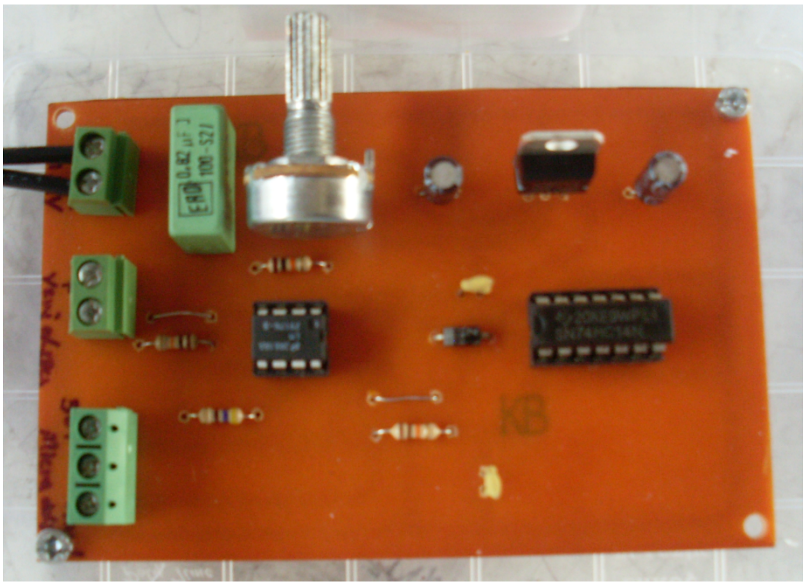

Figure 4. Electronic card using LM2917 integrated circuit.

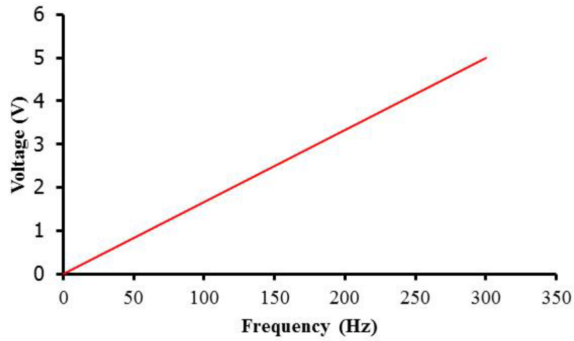

Figure 5. Frequency to voltage response obtained from electronic card using LM2917 integrated circuit.

Test stand

In order to determine the flow rate or seed rate of wheat seeds flowing from seed tubes, a test stand was built in the laboratory. A sketch of this test stand is shown in Figure 6. The test stand consisted of three units: a simulated seed drill unit, a measurement unit, and a data acquisition and data storage unit. The simulated seed drill unit contained a seed hopper, seed metering mechanism, agitator, AC speed control unit, and three-phase asynchronous motor. Speed control of the electric motor was done with an AC speed control unit. Thus, different flow rates were obtained from the studded feed roller mechanism. With the help of this unit, the working condition of the seed drill in the field was simulated. To prevent seed settling and bridging, an agitator was used in the seed hopper. The agitator movement was driven by a gear connected to a studded feed roller mechanism. There is a base flap just below the studded feed roller to ensure uniform seed distribution. This base flap opening and wrapping angle for wheat were set to 2 mm and 48º angle, respectively. The measurement unit contained a microwave sensor module, seed tube, holding container, load cell, and electronic card. The microwave sensor module was installed on the seed tube at 45º angle (Figure 3). A gap of 4 cm was left between the microwave sensor module and the seed tube. The seed tube was made of 0.5 mm thick plastic. The inner surface of the seed tube was covered with wave absorbing material. Thus, the reflection effect of the seed tube was tried to be minimized. A rod-type load cell with a capacity of 10 kg was placed under the seed tube to measure the weight of the seed dropped per unit time, and a plastic container was placed on this load cell to collect the seeds. The data acquisition and data storage unit contained a data logger and a laptop.

