Development and verification of an underground crop harvester simulation model for potato harvesting

Md. Abu Ayub Siddique¹, Hyeon-Ho Jeon², Seok-Pyo Moon³, Sang-Hee Lee³, Jang-Young Choi⁴ and Yong-Joo Kim¹,²*

Received: 21 Dec. 2023, Accepted: 2 Feb. 2024

Key Words: Hydraulic pump, Potato harvester, Power analysis, Underground crop

Abstract: The power delivery is crucial to designing agricultural machinery. Therefore, the tractor-mounted potato harvester was used in this study to conduct the field experiment and analyze the power delivery for each step. This study was focused on an analysis of power delivery from the engine to the hydraulic components for the tractor-mounted harvester during potato harvesting. Finally, the simulation model of a self-propelled potato harvester was developed and validated using the experimental dataset of the tractor-mounted potato harvester. The power delivery analysis showed that approximately 90.22% of the engine power was used as traction power to drive the tractor-mounted harvester, and only 5.10% of the engine power was used for the entire hydraulic system of the tractor and operated the harvester. The statistical analysis of the simulation and experimental results showed that the coefficient of determinations (R²) ranged from 0.80 to 0.96, which indicates that the simulation model was performed with an accuracy of over 80%. The regression models were correlated linearly with the simulation and experimental results. Therefore, we believe that this study could contribute to the design methodology and performance test procedure of agricultural machinery. This basic study would be helpful in the design of a self-propelled potato harvester.

Nomenclature

\[ P_e: \text{Engine power (kW)} \]
\[ T_e: \text{Engine torque (Nm)} \]
\[ N_e: \text{Engine rotational speed (rpm)} \]
\[ P_i: \text{Hydraulic power (kW) of } \text{ith components} \]

Pₚᵢ: Hydraulic pressure (bar) of \text{ith components}
Qᵢ: Flow rate (lpm) of \text{ith components}.

1. Introduction

Potato is one of the major crops, with approximately 356 million tons of production at 1.649 million hectares in 2020 globally⁶. In Korea, potato production was approximately 550 thousand tons at 23,599 hectares in 2020²,³. However, labor costs have been dramatically increasing in Korea, because of the decreasing and aging population⁴,⁵. According to the extension report, agricultural production costs continue to rise⁶. In particular, machinery costs will increase by over 60% in 2022 compared to 2011. Fuel cost is also at the highest peak over the last 10 years⁸. Therefore, efficient and multipurpose equipment attached to the tractor is important to address agricultural production costs.
The power of the tractor is concentrated on the hydraulic power, for example, hydraulic transmission, hydraulic clutch, hydraulic brake, hydraulic steering, hydraulic operated loader, power take-off (PTO), and the proportional valve\textsuperscript{7,8}, because of having high accuracy, smoothness, and comfortable driving\textsuperscript{9,10}. Especially, a self-propelled harvester is operated by hydraulic power. In contrast, the agricultural working load is highly variable due to uneven soil, stones, soil conditions, vibration of the machine, and so on. Therefore, power distribution analysis is crucial for real operations, especially for underground crop harvesters.

Bulgakov et al.,\textsuperscript{11} experimented on the efficiency improvement of a self-propelled harvester. In their study, the plane-parallel motion was analyzed, and evaluated its kinematic parameters. The experiment was conducted for digging the sugar beetroot crops to evaluate the degree of damage. They focused on the root crop damage, which was over 67\%. Zhang et al.,\textsuperscript{12} focused on the optimal shift point of a self-propelled combine harvester using theoretical method. They stated that power distribution was the most important parameter for a self-propelled harvester to optimize the shift point. Therefore, the working load analysis of an underground crop harvester is required for power delivery analysis.

This basic study analyzes the power delivery of the underground crop harvester for potato harvesting. The specific objectives are: (i) to conduct the field experiment using a tractor-mounted harvester, (ii) to analyze the power delivery for each step of the power transmission, and finally (iii) to correlate the experimental result with simulation.

