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Development of a Parallel Hybrid System for Agricultural Tractors

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The purpose of this study was to develop parallel hybrid tractor. The hybrid tractor was constructed by adding major components of a hybrid driving system on a tractor. The tractor has 71 kW engine power and the major components included an EMG (electric motor/generator), an inverter, batteries, a battery management system (BMS), and a hybrid control unit (HCU). The hybrid tractor had three control modes: idle, power assist, and battery charge and it were determined by the workload which estimated by measuring engine rotational speed. Performance of the hybrid tractor was evaluated through the field tests of plowing. Performance tests were conducted by comparing the hybrid tractor and the conventional one, and one hybrid tractor was used for the experiment. The hybrid tractor used the hybrid system for the control of EMG, and the conventional tractor was driven by the engine not using the hybrid system. Performances of the hybrid tractor and the conventional tractor were similar at M2 which is low speed condition and it could work with low load, but the performance of the hybrid tractor was better than one of the conventional tractor at higher load condition (M3, M4). Fuel efficiency of the hybrid tractor at M2 was similar with the one of the conventional tractor, but it was lower at M3 and M4 than the one of the conventional tractor by 74%. Considering all results of this study, the developed parallel hybrid tractor is feasible to improve plowing performance of the conventional tractor.

Key words: Parallel hybrid, Agricultural tractor, EMG, power assist, HCU

INTRODUCTION

Oil prices climbed above $100 a barrel recently. The prices have been rising on geopolitical concerns and are expected to rise further. High oil prices caused recession in most of the industries; as a result, the ways for improving fuel efficiency are needed especially in agricultural area.

The total volume of tractor production in 2012 are 40,449, accounting for 57% of the total volume of major agricultural machineries such as cultivator, tractor, combine, and rice transplanter. And the utilization rate of the tractor reaches 85.7%, which implies that the tractor is the most widely used machine on the farm in 2011. Moreover, the tractor uses 345,000 kL of oil which takes 48.5% of total oil consumption of agricultural machines, so developing high efficiency tractor is needed in this high–oil–price era.

Most studies on improvement efficiency of tractors focused on the development of high efficiency transmission (Bietresato, Friso, Sartori, 2012). One of the studies, Molari and Sedoni (2008) analyzed the fuel efficiency of full power–shift tractors based on the working conditions. The results showed that 52% of the total losses were caused by passive resistance and friction in the transmission together with the power absorbed by the hydraulic circuit in the neutral position. There is a limit to development high efficiency tractors through improving full power–shift efficiency although tractor efficiency should be more improved. For this reason other advanced technology for improving tractor efficiency is needed (Choi *et al.*, 2013).

Hybrid technology is advanced technology for improving fuel efficiency in automobile industry. It could be improved the fuel efficiency of automobile by 25% and it also contributed to improving fuel efficiency of construction machinery (Wang, Zhang, Yin, Zhang, Wang, 2012). In construction machinery industry, Komatsu developed a model (HB205) using hybrid technology in swing function of excavators which required great power, and reduced the fuel efficiency by 25%. Also, Caterpillar developed a hybrid bulldozer (D7E hybrid) and reduced the fuel efficiency by 20%. Unlike in automobile industry, hybrid technologies in construction machinery were applied in working part such as boom and bucket systems, and most studies were focused on excavators. Especially, various studies on control strategies of hydraulic pressure–motor for the working part were conducted to improve the working efficiency: Wang and Wang (2014) developed a pressure compensation scheme to improve the energy efficiency of a hybrid hydraulic excavator, and they reported that 26~33% of energy was recovered through the performance evaluation using test bench. Shen, Jiang, Su, and Karimi (2015) proposed the optimal control variable trajectory of hybrid excavators for reducing fuel consumption of off–road vehicles, and

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Lin, Wang, Hu, and Gong (2010) improved the efficiency of hybrid hydraulic excavators by 17% through the development and simulation of energy regeneration systems. Choi, Kim, Yu, and Yi (2011) developed a control system for the optimal control of hybrid excavators, and Yoon, Truong, and Ahn (2013) developed a parallel hybrid excavator applying electrohydraulic actuator to a boom driving system and reported 60% of energy savings.