Test procedure and data analysis

The seed rate of wheat depends upon the variety, type of cultivation, and time of sowing. Some researchers determined that the seed rate of wheat varies from 100 to 200 kg ha^{-1} (Baloch et al., 2010; Shazma et al., 2015; Akhter et al., 2017;). Generally, spacing between two rows of wheat varies from 15 to 30 cm. Also, the forward speed of the seed drill varies from 3.4 to 9.2 km h^{-1} (Brandelero et al., 2015; Kamgar et al., 2015). The minimum and maximum flow rate flowing from the studded feed roller was determined by considering these data. The minimum flow rate was 1.42 g s^{-1} for a seed rate of 100 kg ha^{-1}, row space of 15 cm, and forward speed of 3.4 km h^{-1}. The maximum flow rate was 15.36 g s^{-1} for a seed rate of 200 kg ha^{-1}, row space of 30 cm, and forward speed of 9.2 km h^{-1}. Based on these values, the experiment was conducted with a flow rate of 1.50, 1.96, 2.55, 2.89, 3.20, 3.81, 4.03, 4.35, 5.18, 5.28, 6.10, 6.41, 7.70, 9.06, 10.50, and 11.91 g s^{-1}. To find these values, the asynchronous motor was run at certain speed intervals, and then the time-cumulative seed weight graph was plotted (Figure 7). Each flow rate was determined with the help of these graphs.

Three repetitions were made in each trial. Thus, microwave sensor module produced pulse signals when the seeds flow through the tube. These seeds were then dropped into the holding container on the load cell due to gravity, and the initial velocity of the seeds was ignored. During the experiment, seeds flowing through the seed tube were weighed continuously and cumulatively at 0.01 second intervals by a load cell. The load cell was calibrated with known weights to establish a linear relationship between measured voltage and actual loads.

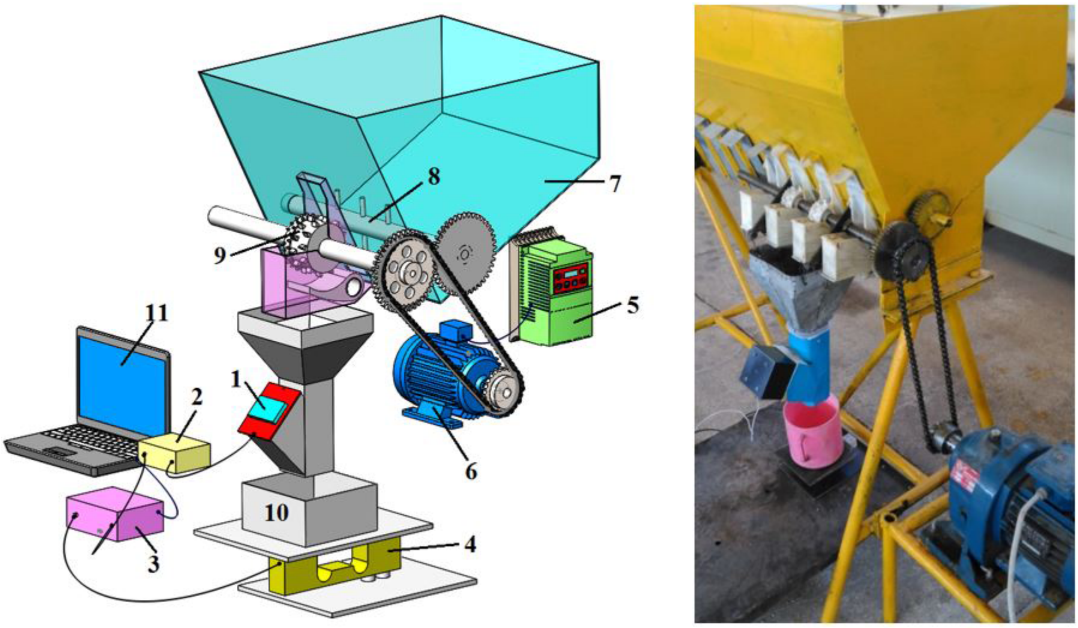

Figure 6. Test stand used to determine the mass flow rate of seeds with the microwave sensor (1: microwave Doppler sensor, 2: electronic card, 3: datalogger, 4: load cell, 5: AC speed control unit, 6: three-phase asynchronous motor, 7: Seed hopper, 8: agitator, 9: studded feed roller, 10: holding container, 11: personal computer).

