Soil & Tillage Research 134 (2013) 90–96

Contents lists available at ScienceDirect

Soil & Tillage Research

journal homepage: www.elsevier.com/locate/still

Effects of gear selection of an agricultural tractor on transmission and PTO load during rotary tillage

Yong-Joo Kim [a], Sun-Ok Chung [b,*], Chang-Hyun Choi [c]

[a] Machinery Technology Group, Advanced R&D Center, LS Mtron Ltd., Anyang, Republic of Korea
[b] Department of Biosystems Machinery Engineering, Chungnam National University, Daejeon, Republic of Korea
[c] Department of Bio-mechatronic Engineering, Sungkyunkwan University, Suwon, Republic of Korea

ARTICLE INFO

Article history:
Received 15 December 2012
Received in revised form 26 July 2013
Accepted 27 July 2013

Keywords:
Agricultural tractor
Gear selection
Transmission
PTO (power take off)
Load severeness
Rotary tillage

ABSTRACT

For better performance and durability of a tractor during field operations, it is necessary to select the optimal gear setting for the operation. The purpose of this study was to analyze effects of the gear selection on load acting on the transmission and PTO shafts of a 75 kW agricultural tractor during rotary tillage with a 20-cm tillage depth. In order to measure the loads acting on the transmission and PTO input shafts, a load measurement system was installed on the tractor. The system consisted of strain-gauge sensors to measure the torque on the transmission and PTO input shafts, a radio telemetry I/O interface to acquire the sensor signals, and embedded software to acquire the data. Rotary tillage was conducted at three ground speeds and three PTO rotational speeds under upland field sites with the same soil conditions. The load data was converted to a load spectrum using the rain-flow counting and SWT (Smith Watson Topper) equations. Sum of damage due to the load was calculated using the Modified Miner's rule for each gear selection, and then the load severeness was calculated as the relative magnitude of the damage sum. The average torque on the transmission input shaft increased significantly as the ground speed increased from L1 (1.87 km h^{-1}) to L3 (3.77 km h^{-1}) at the same PTO rotational speed. Also, the average torque on the PTO input shaft increased as the PTO rotational speed increased at the same ground speed. Rotary tillage exerted significantly greater loads on the PTO input shaft than on the transmission input shaft. The severeness of the load on the transmission and PTO shafts increased, indicating possible decreased fatigue life, as both the ground and PTO rotational speeds increased. Results of the study might provide information useful for optimum gear selection for rotary tillage, considering not only field efficiency, but load severeness on the transmission and PTO input shafts.

1. Introduction

Agricultural tractors are used as a power source for various field operations such as tillage, planting, chemical application, harvesting, transportation, through driving axles, power take off (PTO) devices, and hydraulic lines. The number of agricultural tractors is increasing in many countries in the world. For example, the utilization ratio of a tractor in Korea has been increased to 71.8% of agricultural working days during the spring and autumn seasons in 2010 (Park et al., 2010a,b). A tractor has various levels of driving and PTO gear settings, and different combinations of the gear settings are used to provide the required power suitable for an operation type and field condition.

Optimum gear setting for operation type is important since the load acting on the tractor, part durability and working performance are determined by the gear setting (Park et al., 2010c). Durability of tractor parts is one of the important concerns (Rotz and Bowers, 1991). Simens and Bowers (1999) reported that American farmers spent about 40% of the total maintenance costs to repair the tractor and about 30% to repair the failure of powertrain parts due to excessively high operating speeds. Also, working performance affects fuel consumption of the tractor. In the case of the Republic of Korea, annual fuel consumption by tractors was 345 ML/year, accounting for about 48.5% of the total annual fuel consumption of agricultural machinery (KAMICO and KSAM, 2010). Therefore, it would be meaningful to analyze effects of gear selection on tractor load during field operations.

Kichler et al. (2011) analyzed the effects of the transmission gear selection on the tractor performance and reported a 105% increase in fuel consumption rate, a 28% increase in implement draft, and a 255% increase in required power when the gear setting was changed from 3.0 km h^{-1} to 8.3 km h^{-1} in plow tillage. Several

* Corresponding author at: Department of Biosystems Machinery Engineering, Chungnam National University, Daejeon 305-764, Republic of Korea.
Tel.: +82 42 821 6712; fax: +82 42 823 6246.
E-mail address: sochung@cnu.ac.kr (S.-O. Chung).