In some of studies, hybrid technologies were applied to the driving part of the construction machinery. Zeng, Yang, Peng, Zhang, and Wang (2014) applied several energy management strategies to the wheel loader and reduced fuel efficiency by 10% through the optimal control of engine–motor driving. Hui and Jungqing (2010) developed a parallel hydraulic hybrid system to reduce energy consumption during frequent starts/stops operation of the wheel loader and proved the work efficiency and fuel savings through the simulation. Dagci, Peng, and Grizzle (2015) applied a power split hybrid system having two simple planetary gears (PGs) into light duty trucks, and Keulen, Mullem, Jager, Kessels, and Steinbuch (2012) proposed an optimal control strategy which was adaptive for truck mass and road elevation, and applied hybrid technology into heavy duty trucks.

In agricultural machinery industry, John Deere developed a mild hybrid tractor (model 7030E) driving cooling device of engine and air conditioning compressor with a motor and reduced the fuel efficiency by 10%. Efficient use of power in the driving part is important because tractors require high traction force during operation depending on towing implements and soil load; however, there is no study of hybrid technologies into the driving part.

Thus, this study was conducted to develop a high efficiency hybrid tractor. The purposes of this study were 1) to construct a parallel hybrid tractor using major components of a hybrid driving system, 2) to establish power management strategies for the hybrid tractor 3) to evaluate the performance of the hybrid tractor comparing with the conventional tractor through field tests.

MATERIALS AND METHODS

Hybrid tractor

A parallel type hybrid tractor was developed by adding major components of a hybrid driving system on a tractor as in Fig. 1. To construct the hybrid tractor, the most widely used 4WD tractor model in Korea (PS100, LS Mtron Ltd., Korea) was used in this study. The engine of the tractor had rotational speed of 2,300 rpm, torque of 320Nm, and rated power of 71kW. The total weight was 3,260 kg, and the dimension was 4,077 × 2,000 × 2,640 mm (length × width × height). Transmission of the tractor had two direction gears, four main gears, and three sub gears, and power transfer efficiency of it was approximately 90%.

The major components included an EMG (electric motor/generator), an inverter, batteries, and a battery management system (BMS) (Finesso, Spessa, Venditti, 2014). The EMG used a PMSM (permanent magnet synchronous motor), and maximum power was determined within the maximum load–ability of transmission to minimize the design change of the conventional tractor. The EMG had 7.4 kW rated power with 90% efficiency and 30 Nm max torque, and it was installed between the tractor engine and clutch. The EMG was made into integral type which had only one case including stator and rotor. The rotor was connected in series to main shaft which was connected to the transmission from the engine, and it had same rotational speed with the engine crankshaft (Mayr, Fleck, Jakubek, 2011; Ehsani, Gao, Emadi, 2007). It is also working as moment of inertia instead of the flywheel. The stator was fixed connecting to the clutch housing and engine case.

The inverter was used to convert battery DC power to AC power for control the EMG. A 10 kW inverter was installed with a protective case on the right side of the tractor cabin, and it was electrically connected to the EMG and battery using 3 phase AC power cables and DC cables, respectively. $LiFePO_4$ type battery was used because it had long life cycle and large capacity as well as it was more stable than other Li– type battery: no explosion and fire of itself in case of circuit short or penetration (Safari & Delacourt, 2011). Because of the tractor was frequently damaged by obstacles on off–road conditions. Battery had a capacity of 3 kWh, a rated voltage of 300 V, and a current of 10A and it was installed under the right side of the tractor cabin in a protective case. To manage battery status such as SOC (state of charge) which is defined as the ratio of the remaining capacity to the rated capacity of the battery (Zhang, Yang, Zhao, Qiang, 2015), voltage, and temperature etc. and to prevent battery trouble, the BMS was used (Unger, Kozek, Jakubek, 2015). The BMS was installed in the same case

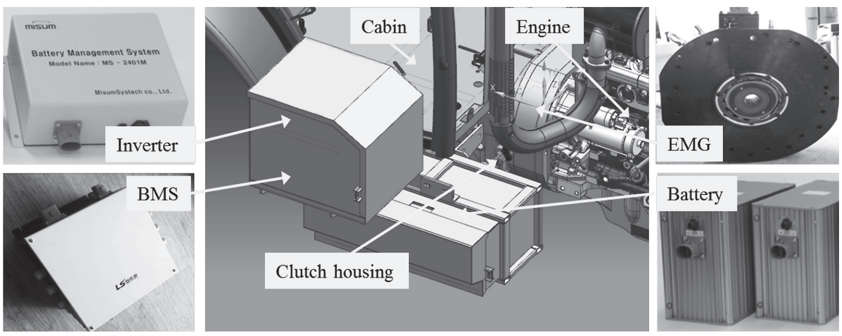

Fig. 1. Major components for the parallel hybrid tractor.