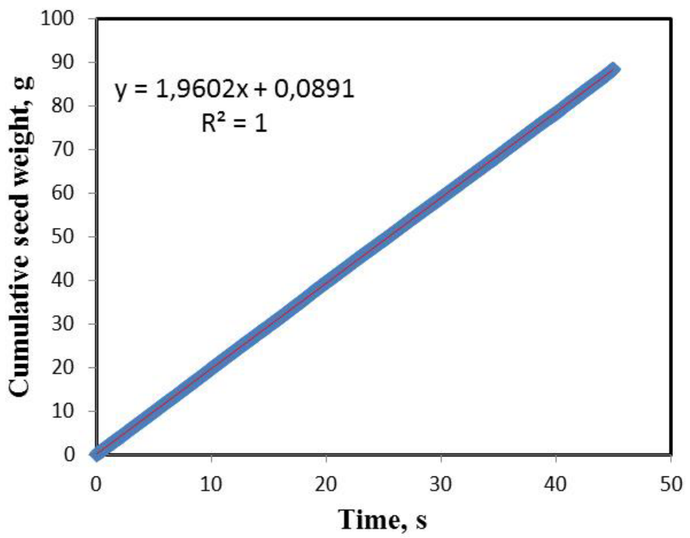

Figure 7. The graph obtained for 1.96 g s^{-1} flow rate.

Then voltage obtained from the load cell was transmitted to a data logger. These voltage values were converted to weight by means of the software in the data logger. Data obtained from both sensors were stored in the laptop simultaneously. The recorded data included the sampling time, the weight of the seed dropped per unit time, and the voltage output generated by the microwave sensor module.

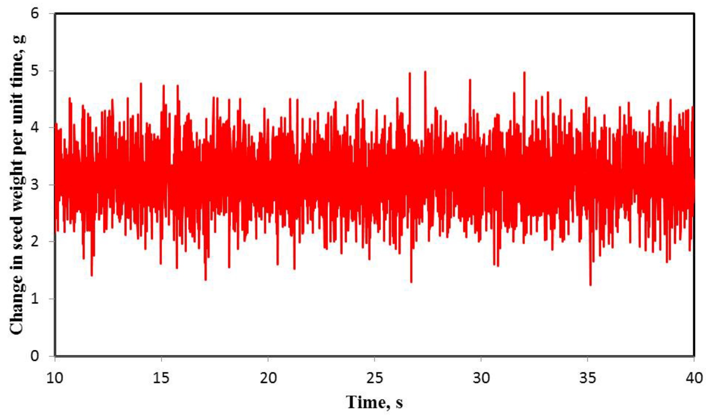

Figure 8. Change in seed weight for per unit time obtained from the flow rate of 3.20 g s^{-1}

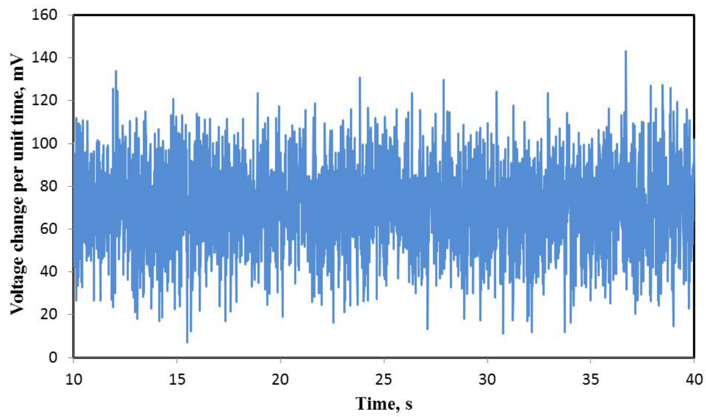

Figure 9. Voltage change for per unit time obtained from the flow rate of 3.20 g s^{-1}.

Results and Discussion

In this study, the cumulative seed weights flowing from the studded feed roller on the scale were subtracted from each other in unit time intervals and the number of seeds in the unit time interval was determined. Change in the number of seeds in the unit time interval at a flow rate of 3.20 g s^{-1} is shown in Figure 8 as an example. The voltage values measured from the microwave sensor were simultaneously recorded on the computer. The voltage variation obtained from the microwave sensor at a flow rate of 3.20 g s^{-1} is shown in Figure 9 as an example. Then, the mean, standard deviation, and coefficients of variation of these obtained values were calculated. These values were determined for each flow rate considered in the study and are given in Table 3. Correlation analysis was performed to determine the relationship between the mean values obtained from the balance and the mean values obtained from the microwave sensor. Two correlation coefficients were used; the Pearson and Spearman correlation coefficients, to measure linear and nonlinear relationships, respectively. The results of the correlation analysis of the mean values obtained from the scales and the microwave sensor in the study are given in Table 4.