0167-1987/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.still.2013.07.013

studies have analyzed tractor load during field operations (Gerlach, 1966; Van et al., 2009) for efficient and optimum design of a tractor (Han et al., 1999). Most studies on the load analysis have focused on the transmission since it makes up about 30% of the total tractor costs (e.g., Kim, 1998). For analysis of the transmission load, researchers analyzed torque load acting on the transmission input shaft and the driving axle shafts of the tractor during field operations such as plow tillage (Kim et al., 2001; Nahmgung, 2001). The load on the transmission input shaft and the driving axle shafts increased with plowing speed in most of the field conditions.

Some research considered load on PTO shafts during rotary tillage and baling operations. Kim et al. (2011b) analyzed power consumption of a tractor with a rated engine power of 75 kW during baler operation and reported that ratios of the power consumption to the engine power were 50–75% for all PTO gear levels. Also, Kim et al. (2011a) analyzed power requirement of major components (driving axles, PTO shaft, and hydraulic pumps) of a 30 kW agricultural tractor during plow tillage, rotary tillage, and loader operations. Rotary tillage required the greatest power, and the PTO shaft experienced the greatest amount of the power among the components during the process. Summarizing the findings above, considerable amount of the load was applied on PTO shaft during rotary tillage. However, research related to the effects of transmission (i.e., operation speed) and PTO gear selection on the tractor load during field operations has not been reported.

This study was an attempt to provide guidelines for the optimum gear setting, considering both field efficiency and load severeness of the major power transmission parts. The purpose of this study was to analyze effects of gear selection on loads acting on the transmission and PTO shafts of a 75 kW agricultural tractor during rotary tillage.

2. Materials and methods

2.1. Measurement system

A 75-kW agricultural tractor (L7040, LS Mtron Ltd., Korea) was used in this study. The tractor had a total mass of 3260 kg and dimensions of 4077 mm × 2000 mm × 2640 mm (length × width × height). The rated engine power and the PTO power of the tractor at an engine revolution speed of 2300 rpm were 75 kW and 65 kW, respectively. The tractor was equipped with a Synchro-mesh type manual transmission composed of two direction-gears, four main-gears, and four sub-gears. The 16 forward and 16 backward ground speeds of the tractor were determined by combination of the gear settings. The PTO rotational speeds of the tractor at P1, P2, and P3 settings were 540 rpm, 750 rpm, and 1000 rpm, respectively. Fig. 1 shows the torque transducers and radio telemetry systems fitted on the transmission and PTO input shafts for load measurement. The transmission and PTO input shafts were connected directly to the engine crankshaft; therefore, the speed ratio between the engine crankshaft and the shaft was 1:1. The load measurement system was installed inside of the clutch housing. The load measurement system was constructed with strain-gauge sensors (CEA-06-250US-350, MicroMeasurement Co., USA) to measure torque, radio telemetry I/O interfaces (R2, Manner, Germany) to acquire the sensor signals, and an embedded system to analyze the load. For load measurement of the transmission, a strain-gauge with a rotor antenna was installed on the transmission input shaft, and a stator antenna was installed on the shaft case. For PTO load measurement, a strain-gauge was installed on the flywheel-sleeve, and a rotor antenna and a stator antenna were installed on the flywheel and engine case, respectively. The embedded system had the maximum resolution of 24 bits. Load signal from the strain gauges of the calibrated torque transducers was digitized with a sampling rate of 19.2 kHz at a 24-bit resolution and stored in the embedded system (MGC, HMB, Germany). A program to measure the load signal was developed based on Labview software (version 2009, National Instrument, USA).

2.2. Experimental methods

The load acting on the tractor during field operation depends on many factors such as soil condition and driver skill. Because taking all of these factors into consideration was not practical (Nahmgung, 2001), effects of these factors were minimized in the study to focus on effects of ground speed and PTO rotational speed on the load through gear selection.

Rotary tillage was conducted at three ground speeds and three PTO rotational speeds in upland field sites located at 35°59′23″ and 35°59′26″ North and 127°12′56″ and 127°13′3″ East. The soil type was sandy, the average water content was 22.3%, and the average cone index was 1236 kPa, over the depths of 0–250 mm.