### 2. Materials and Methods

#### 2.1 Potato harvester specifications

A 55.4 kW power shuttle tractor (TX76, TYM Co., Ltd., Iksan, Korea) was used to operate the tractor-mounted potato harvester. The rated power and torque of the engine at the rated rotational speed of 2,200 rpm were 55.4 kW and 240 Nm, respectively. The hydraulic main and auxiliary pumps were specified with 39.1 lpm and 22 lpm, respectively at the rated speed of 2200 rpm. The specifications of the tractor are listed in Table 1. The tractor-mounted potato harvester (HD-PC900, Hyundai Agricultural Machinery, Iksan, Korea) requires a minimum 39 kW tractor. The PTO speed was 540 rpm with an oil tank capacity of 60 L. The harvester specifications are listed in Table 2.

#### 2.2 Load measurement system

The sensors to measure pressure were installed at each pump's inlet and outlet pipes. The pressure sensors for measuring harvesting and conveyor belt pressures were also installed as shown in Fig. 1 (A). The pressure sensor (DPS8381, Trafag AG, Switzerland) is configured with the range of 0–250 bar and measures the pressure using the thin-film-on-steel principle. The data acquisition system (DAQ), which was QuantumX 840B, HBM, Germany, was installed in the

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model, Company</td>
<td>TX76, TYM Co., Ltd., Iksan, Korea</td>
</tr>
<tr>
<td>Engine</td>
<td></td>
</tr>
<tr>
<td>Rated power (kW) at speed (rpm)</td>
<td>55.4 at 2,200</td>
</tr>
<tr>
<td>Rated torque (Nm) at speed (rpm)</td>
<td>240 at 2,200</td>
</tr>
<tr>
<td>PTO</td>
<td></td>
</tr>
<tr>
<td>PTO type</td>
<td>Independent</td>
</tr>
<tr>
<td>PTO speed (rpm)</td>
<td>540, 750, 1000</td>
</tr>
<tr>
<td>Hydraulic pump</td>
<td></td>
</tr>
<tr>
<td>Main pump (lpm)</td>
<td>39.1</td>
</tr>
<tr>
<td>Auxiliary pump (lpm)</td>
<td>22</td>
</tr>
</tbody>
</table>

Table 1: The specifications of the tractor used in this study.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model, Company</td>
<td>HD-PC900, Hyundai Agricultural Machinery, Iksan, Korea</td>
</tr>
<tr>
<td>Type</td>
<td>Tractor-Mounted</td>
</tr>
<tr>
<td>Dimension (L× W × H) (mm)</td>
<td>3,750 × 2,210 × 1,375</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>1,100</td>
</tr>
<tr>
<td>PTO speed (rpm)</td>
<td>540</td>
</tr>
<tr>
<td>Oil tank capacity (L)</td>
<td>60</td>
</tr>
</tbody>
</table>

Table 2: The specifications of the tractor-mounted harvester used in this study.
Development and verification of an underground crop harvester simulation model for potato harvesting

Fig. 1 The tractor-mounted harvester: (A) Sensor installed, and (B) Experimental field

tractor-mounted harvester for reading the pressure during the potato harvesting operation in this study. The field experiment was conducted at Gaejin-myeon, Goryeong-gun, Gyeongsangbuk-do, Republic of Korea (35°42’14.6"N 128°23’12.2"E), as shown in Fig. 1 (B).

2.3 Power delivery estimation

The engine power is generally divided into three powers: axle power used for tractor operation, PTO power applied for towing implements, and hydraulic power used to operate tractor-mounted implements like balers, and potato harvesters, which was shown in Fig. 2. In addition, the hydraulic power of the tractor is divided into main pump pressure used for traction power and sub-pump pressure used for tractor steering.

The engine delivery power was estimated using the following equation (1):

\[ P_e = \frac{2 \times \pi \times N_e \times T_e}{60000} \]  

Where \( P_e \) is the engine power (kW), \( T_e \) is the engine torque (Nm), and \( N_e \) is the engine rotational speed (rpm). The traction power was calculated by subtracting the PTO and hydraulic power from engine power of the tractor. The hydraulic powers for different hydraulic components were calculated using the following equation (2):

\[ P_{hi} = \frac{P_{ri} \times Q_i}{600} \]  

Where \( P_{hi} \) is the hydraulic power (kW) of \( i^{th} \) components, \( P_{ri} \) is the hydraulic pressure (bar) of \( i^{th} \) components, and \( Q_i \) is the flow rate (lpm) of \( i^{th} \) components.