The Pearson correlation coefficient was 0.961. Also, the Pearson correlation coefficient is significant, and the *p*-value is less than 0.001. There was a strong positive correlation between scales mean values and microwave sensor mean values. Thus, the Pearson correlation coefficients confirm that the scales mean value and microwave sensor mean value were correlated strongly and positively. Regression analysis is widely used to estimate the relationship between two variables. When the independent variable is changed, approximate values of the dependent variables can be found. Thus, with the regression analysis, it can be derived a mathematical equation for the values obtained from the microwave sensor with the help of the mean values obtained from the scales. It was found that the coefficient of determination (R^2) was 0.974 (Table 5). So, mean 97.4% variation in the dependent variable (scales mean value) could be explained by the independent variable (microwave sensor mean value). The Durbin-Watson value was found as 1.761. Since this value was between 1.5 and 2.5, it shows that there was no autocorrelation in the residual.

Table 3. The mean, standard deviation, and coefficients of variation determined for each flow rate obtained from scales and microwave sensor.

	scales			Microwave sensor		
Determined mass flow rate, g s^{-1}	**Mean of mass flow measured from the scales, g s^{-1}**	**Standard Deviation**	**Variation coefficient, %**	**Mean of mass flow measured from the microwave sensor, mv**	**Standard Deviation**	**Variation coefficient, %**
1.50	1.48	0.36	24.19	43.70	17.55	40.17
1.96	1.97	0.43	21.44	59.89	17.50	29.22
2.55	2.48	0.54	21.99	57.44	16.62	28.93
2.89	2.87	0.55	19.16	38.67	17.64	45.61
3.20	3.13	0.55	18.41	69.28	19.07	27.53
3.81	3.75	0.65	17.20	73.25	19.29	26.34
4.03	3.97	0.63	15.87	102.89	18.62	18.10
4.35	4.37	0.68	15.79	82.30	19.65	23.88
5.18	5.18	0.74	14.14	118.18	19.67	16.64
5.28	5.22	0.73	13.92	110.20	20.11	18.25
6.10	6.07	0.77	13.10	111.84	20.89	18.68
6.41	6.35	0.78	12.27	113.38	20.46	18.04
7.70	7.62	0.92	12.08	138.08	20.73	15.01
9.06	8.97	1.03	11.64	164.49	21.46	13.05
10.50	10.38	1.04	10.01	166.95	20.55	12.31
11.91	11.94	1.05	8.68	179.49	18.47	10.29

Table 4. Correlation results between balance and microwave mean values.

		Microwave sensor	**Scales**
Microwave sensor	Pearson Correlation	1	0.961**
	Sig. (1-tailed)		<0.001
	N	16	16
Scales	Pearson Correlation	0.961**	1
	Sig. (1-tailed)	<0.001	
	N	16	16

**. Correlation is significant at the 0.01 level (1-tailed).

Table 5. Durbin Watson statistic for independence of errors.

Model summary[b]					
Model	**R**	**R Square**	**Adjusted R square**	**Std. Error of the estimate**	**Durbin-Watson**
1	0.961[a]	0.974	0.919	0.86852	1.761

[a] Predictor: (Constant), microwave sensor mean value

[b] Dependent Variable: scales mean value

The ANOVA test was performed to determine the importance of the relationship between variables (Table 6). The ANOVA test results showed that there was a linear relationship between the variables, and this relationship was highly significant ($F_{1,14}$=171.188, p<0.001). To determine the regression equation, the regression coefficients were given in Table 7. Thus, the following equation 1 was obtained with the help of the regression coefficients.

$$y = 0.0662x - 1.388 \quad (4)$$

where, y is scales mean value (g s^{-1}), x is microwave sensor mean value (mV)

The regression coefficient was significant (p<0.001). The regression slope was 0.066. It was found that both the intersection and the variable were highly significant with the t-test (p<0.05). The scatterplot, the regression line, and the regression equation were showed in Figure 10.

The difference between the actual values in the data and the predicted values from the model is called the residual value. If the model does not fit well, the residual values will be large. Large residual values indicate that we have an outlier. Residual statistical values were given in Table 8. The Cook's distance and Mahalanobis distance give us information about outlier. The Cook's distance must be less than 1, and the Mahalanobis distance must be less than 16.27. Looking at Table 8, the maximum Cook's distance value was 0.684, and the maximum Mahalanobis distance value was 3.069. Both values were found to be appropriate. In addition, the errors must have a normal distribution. Therefore, a histogram of the residuals was plotted to check normality (Figure 11). Looking at Figure 11, It was observed that the histogram exhibited a normal distribution. Homoscedasticity is important in linear regression models. This was shown in Figure 12. The scatter plot showed residual versus predicted value. There should be no pattern in the scatter. The residual value against the

Table 6. ANOVA test results to determine the importance of the relationship between variables.