The tillage depth was set as 20 cm. The transmission gear was set to at L1, L2, and L3 gears to match with PTO gears of P1, P2, and P3, respectively. The gear settings were selected based on the results of a survey for the annual usage ratio of tractor reported by Kim et al. (2011a). The ground speeds of the tractor at L1, L2, and L3 were 1.87 km h^{-1}, 2.64 km h^{-1}, and 3.77 km h^{-1} and the PTO rotational speeds at P1, P2, and P3 were 540 rpm, 750 rpm, and 1000 rpm, respectively. The rotary tillage tool was a heavy duty rotavator (WJ220E, WOONGJIN, Korea), and the required rated power, total mass, tillage width, and dimensions were 75 kW, 750 kg, 2220 mm, and 1050 mm × 2390 mm × 1380 mm (length × width × height), respectively.

2.3. Load analysis

Procedures to analyze the tractor load would be different, depending on the purpose. Many researchers have used simple statistics such as average, maximum, and minimum values in order to represent the load. This method extracts representative values to show the difference of amplitude, but this simplification prohibits characterizing the whole load profiles since the field load is irregular. Effects of gear setting on the transmission and PTO load, One-Way ANOVA and the least significant difference test (LSD) were conducted with SAS (version 9.1, SAS Institute, Cary, USA). Also, it is difficult to represent effects of the load on the tractor since the load causes damages to the tractor, and fatigue of the tractor parts also needs to be investigated. Fatigue of a tractor is defined as the damage sum from repeated loadings (Lampman, 1997).

Severeness, another method of load representation proposed by Kim et al. (1998, 2000), is defined as the ratio of the damage sum at each operation to the minimum damage sum from all the operations. Severeness would be inversely proportional to fatigue life. When load severeness is greater, fatigue life would be shorter. Kim et al. (1998) measured the loads acting on the transmission input shaft and analyzed the load severeness during plow tillage, rotary tillage, and transportation operations. They found that the severeness during transportation operation was similar to that during plow tillage, but the severeness during rotary tillage was about 63 times greater than that during the transportation operation. Later, Kim et al. (2000) analyzed the severeness of the transmission input shaft during rotary tillage at four speed combinations of the tractor ground speeds (2.9 km h^{-1} and 4.1 km h^{-1}) and PTO rotational speeds (588 and 704 rpm) using a tractor with a rated engine power of 30 kW. The load severeness increased by 2.3–2.6 times when the PTO speed increased with the

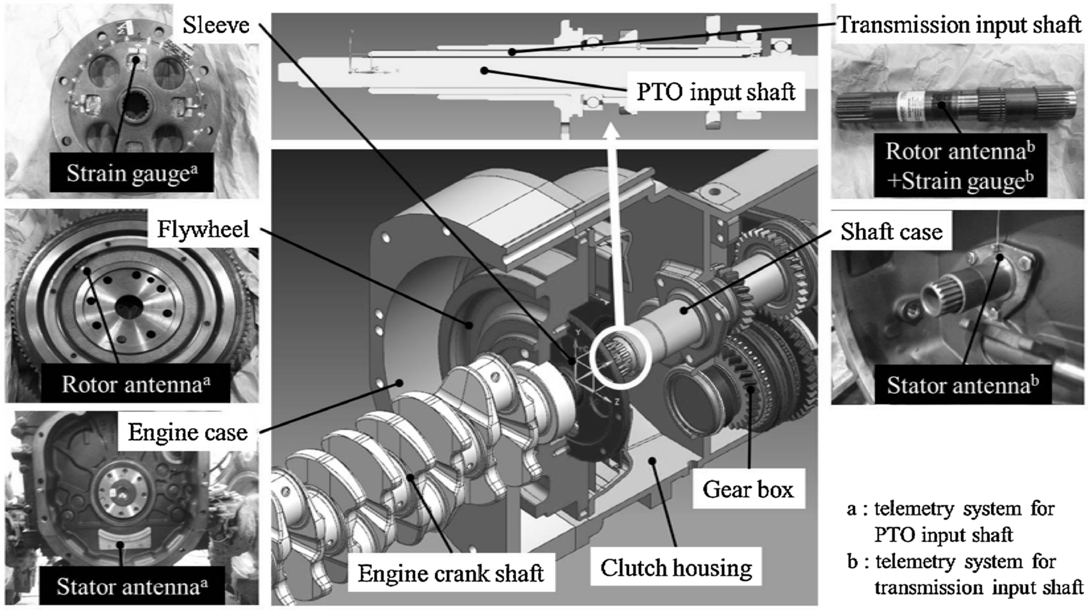

Fig. 1. Strain-gauges and radio telemetry systems for torque measurement on the transmission and PTO input shafts.

same ground speed, while the severeness decreased by 0.2–0.3 times when the ground speed increased with the same PTO speed.