2.4 Simulation model

The simulation model of the tractor-mounted potato harvester was developed and simulated by LMS AMESim (version 16, SIEMENS AG, Munich, Germany), which is shown in Fig. 3. The tractor hydraulic model was developed and the truck physical model like tractor was used in this model, which was attached to the PTO of the tractor as a harvester. The specifications of the simulation model are listed in Tables 1 and 2. The simulation was conducted at the rated speed of engine. The measured engine rotational speed was used as an input parameter of the simulation to ensure the real condition. The entire weight of the tractor and harvester were 2865 and 1100 kg, respectively. The model was validated for the power delivery of each hydraulic component of the tractor-mounted potato harvester.

Fig. 2 The power flow diagram of the tractor-mounted harvester

2.5 Statistical analysis

The statistical analysis was conducted for the hydraulic power of the main pump, sub-pump, harvesting motor, and conveyor belt motor for potato
harvesting. One-way ANOVA, and DMRT (Duncan’s multiple range test) were also conducted to analyze the significance level of the powers to the harvesting section. The software used for the statistical analysis was IBM SPSS Statistics (SPSS 25, SPSS Inc., New York, USA). The regression analysis was conducted using the average power for 5 replications of each component of the tractor-mounted potato harvester.

3. Results and Discussion

3.1 Power analysis for the tractor-mounter harvester

In this study, the harvester’s engine power, the tractor’s hydraulic and traction power, and the harvesting and conveyor belt’s hydraulic power were measured and analyzed for harvesting potatoes. The working period was considered in this study, which is shown in Fig. 4.

The average engine power ($P_e$) for the harvesting period was delivered at approximately 22.50±3.77 kW. The tractor’s total hydraulic power ($P_h$) and traction power ($P_T$) were approximately 1.15±0.25 and 20.30±3.60 kW, respectively for harvesting. The main pump powers ($P_{hm}$) and secondary pump powers ($P_{hs}$) were almost 0.52±0.22 and 0.63±0.11 kW, respectively for harvesting. Accordingly, the harvesting motor powers ($P_{hm}$) and conveyor belt motor powers ($P_{hs}$) were around 0.52±0.14 and 0.11±0.02 kW, respectively for the harvesting period. There were statistically significant differences among the powers for various hydraulic components of tractor-mounted harvester. The statistical analysis of the powers of tractor and harvester are listed in Table 3.

It was observed that approximately 90.22% of the engine power was used as traction power to drive the tractor-mounted harvester, and only 5.10% of the engine was used as hydraulic power to steer the tractor and harvest the potato. Among the hydraulic power, the sub-pump consumed almost 45.25% of power to steer the tractor, and 54.72% of power was used to operate the harvester using the main pump. The main pump power was transferred 81.91% for harvesting operation and 18.09% of power was transmitted for operating the conveyor belt of the harvester. The power delivery for each operation is shown in Fig. 5. Kim et al.,15,16) analyzed the power requirement of a 78-kW tractor for major agricultural field operations. They stated that the tractor’s hydraulic system consumed only 7.90% of the engine power during plow, rotary, baling, and loader operations. Their study proved that 5.10% of the engine power was sufficient for potato harvesting operations.

Table 3 Statistical analysis of powers for each step during potato harvesting.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Harvesting section</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Max</td>
</tr>
<tr>
<td>Engine $P_e$ (kW)</td>
<td>29.23</td>
</tr>
<tr>
<td>$P_h$ (kW)</td>
<td>2.27</td>
</tr>
<tr>
<td>$P_T$ (kW)</td>
<td>26.95</td>
</tr>
<tr>
<td>$P_{hm}$ (kW)</td>
<td>1.73</td>
</tr>
<tr>
<td>$P_{hs}$ (kW)</td>
<td>0.90</td>
</tr>
<tr>
<td>Harvester $P_{dh}$ (kW)</td>
<td>0.99</td>
</tr>
<tr>
<td>$P_{dc}$ (kW)</td>
<td>0.22</td>
</tr>
</tbody>
</table>

Means within each row for harvesting section with the different lettering are significantly different at p<0.05 according to Duncan’s multiple-range test. *Avg. ± S.D. is the Average ± Standard Error.
Development and verification of an underground crop harvester simulation model for potato harvesting

3.2 Performance of the simulation model

In this study, the simulation results were analyzed statistically. The simulation and experimental traction, tractor hydraulic, main pump, secondary pump, harvesting motor, and conveyor motor powers were compared.