Model		**Sum of squares**	**df**	**Mean square**	**F**	***p*-value**
1	Regression	129.130	1	129.130	171.188	<0.001
	Residual	10.560	14	0.764		
	Total	139.691	15			

Table 7. The regression coefficient statistics for scales mean values as dependent variable.

Model		**Unstandardized Coefficients**		**Standardized Coefficients**			**95.0% Confidence Interval for B**	
		B	**Std. Error**	**Beta**	**t**	**Sig.**	**Lower Bound**	**Upper Bound**
1	Constant	-1.388	0.560		-2.480	0.026	-2.588	-0.188
	the microwave sensor	0.066	0.005	0.961	13.084	<0.001	0.055	0.77

predicted value was fit to the linear regression model. The width of the scatter remained roughly the same as predicted values increased, so the assumption was met. In particular, it was observed that these sensors should be well calibrated. Similarly, Väyrynen et al. (2013) tested four different noncontact measurement methods, and found that all measurement systems provided good results. However, they emphasized that calibration equations, parameters, and measurement noise levels needed to be considered. Same way, Swisher et al. (2002) measured the granular fertilizer flow rate by using an optical sensor. They detected that for good accuracy, the measurement system should be calibrated separately for each fertilizer.

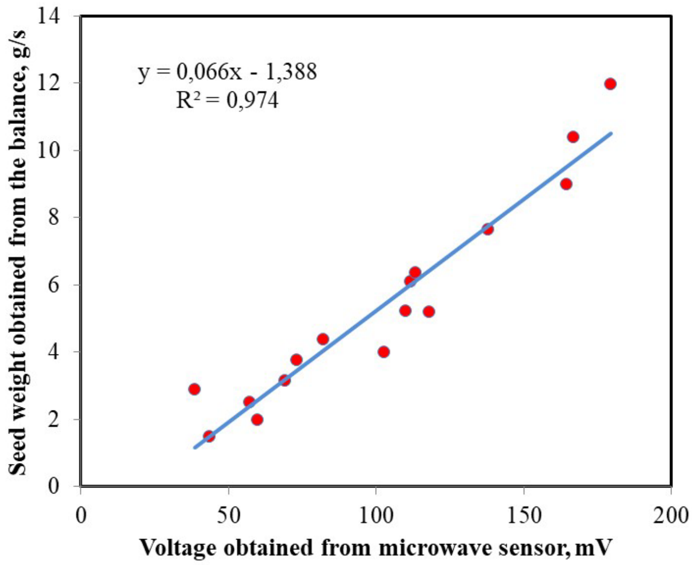

Figure 10. The scatterplot, the regression line, and the regression equation were obtained from the microwave sensor versus the seed weight obtained from the scales.

Table 8. Residuals statistics values for the difference between the actual values in the data and the predicted values from the model.

	Min.	Max.	Mean	Std. Deviation	N
Predicted Value	1.1732	10.4996	5.3594	2.93406	16
Std. Predicted Value	-1.427	1.752	.000	1.000	16
Standard Error of Predicted Value	.217	.449	.298	.076	16
Adjusted Predicted Value	.7538	9.9746	5.3141	2.91248	16
Residual	-1.45647	1.69676	.00000	.83907	16
Std. Residual	-1.677	1.954	.000	.966	16
Stud. Residual	-1.732	2.182	.024	1.055	16
Deleted Residual	-1.55363	2.11620	.04532	1.00474	16
Stud. Deleted Residual	-1.883	2.588	.050	1.164	16
Mahal. Distance	.001	3.069	.938	.963	16
Cook's Distance	.000	.684	.107	.211	16
Centered Leverage Value	.000	.205	.062	.064	16

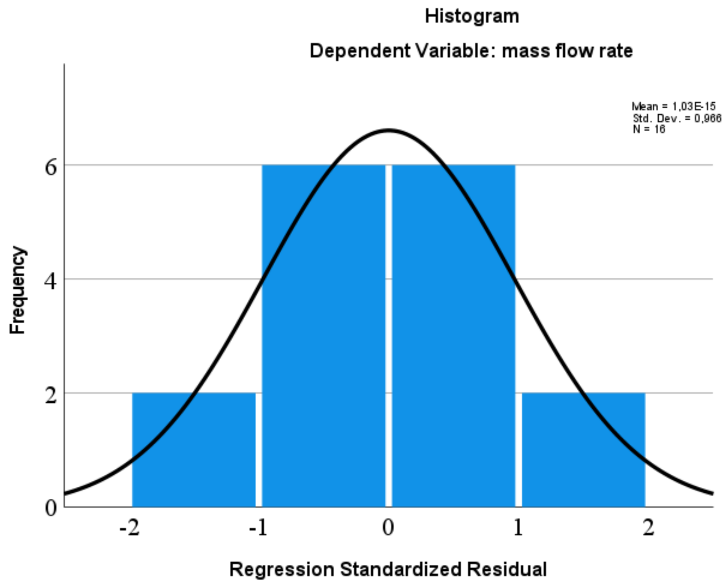

Figure 11. Residual plots to check the normality assumption.