Fig. 2 is a block diagram explaining the procedures of severeness calculation. The measured torque data was converted from time domain to frequency domain using the rainflow cycle counting method since the torque data was irregular (Xiong and Shenoi, 2005). The rainflow cycle counting technique is commonly recognized as a good cyclic counting method in fatigue life prediction (Hong, 1991). It decomposes a variable amplitude load history into a series of simple events equivalent to individual cycles of constant load amplitude (Glinka and Kam, 1987). In addition, the Smith-Waston-Topper uniaxial method was used for calculation of spectrum magnitude to remove effects of the mean torque using Eq. (1) (Dowling, 1972).

$$T_e = \sqrt{(t_a + t_m)t_a} \quad (1)$$

where T_e is equivalent torque (Nm), t_a is torque amplitude (Nm), and t_m is mean of torque (Nm).

Since the recorded time of the measured load data was relatively short (180–200 s), it was necessary to extend the number of cycles to the total usage time of rotary tillage of the tractor. In order to calculate the total number of cycles at the magnitude of the load, the entire life of the test tractor was assumed. The total number of cycles of the load was calculated in Eq. (2).

$$N_T = 3600NLh \quad (2)$$

where N_T is total number of cycles of the load (cycles), N is number of calculated cycles of the measured load (cycles s^{-1}), L is entire life of the used tractor (year), and h is annual usage time of the tractor for the operation (h $year^{-1}$).

The annual usage time of the used tractor was 204 hours for rotary tillage in Korea (Lee, 2011). The entire life of the used tractor was assumed as 10 years, which was normal in Korean agricultural conditions. The load spectra for the entire life of the used tractor at different gear settings for rotary tillage were represented by the ratio of the measured loads to the rated engine torque load, which was 275 Nm. The ratios greater than 1 indicates unfavorable load levels greater than the rated engine torque load.

The damage sum was calculated using measured load and *S–N* (bending stress vs. number of cycle) curve to estimate the number of cycles of loading to failure (Fatemi and Yang, 1998). The *S–N* curve was converted to a torque-cycle curve because of the damage caused by torque signal (Graham et al., 1962; Nguyen et al., 2011). The *S–N* curve was obtained for the material of the input shaft, SCM 420H, using the ASTM standard (2004) in Eq. (3). The ASTM standard has been widely used for fatigue analysis of materials (Wannenburg et al., 2009; Mao, 2010).

$$N = 10^{(6-6.097\log(S/223))} \quad (3)$$

where N is the number of cycles, S is shear stress (MPa).

To calculate damage sum, equivalent torque of load spectrum was converted to stress (Rahama and Chancellor,

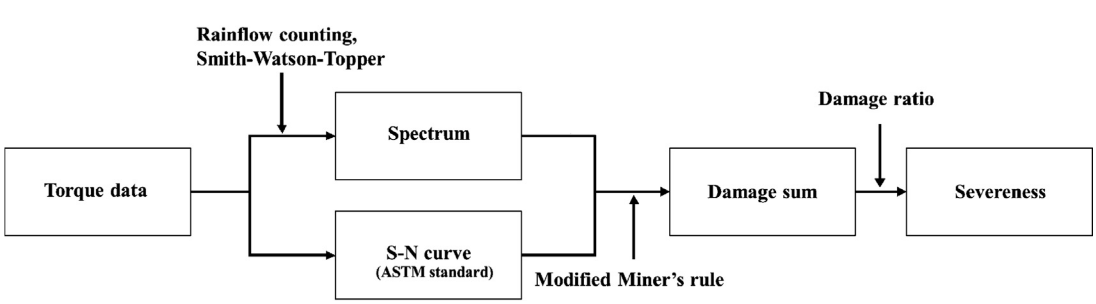

Fig. 2. Schematic diagram explaining the procedures of severeness evaluation.