Table 1. Specification of the tractor and hybrid driving system

Item			Specification
Tractor	Length × Width × Height (mm)		4,000 × 2,677 × 2,640
	Weight (kg)		3,260
	Engine	Rated power (kW)	71 @2,310 rpm
		Max. torque (Nm)	398 Nm @1,300 rpm
	Transmission	Type	Manual
		Efficiency (%)	90
Hybrid driving system	EMG	Length × Width × Height (mm)	496 × 160 × 564
		Type	Permanent magnet synchronous motor
		Rated power (kW)	7.4
	Inverter	Length × Width × Height (mm)	360 × 310 × 220
		Rated power (kW)	10
		Input DC voltage (V)	300
	Battery	Length × Width × Height (mm)	200 × 230 × 160 (1 pack)
		Type	LiFePO4
		Number of pack	4
		Capacity (kWh)	3

with the inverter.

Specifications of the hybrid tractor are shown in Table 1.

Control system

In this study, the hybrid system was operated that assisting the engine power using battery energy at high workload and generating battery energy using surplus engine power at low workload. Thus, the hybrid tractor had three control modes: idle, power assist, and battery charge (Johnson, Wipke, Rausen, 2000; Choi, Song, Kim, 2014).

Figure 2 shows the power flow of each control mode. Power assist mode drove the EMG in the same engine rotation direction using the battery energy to assist engine power. In battery charge mode, the EMG was operated as generator, and it generated power and saved to the battery (Guardiola, Pla, Onori, Rizzoni, 2014). Idle mode had no power flow among battery, inverter, and EMG, and the EMG acted as a moment of inertia.

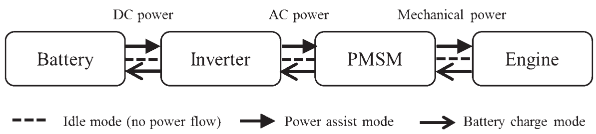

Fig. 2. Power flow by control mode of hybrid tractor.

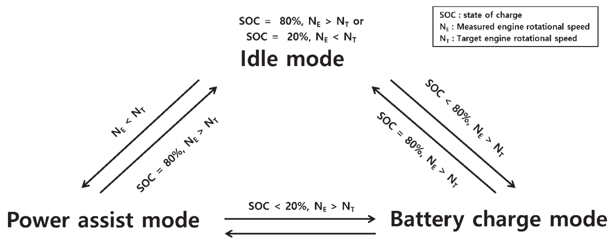

Fig. 3. State diagram of the control mode of the hybrid control unit.

Figure 3 shows the state diagram of each control mode. The control mode was determined by measured engine rotational speed (NE), target engine rotational speed (NT), and SOC. In this study, the engine torque was estimated by engine rotational speed, because it is not easy to measure engine torque directly (Lee *et al.*, 2015). The engine rotational speed decreased with increasing workload and engine torque, and it increased with decreasing workload and engine torque. The control mode was also determined by the maximum SOC control strategy having SOC upper and lower limit boundaries (Ehsani *et al.*, 2007). The SOC range from 20% to 80% was used because it has stable voltage output with no rapid voltage drop according to SOC changes (Pop, Bergveld, Danilov, Regtien, Notten, 2008).

Control mode was set idle mode as an initial state; it was changed into battery charge mode when SOC was less than 80% and measured engine rotational speed was higher than target engine rotational speed, and it was changed into power assist mode when SOC was more than 20% and measured engine rotational speed was lower than target engine rotational speed (Guardiola *et al.*, 2014). When target engine rotational speed was the same with measured engine rotational speed or battery could not be charged in the battery charge mode (SOC= 80%) or battery could not be discharged in the power assist mode (SOC=20%), the control mode was changed into idle mode (Ehsani *et al.*, 2007).