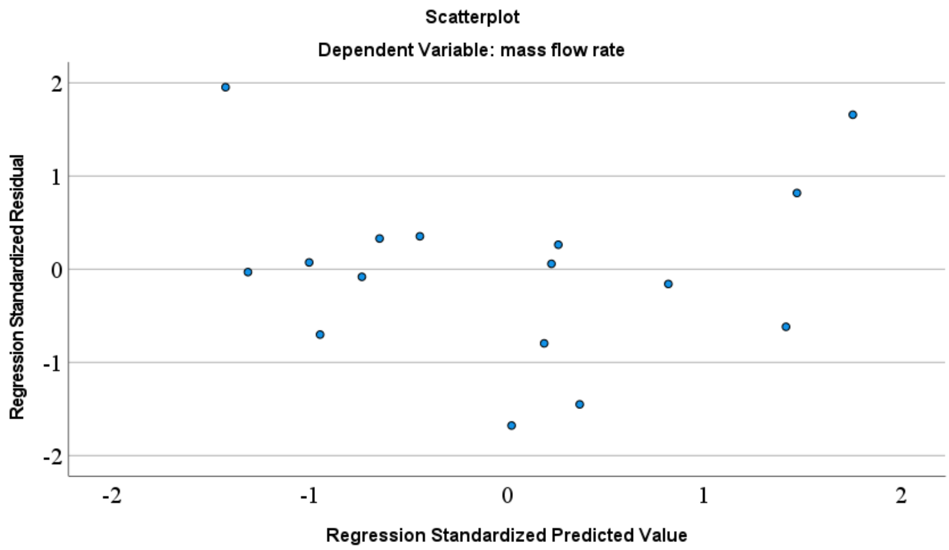

Figure 12. Homoscedastic behavior of the residuals via scatter plot.

Conclusions

Determining the flow rate of agricultural products such as grain is of great importance for sustainable precision agriculture. In laboratory conditions, the sensitivity of seed metering units can be determined by measuring methods such as precision scales or adhesive tape conveyors. However, these measurement systems are not capable of measuring the instantaneous amount of seed released from a seed drill operating in the field. Instead, it is necessary to use measurement systems that will measure the seed flow amount without contacting the seed. Thus, with the instant intervention to be made in the field, both the amount of seeds and energy usage can be reduced. In this study, the seed flow rate was tried to be estimated with a low-cost microwave Doppler sensor. For this, a seed drill simulator prepared in the laboratory was used. A studded feed roller metering unit was used in the seed drill simulator. In the experiment, 16 different seed rates of wheat were taken into consideration. these mass flow values ranged between 1.50 and 11,91 g s^{-1}. The seed flow rate was measured cumulatively with a precision balance placed under the seed tube. Meanwhile, the measurement was made with the microwave Doppler sensor placed in the seed tube at an angle of 45 degrees. The velocity of the seeds passing through the detection area of the microwave Doppler sensor and the seed density caused a change in the microwave Doppler sensor output frequency. These obtained frequencies were converted into voltage with the help of an electronic card using the LM2917 integrated circuit. Thus, a relationship was established between the mass flow rate obtained from the precision balance and the voltage values obtained from the microwave Doppler sensor. Some statistical methods were established to describe this relationship. Correlation and regression analysis were applied to the obtained measurements with the help of the SPSS statistics program. The Pearson correlation coefficient was significant (p<0.001). Results show that there was a strong positive correlation between scales mean values and microwave sensor mean values. According to ANOVA regression analysis, there was a linear relationship between the scales mean values and the microwave Doppler sensor mean values. This relationship was highly significant (p<0.001). R squared was 0.974. Thus, 97.4% of the variability in microwave sensor values was explained by the linear model. The other 2.6% could be explained by other variables. The regression equation y=0.0662x-1.388 was found to estimate the mass flow rate from the voltage values obtained from the microwave Doppler sensor. The results of the research showed that the microwave sensor can be used to measure the seed flow rate in seed drills. This can potentially offer benefits such as non-contact measurement and real-time monitoring. However, it is crucial to ensure proper calibration of the sensors for accurate measurements. In order to obtain reliable results in similar studies, it is of great importance to consider calibration equations, parameters, measurement noise levels, and different seeds.