3.2.1 Traction power

Fig. 6 shows the correlation between the simulation and experimental traction power for potato harvesting. It was observed that the regression model was found linearly correlated, with an $R^2$ of 0.8049. The statistical results proved that the simulation model performed accurately.

3.2.2 Hydraulic power

The correlation of the tractor hydraulic powers between the simulation and experimental potato harvesting is shown in Fig. 7. The regression model of the simulation and experimental hydraulic power was linearly correlated, with an $R^2$ of 0.9597.

3.2.3 Main pump power

The main pump powers between the simulation and experimental for potato harvesting were compared, which is shown in Fig. 8. The regression model of both simulation and experimental main pump powers were linearly correlated, whereas $R^2$ is 0.814.

3.2.4 Sub-pump power

In the case of sub-pump powers, the simulation and experimental powers for potato harvesting were analyzed, which is shown in Fig. 9. The regression model of both simulation and experimental sub-pump powers were linearly correlated, whereas $R^2$ value was 0.841.
3.2.5 Harvesting motor power

The simulation and experimental powers of the harvesting motor for potato harvesting were also analyzed, which is shown in Fig. 10. The regression model of both simulation and experimental harvesting motor powers were linearly correlated, whereas $R^2$ value was 0.961.

3.2.6 Conveyor belt power

The powers of the conveyor belt motor were also analyzed for both simulation and experimental, which is shown in Fig. 11. The regression model of both simulation and experimental conveyor belt motor powers were linearly correlated, whereas $R^2$ value was 0.8713.

4. Conclusion

Finally, the statistical analysis showed that the $R^2$ for traction power, tractor hydraulic power, main pump power, secondary pump power, harvesting motor power, and conveyor belt motor power were in a range of 0.8 to 0.96. It indicates that over 80% of the simulation results could be explained by the experimental results. The regression models were also fitted linearly, which were listed in Table 4. Therefore, we summarized that the simulation model of the potato harvester was highly correlated with the real tractor-mounted potato harvester.

### Table 4: The comparison between simulation and experimental results.

<table>
<thead>
<tr>
<th>Component</th>
<th>Regression model</th>
<th>$R^2$ value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_t$ (kW)</td>
<td>$y = 0.9222x + 1.5002$</td>
<td>0.8049</td>
</tr>
<tr>
<td>$P_h$ (kW)</td>
<td>$y = 0.8846x + 0.1187$</td>
<td>0.9597</td>
</tr>
<tr>
<td>$P_{hm}$ (kW)</td>
<td>$y = x - 0.006$</td>
<td>0.814</td>
</tr>
<tr>
<td>$P_{hs}$ (kW)</td>
<td>$y = 0.6216x + 0.2378$</td>
<td>0.841</td>
</tr>
<tr>
<td>$P_{hh}$ (kW)</td>
<td>$y = 1.1622x - 0.0986$</td>
<td>0.961</td>
</tr>
<tr>
<td>$P_{hc}$ (kW)</td>
<td>$y = 1.2308x - 0.0394$</td>
<td>0.8713</td>
</tr>
</tbody>
</table>

This study focused on analyzing power delivery from the engine to the hydraulic components of the tractor-mounted harvester during potato harvesting. Finally, the simulation model of a tractor-mounted potato harvester was developed and validated using the
experimental data. The power delivery analysis showed that approximately 90.22% of the engine power was used as traction power to drive the tractor-mounted harvester, and only 5.10% of the engine power was used for the entire hydraulic system of the tractor and operated the harvester. The simulation model of the potato harvester was performed well with the $R^2$ range from 0.8 to 0.96, which indicates the simulation model of the potato harvester was explained over 80% by the experimental results. The regression analysis proved that the simulation and experimental results were correlated linearly. Therefore, we believe that this study could contribute to the literature on design methodology and performance test procedure of agricultural machinery at the academic and industry levels. This basic study would be helpful to design a self-propelled potato harvester.

Acknowledgment

This work was carried out with the support of “Cooperative Research Program for Agriculture Science and Technology Development (Project No. RS-2023-RD009789)” Rural Development Administration, Republic of Korea.

Conflicts of Interest

The authors declare that there is no conflict of interest.

References

2) KOSIS (Korea Statistical Information Service). Potatoes Production (Field), 2022, Available online: https://kosis.kr/ (accessed on 10 December 2023).