Target engine rotational speed was determined based on the fuel efficiency of the engine as in figure 4 (Sundstrom, Guzzella, Soltic, 2010). Tractor engine consumed 275 g $kW^{-1}h^{-1}$ at 2,300 rpm that was the rotational speed of rated power, and it decreased with decreasing rotational speed. Lowest fuel efficiency (237 g $kW^{-1}h^{-1}$) was observed at the rotational speed of 1,700~1,800 rpm. To prevent excessive switching of control mode at the boundary points, target engine rotational speed was set 1,800 rpm when the engine speed increased, and it was set 1,700 rpm when the engine speed decreased.

Hybrid control unit (HCU) was constructed to control hybrid system by control modes and it showed in figure 5. The HCU included a relay module (NI Crio 9481, National Instrument, USA) for power control of the BMS and the inverter, a connection module (NI USB 9162, National Instrument, USA), a CAN module (NI USB 8473, National Instrument, USA) for communications among HCU, inverter, and BMS, and a 12 V power supply for power supply of the inverter and BMS. Control program was developed using LabVIEW (version 2012, National Instrument, USA) and table 2 shows the modules and specifications of the HCU.

The HCU was operated by one mode among idle, power assist, or battery charge mode after receiving rotational speed of the EMG (same with the engine speed) measured by the inverter and SOC measured by the BMS through CAN. Control message sending from HCU to the inverter was included control torque of the EMG and rotational direction, and control torque was calculated with PID algorithm having feedback of the EMG's rotational speed. The initial value of PID gains was set by the Z–N method, and optimized by trial and error experiments (Choi, Woo, Lee, Kim, Jeong, 2010).

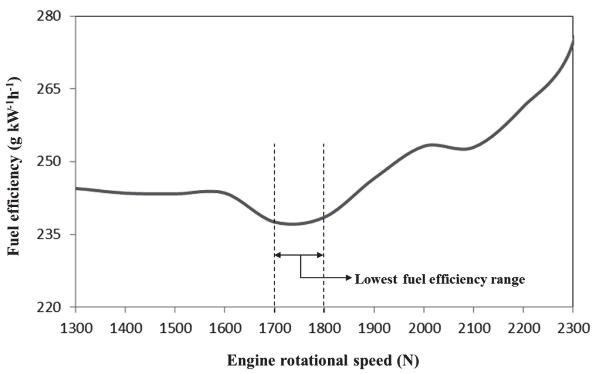

Fig. 4. Fuel efficiency curve of used the tractor engine.

Performance evaluation

Performance of the hybrid tractor was evaluated by comparing the conventional one through field tests of plowing. The tests were conducted by gear settings using a hybrid tractor. The hybrid tractor used the hybrid system for the control of EMG, and the conventional tractor was driven by the engine not using the hybrid system. Most workload during the plowing was generated in the driving shaft (Lee, 2011). Therefore, transmission input torque with the engine rotational speed, fuel consumption, and SOC were measured as field data. The field data and calculated fuel efficiency were compared between the ones of the each tractor. The fuel efficiency was calculated using the measured fuel consumption and calculated power of the transmission input shaft as in eq. 1 (Bietresato *et al.*, 2015). The power of the transmission input shaft was calculated as in eq. 2 (Ryu, 2004) using the measured torque and engine rotational speed which were the same with the input shaft speed.

$$E_{fuel} = \frac{C_{fuel}}{P_{shaft}} \quad (1)$$

Where, is fuel efficiency of the engine (L $kW^{-1}h^{-1}$), is fuel consumption of the engine (L h^{-1}), and is power of

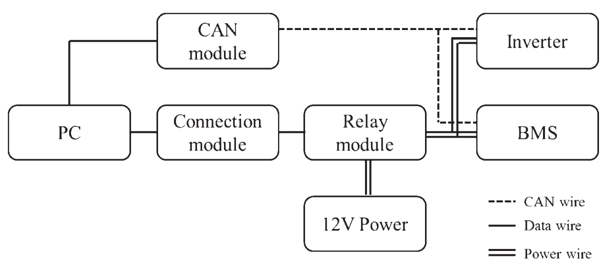

Fig. 5. Structure of the hybrid control unit.