Acknowledgements: The author would like to thank Atatürk University for providing the environment and equipment for this study.

Competing interests: The author has declared that no competing interests exist.

Statement about use of generative AI: The translation of the title, abstract, and keywords from the original version in English to Spanish has been generated by the SJAR Editorial Office using OpenAI, ChatGPT GPT-4o mini (2025). Following their use, the author(s) assumed full responsibility for the publication's content and reviewed and edited it as necessary.

Authors' contributions: Mustafa G. Boydas: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Supervision, Visualization, Writing - original draft, Writing - review & editing.

Funding: The author received no specific funding for this work.

References

Akhter MM, Sabagh AE, Alam MN, Hasan MK, Hafez E, et al. 2017. Determination of seed rate of wheat (Triticum aestivum L.) varieties with varying seed size. Sci J Crop Sci 6(3): 161-67.

Alimenti F, Bonafoni S, Gallo E, Palazzi V, Gatti RW, Mezzanotte P, Roselli L, Zito D, Barbetta S, Corradini C, Termini D, Moramarco T, 2020. Noncontact measurement of river surface velocity and discharge estimation with a low-cost doppler radar sensor. IEEE Trans Geosci Remote Sens 58(7): 5195-5207. https://doi.org/10.1109/TGRS.2020.2974185

Al-Mallahi AA, Kataoka T, 2013. Estimation of mass flow of seeds using fibre sensor and multiple linear regression modelling. Comput Electron Agric 99: 116-22. https://doi.org/10.1016/j.compag.2013.09.005

Al-Mallahi AA, Kataoka T, 2016. Application of fibre sensor in grain drill to estimate seed flow under field operational conditions. Comput Electron Agric 121: 412-19. https://doi.org/10.1016/j.compag.2016.01.006

Awika JM, 2011. Major cereal grains production and use around the World. Acs Sym Ser 1089: 1-13. https://doi.org/10.1021/bk-2011-1089.ch001

Baloch M, Shah I, Nadim M, Khan M, Khakwani A, 2010. Effect of seeding density and planting time on growth and yield attributes of wheat. J Anim Plant Sci 20(4): 239-42.

Boydas MG, Turgut N, 2007. Effect of vibration, roller design, and seed rates on the seed flow evenness of a studded feed roller. Appl Eng Agric 23: 413-18. https://doi.org/10.13031/2013.23482

Brandelero EM, Adami PF, Modolo AJ, Baesso MM, Fabian AJ, 2015. Seeder performance under different speeds and its relation to soybean cultivars yield. J Agron 14: 139-45. https://doi.org/10.3923/ja.2015.139.145

Cakir E, Aygun I, Yazgi A, Karabulut Y, 2016. Determination of in-row seed distribution uniformity using image processing. Turk J Agric For 40(6): 874-81. https://doi.org/10.3906/tar-1604-110

Collins TS, Gutteridge MV, Francis CD, 1976. Methods for improving the performance of cereal drills: Part I. metering mechanisms and initial sowing depth studies, NIAE, SILSOE

Fraden J, 2010. Handbook of Modern Sensors. 4th Edition. Springer New York Heidelberg Dordrecht London. https://doi.org/10.1007/978-1-4419-6466-3

Griepentrorong HW, 1994. Saatgutzuteilung von raps, Kiel

Grift TE, Walker T, Hofstee JW, 2001. Mass flow measurement of granular materials in aerial application - Part 1: Simulation and modeling. Trans ASABE 44(1): 19-26. https://doi.org/10.13031/2013.2299

Guo Z, Zhang G, 2018. Application of a microwave mass flow meter in a dense phase pneumatic conveying system of pulverized coal. 2018 IEEE 3rd Advanced Information Technology, Electronic and Automation Control Conference, Oct 12-14. pp: 2547-2551. https://doi.org/10.1109/IAEAC.2018.8577472

Kamgar S, Noei-Khodabadi F, Shafaei SM, 2015. Design, development and field assessment of a controlled seed metering unit to be used in grain drills for direct seeding of wheat. Inf Process Agric 2(3): 169-76. https://doi.org/10.1016/j.inpa.2015.08.001