Table 2. Specification of hybrid control unit

Module	Specification
CAN module (NI USB 8473)	– 1 port high–speed CAN, low–speed/fault tolerant CAN – Support for CAN 2.0A and extended CAN 2.0B – Interfaces available with optional hardware synchronization and 1μs timestamping resolution
Relay module (NI Crio 9481)	– 4 channels, EM form a electromechanical relay output – 30 VDC (2A), 60 VDC (1A), 250 VAC (2A) SPST relay – 250 Vrms channel to channel isolation
Connection module (NI USB 9162)	– Bus power carrier – NI Crio module support for connection

the transmission input shaft (kW).

$$P_{shaft} = \frac{2\pi \times N \times N}{60000} \quad (2)$$

Where, is power of shaft (kW), is torque (Nm), and is rotational speed (rpm).

Field data measurement system

A measurement system was installed on the hybrid tractor to acquire the field data. Transmission input torque was measured on the transmission input shaft which connected from the engine crank shaft and flywheel to the gearbox. To measure the torque, a four elements full–bridge strain–gauge (CEA–06–250US–350, Micro Measurement Co., USA) was attached on outer of input shaft and it detected the signals using radio telemetry I/O interfaces (R2, Manner, Germany). The radio telemetry system included two antennas and a data receiver. A rotor antenna was installed on transmission input shaft, and a stator antenna was installed on the shaft case. The gear flow meter (M05, NURITECH, Korea) was fitted between the fuel tank and fuel filter to measure the precise fuel consumption during plowing (Park *et al.*, 2010). The measuring range of the flow meter was 0.003~0.8 L min^{-1}. The rotational speed of the EMG measured in the inverter was used as engine rotational speed data and SOC was measured through CAN between HCU and BMS.

Field test condition

Field test was conducted at a field in Daechang–ri, Hampyeong, Jeonnam Province, and a skilled tractor driver participated in this study for two months from March, 2014. The skilled driver improved the reliability of this study, and M2 (7.2 km h^{-1}), M3 (10.3 km h^{-1}), and M4 (14.7 km h^{-1}) gears were selected after an interview and test with the driver. Throttle lever was fixed at the maximum point (engine speed: 2510 rpm) and three–point hitch was placed down to keep depth of 20 cm at this study (Kim, Chung, Park, Choi, 2011). The plowing work path followed the C–shape of round trip plowing work pattern (Seo, 2010). The C–shape path (one cycle plowing) comprised preparation to descend the 3–point hitch, operation to proceed with plowing operation forward, and completion to ascend the 3–point hitch and to steer for turning.

The plow used in this study was an eight–furrow common plow (SW–PN2408, Sewoong, Korea) with furrow width of 2,420 mm. And its dimension was 2,465 × 2,415 × 1,165 mm (length × width × height), and its weight was 514 kg.

Soil of the test site was analyzed with moisture content and Cone Index (CI) according to UDSA standard for the upland field sites. Results of the analysis showed that the test site had the moisture content of 18.9% and Cone Index of 1,039 kPa on average.

Evaluation methods

In the performance evaluation of the hybrid tractor, averaged values of the field data and calculated fuel efficiency during one cycle plowing were used.

Performances were evaluated by gear settings and each tractor using statistical analysis. And for doing this, SAS (version 9.1, SAS Institute, USA) was used as analysis software. Duncan's multiple range test was used for the comparison by each gear setting, and t–test was used for the comparison of the hybrid tractor and the conventional tractor.

In addition, performance of the hybrid tractor was validated using SOC. SOCs at the end of plowing operation for each gear setting were measured as SOC_{final}, and maximum variation and final variation were calculated by eqs. 3 and 4, respectively. SOC_{init} was 80%.

$$SOC_{fv} = SOC_{init} - SOC_{final} \quad (3)$$

$$SOC_{mv} = SOC_{init} - SOC_{min} \quad (4)$$

Where, SOC_{fv} is final variation, SOC_{mv} is maximum variation, SO_{Cinit} is initial value, SOC_{final} is final value, and SOC_{min} is minimum value of SOC.

RESULTS AND DISCUSSION

Load and fuel consumption data

Figure 6 shows the representative field data of engine rotational speed, transmission input torque, and fuel consumption during plowing with the conventional tractor. Working time, the length of the field data, decreased with increasing working speed (55 s at M2, 52 s at M3, and 46 s at M4). Engine rotational speed decreased with

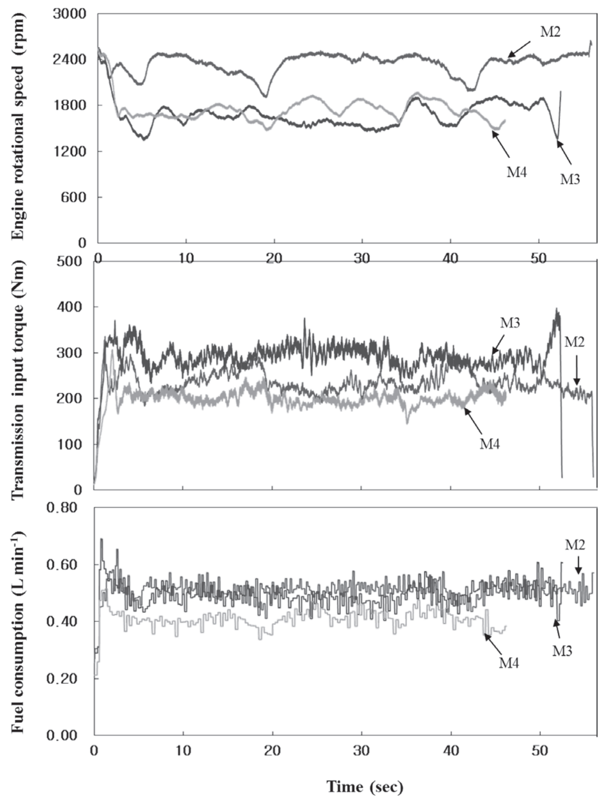

Fig. 6. Representative measured data of the conventional tractor during plowing.

increasing ground speed, and it was lowest at M3 gear setting. Transmission input shaft torque was highest by average 300 Nm at M3, and followed by 230 Nm at M2 and 200 Nm at M4. Engine rotational decreased and transmission input shaft torque increased with increasing ground speed of the tractor (from M2 to M3); however, they are not with changing ground speed from M3 to M4.

From the results, plowing at M4 gear setting, the highest speed working, showed the lowest both working time and the measured torque. If the ground speed is too fast, the implement slides on the soil with incomplete plowing, causing a decrease in the transmission load although the ground speed increased (Lee *et al*, 2015). Fuel consumption based on the tractor ground speed was observed in a similar range of average 0.5 L min^{-1} at M2 and M3, but it was low by 0.4 L min^{-1} at M4.

Figure 7 shows the representative field data of engine rotational speed, transmission input torque, and fuel consumption during plowing with the hybrid tractor. Engine rotational speed was higher than the one of the conventional tractor for most gear settings, and it decreased with increasing ground speed. The engine rotational speed was lowest at M4 unlike one from the conventional tractor, and transmission input shaft torque also was highest at M4. This was caused by the power assist mode of the hybrid system at high load, which improved the output power and increased engine rotational speed. Working time showed similar tendency with the one from the conventional tractor at M2 and M3, but it increased to 64 s at M4.

From the result of workload comparison, Torque of the conventional tractor decreased by high workload when the ground speed was changed from M3 to M4, however, torque of the hybrid tractor was increased with changing the speed. Therefore, hybrid tractor performed the plowing with higher speed than the conventional tractor. In addition, fuel consumption of the hybrid tractor was lower than one of the conventional tractor and it observed in a similar rage of average 0.5 L min^{-1} at M2 and M4, but it was low by 0.4 L min^{-1} at M3.

Plowing performance

Table 3 shows the comparison of the hybrid tractor and the conventional tractor based on gear settings in terms of engine rotational speed and transmission input torque. Engine rotational speed of the conventional tractor decreased with increasing ground speed, and it was lowest by 1,677 rpm at M3. Transmission input torque of the conventional tractor increased by 25% (from 232.9 Nm to 290.8 Nm) with increasing speed from M2 to M3, but it decreased by 32% (199.8 Nm) with the increasing speed from M3 to M4. It meant that plowing was conducted abnormally due to too high workload with too high ground speed.