Karayel D, Wiesehoff M, Özmerzi A, Müller J, 2006. Laboratory measurement of seed drill seed spacing and velocity of fall of seeds using high-speed camera system. Comput Electron Agric 50: 89-96. https://doi.org/10.1016/j.compag.2005.05.005

Karimi H, Navid H, Mahmoudi A, 2015. Online laboratory evaluation of seeding-machine application by an acoustic technique. Span J Agric Res 13(1). https://doi.org/10.5424/sjar/2015131-6050

Kelly P, Gould NS, 1995. To improve machinery for the effective establishment of pastures, NSW agriculture, Trangie

Kocher MF, Lan Y, Chen C, Smith JA, 1998. Opto-electronic sensor system for rapid evaluation of planter seed spacing uniformity. Trans ASABE 41(1): 237-45. https://doi.org/10.13031/2013.17143

Lan Y, Kocher MF, Smith JA, 1999. Opto-electronic sensor system for laboratory measurement of planter seed spacing with small seeds. J Agr Eng Res 72(2): 119-27. https://doi.org/10.1006/jaer.1998.0353

Li J, Kong M, Xu C, Wang S, Fan Y, 2015. An integrated instrumentation system for velocity, concentration and mass flow rate measurement of solid particles based on electrostatic and capacitance sensors. Sensors (Basel) 15(2): 31023-35. https://doi.org/10.3390/s151229843

Liu Q, Cui T, Zhang D, Yang L, Wang Y, et al. 2018. Design and experimental study of seed precise delivery mechanism for high-speed maize planter. Int J Agric Biol Eng 11(4): 61-66. https://doi.org/10.25165/j.ijabe.20181104.2802

Nandede B, Ranjeet K, Padhee D, 2012. Sensor for seedling spacing and flow measurement in vegetable transplanter. Int J Agric Biol Eng 5(2): 225-28. https://doi.org/10.25165/j.ijabe.20181104.2802

Panning JW, Kocher MF, Smith JA, Kachman SD, 2000. Laboratory and field testing of seed spacing uniformity for sugarbeet planters. Appl Eng Agric 16(1): 7-13. https://doi.org/10.13031/2013.4985

Pang L, Shao Y, Geng C, Zhong W, Liu G, Liu L, Tian W, 2018. Measurement of solid mass flow rate by a non-intrusive microwave method. Powder Technol 323: 525-532. https://doi.org/10.1016/j.powtec.2017.10.030

Polivka J, 2007. An overview of microwave sensor technology. High Freq Electron 6(4): 32-42

Shazma A, Khattak WA, Muhammad I, Saqib B, Muhammad S, Jehan B, 2015. Effect of sowing dates and seed rates on the agro-physiological traits of wheat. J Environ Earth Sci 5(1): 135-41

Swisher DW, Borgelt SC, Sudduth KA, 2002. Optical sensor for granular fertilizer flow rate measurement. Trans ASABE 45: 881-88. https://doi.org/10.13031/2013.9934

Väyrynen T, Itävuo P, Vilkko M, Jaatinen A, Peltonen M, 2013. Mass-flow estimation in mineral-processing applications. IFAC Proc Vol 46(4): 271-76. https://doi.org/10.3182/20130825-4-us-2038.00023

Wikipedia, 2023. Christian Doppler. https://en.wikipedia.org/wiki/Christian_Doppler

Yan Y, 1996. Mass flow measurement of bulk solids in pneumatic pipelines. Meas Sci Technol 7:1687-1706. https://doi.org/10.1088/0957-0233/7/12/002

Yang L, Huang J, Zhang J, Hu H, Liu G, Lü S, 2020. Mass flow measurement system of granular fertilizer based on microwave doppler method. Trans Chin Soc Agric Mach 51(s1): 210-217. https://doi.org/10.6041/j.issn.1000-1298.2020.S1.024

Yin X, Noguchi N, Yang T, Jin C, 2018. Development and evaluation of a low-cost precision seeding control system for a corn drill. Int J Agric Biol Eng 11(5): 95-99. https://doi.org/10.25165/j.ijabe.20181105.3369

Zheng Y, Liu Q, 2011. Review of techniques for the mass flow rate measurement of pneumatically conveyed solids. Measurement 44(4): 589-604. https://doi.org/10.1016/j.measurement.2011.01.013

Zou J, Wang H, Liu C, He D, Wu ZP, 2018. Real-time solid flow velocity measurement based on a microwave sensor. Trans Inst Meas Control 41(10): 1-9. https://doi.org/10.1177/0142331218808857