Engine rotational speed of the hybrid tractor was observed higher than the one of the conventional tractor except M4. It decreased with increasing ground speed and was lowest by 1,613 rpm at M4. Transmission input torque of the hybrid tractor increased by 47% (from 216.2 Nm to 318.7 Nm) with increasing ground speed from M2 to M3, and it increased by 5% (17Nm) with the

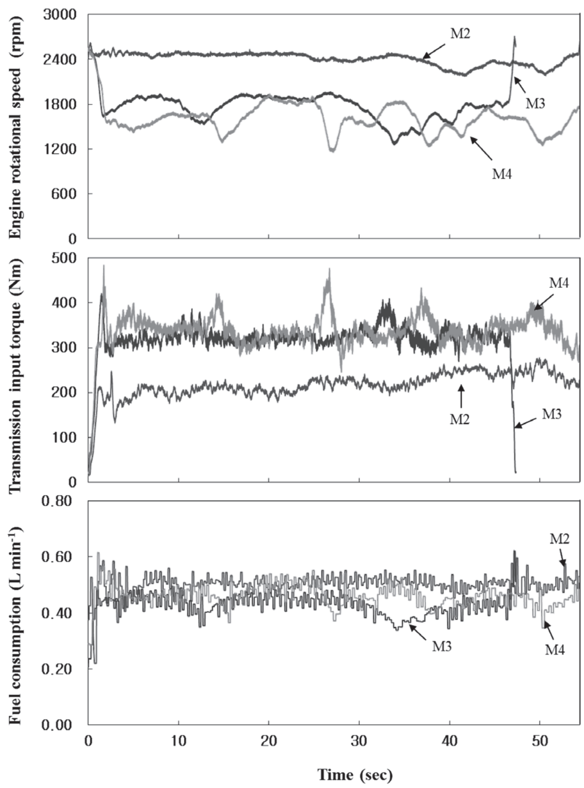

Fig. 7. Representative measured data of the hybrid tractor during plowing.

Table 3. Comparison of working performance between conventional and hybrid tractors based on gear settings during plowing

Gear setting (Rated speed)	Engine rotational speed (rpm)			Transmission input torque (Nm)		
	Conventional	Hybrid	p value	Conventional	Hybrid	p value
M2 (7.2 km h^{-1})	2,346±69a	2,406±62a	0.082	232.9±13.2b	216.2±12.6 b	0.105
M3 (10.3 km h^{-1})	1,677±58b	1,775±49b	0.047	290.8±14.4 a	318.7±13.1a	0.045
M4 (14.7 km h^{-1})	1,752±45c	1,613±48c	0.016	199.8±22.5c	335.4±14.9a	0.014

[a)] Average ± standard deviation

[b)] Means with different superscript (a, b, c) in each column are significantly different at $p<0.05$ by Duncan's multiple range tests increasing speed from M3 to M4. Power output of the hybrid tractor did not decreased at M4 while one from the conventional tractor decreased.

From the results of the t–test between hybrid and conventional tractors, the differences of engine rotational speed and transmission input torque in each tractor increased with increasing speed, and M3 and M4 showed difference with statistical significance at the 5% level.

Performances of the hybrid tractor and the conventional tractor were similar at M2 which is low speed condition and it could work with low load, but the performance of the hybrid tractor was better than one of the conventional tractor at higher load condition (M3, M4).

Table 4 shows the comparison of fuel consumption and efficiency by each tractor and each ground speed, and each value represents the average field data.

Fuel consumption of the conventional tractor was lowest by 0.31 L at M4 and followed by 0.43 L at M3 and 0.47 L at M2, and fuel efficiency increased with increasing ground speed and showed highest (0.67 L $kW^{-1}h^{-1}$) at M4. The results showed that the higher ground speed during plowing, the worse fuel efficiency of the conventional tractor. Especially, fuel efficiency at M4 decreased rapidly by power output lowering. Fuel consumption and fuel efficiency of the hybrid tractor were lowest at M3 by 0.34 L and 0.43 L $kW^{-1}h^{-1}$, respectively, and they were lower than the ones of the conventional tractor at most ground speeds. From the results of the comparison between the tractors using t–test for the ground speed, there was no difference in fuel consumptions at M2, but it was lower at M3 and higher at M4 of the hybrid tractor than the one of the conventional tractor. Fuel efficiency of the hybrid tractor at M2 was similar with the one of the conventional tractor, but it was lower at M3 and M4 than the one of the conventional tractor by 74%. Therefore, fuel efficiency of the hybrid tractor improved significantly with increasing ground speed during plowing.

Performance evaluation

Table 5 shows the SOC variation of the hybrid tractor based on gear settings. Maximum variation increased with increasing ground speed by 5 (M2), 32 (M3), and 60% (M4), and it was highest at M4. This was because hybrid driving consisting of power assist and battery charging modes was not used often at low gear setting that had low load and used less battery. Final variation increased with increasing ground speed by 2 (M2), 3 (M3), and 57% (M4), and it was highest at M4 as maximum variation. Final variation was the difference between initial SOC and final SOC, and the value greater than zero meant that charging and discharging did not occur evenly. Therefore, maximum battery use of M3 was smaller than the one of M4, but the final variation of M3 was less than 10%, which was more efficient during plowing.

SUMMARY AND CONCLUSIONS

In this study, a parallel hybrid tractor was developed and evaluated its performance. For doing this, this study conducted constructing the parallel hybrid tractor using major components of a hybrid driving system, establishing power management strategies for the hybrid tractor, and evaluating the performance of the hybrid tractor comparing with the conventional tractor through field tests. Performances of the hybrid tractor and the conventional tractor were similar at M2 which is low speed condition and it could work with low load, but the performance of the hybrid tractor was better than one of the conventional tractor at higher load condition (M3, M4). Fuel efficiency of the hybrid tractor at M2 was similar with the one of the conventional tractor, but it was

Table 4. Comparison of fuel efficiency in terms of gear settings between conventional and hybrid tractors during plowing

Gear setting (Rated speed)	Fuel consumption (L)			Fuel efficiency (L $kW^{-1}h^{-1}$)		
	Conventional	Hybrid	p value	Conventional	Hybrid	p value
M2 (7.2 km h^{-1})	0.47±0.019^{a}	0.46±0.018^{a}	0.288	0.53±0.021^{c}	0.56±0.022^{a}	0.095
M3 (10.3 km h^{-1})	0.43±0.016^{b}	0.34±0.015^{c}	0.034	0.58±0.025^{b}	0.43±0.021^{c}	0.018
M4 (14.7 km h^{-1})	0.31±0.015^{c}	0.42±0.019^{b}	0.032	0.67±0.192^{a}	0.49±0.024^{b}	< 0.001

a) Average ± standard deviation
b) Means with different superscript (a, b, c) in each column are significantly different at p<0.05 by Duncan's multiple range tests

Table 5. SOC variation of the hybrid tractor in terms of gear settings during plowing

SOC (%)	M2 (7.2 km h^{-1})	M3 (10.3 km h^{-1})	M4 (14.7 km h^{-1})
Maximum variation	5±3.9^{c}	32±3.6^{b}	60±1.2^{a}
Final variation	2±1.3^{b}	3±1.0^{b}	57±2.4^{a}

a) Average ± standard deviation
b) Means with different superscript (a, b, c) in each row are significantly different at p<0.05 by Duncan's multiple range tests

lower at M3 and M4 than the one of the conventional tractor by 74%.

The parallel hybrid tractor showed the same performance with the conventional tractor at lower gear setting, but it improved the power output and fuel efficiency at higher gear setting that had high workload compared with the conventional tractor. Especially, fuel efficiency at M3 was 0.43 L $kW^{-1}h^{-1}$ which reduced by 25% compared with the one of the conventional tractor. And no power output lowering was observed at higher ground speed, M4. This study showed that the performance of the hybrid tractor was more improved than the conventional tractor, but this study was carried out under certain constraints such as similar field conditions and same operator.

Thus, to use the hybrid tractor as general product in agricultural area, performance and reliability of the hybrid tractor should be validated through field tests under various regions and working conditions (field operations, operators, attached implements, etc), and target engine speed based on the working conditions should be optimized. In addition the mode control of HCU algorithm needs to be improved with various control factors.

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