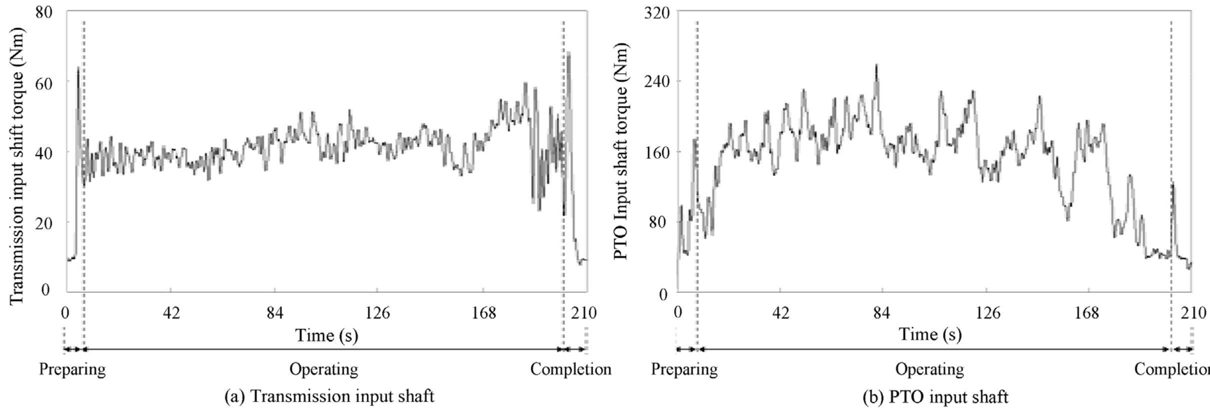

Fig. 3. Example of torque loads on the transmission and PTO input shafts torque at the L1P2 selection during rotary tillage.

1994; Petracconi et al., 2010). The diameters of the transmission and the PTO input shafts were 28 mm and 26.5 mm, respectively.

$$S = \frac{16T}{\pi d^3} \quad (4)$$

where S is stress (MPa), T is equivalent torque (Nm), and d is diameter of the shaft (mm).

The damage sum was calculated based on the Miner's rule (Miner, 1945) in Eq. (5). Miner's rule is a procedure for estimating the number of cycles of loading to failure (Miner, 1945; Robson, 1964; Renius, 1977). The number of cycles (n) was derived from an equivalent torque of the load spectrum. The fatigue life cycles (N) was derived from the S–N of SCM 420H. The damage (D) was calculated by dividing the number of the fatigue life cycles into the number of cycles.

$$D_t = \sum_{i=1}^{k} \frac{n_i}{N_i} \quad (5)$$

where D_t is damage sum, n_i is number of cycles, and N_i is fatigue life (cycles).

3. Results and discussion

3.1. Transmission and PTO loads by gear selection

Fig. 3 shows examples of torque loads on the transmission and PTO input shafts for the ground speed at L1 and the PTO rotational speed at P2 during the rotary tillage operation. The rotary tillage operation consisted of a preparing period to descend the 3-point hitch, an operating period to till the soil, and a completion period to ascend the 3-point hitch. The measured torque on the transmission and PTO input shafts showed steep increasing in the preparing period and decreasing in the completion period, and torque on these components showed irregular fluctuation patterns in the operating period. The magnitude and range of the measured torque on the PTO input shaft were greater than those on the transmission input shaft in the operating period.

Table 1 shows torque levels on the transmission and PTO input shafts by speed combination of the ground speeds (L1, L2, L3) and the PTO rotational speeds (P1, P2, P3). The average torque was calculated only for the operating period data, not for the preparing and completion periods. The averaged torque levels of the PTO input shaft were greater than those of the transmission input shaft at all gear levels during the rotary tillage. These results were similar to the results by Kim et al. (2011a) that the PTO required the greatest amount of power among the major components during rotary tillage.

The average torque on the transmission input shaft was considerably and significantly increased as the ground speed increased from L1 to L3 at the same PTO rotational speeds. Load increases on the transmission and driving shafts with the speed increase of plow tillage were also found by Kim et al. (2011a,b) and Nahmgung (2001). Also, the averaged load on the transmission input shaft increased as the PTO rotational speed increased, except that the load values were not significantly different between L1P2 and L1P3. The average torque on the PTO input shaft increased as the ground speed and PTO rotational speed increased. The increases were statistically significant for the PTO rotational speed, but not significant for the ground speed.

3.2. Severeness evaluation

Figs. 4 and 5 show load spectra of the transmission and the PTO input shafts by gear setting during the rotary tillage, respectively. The spectra were constructed considering the entire life of the tractor, and the numbers of cycles were in the ranges from 10^3 to 10^7. The range of the maximum torque ratio of the transmission input shaft was 0.7–1.5 for the speed-combinations and the greatest torque ratio was found at L3P1 as shown in Fig. 4. In

Table 1
Average torque (Nm) on the transmission and PTO input shafts by gear setting during rotary tillage.

	Transmission input shaft			PTO input shaft		
	P1	P2	P3	P1	P2	P3
L1	29.8 ± 2.8^{Aa} [1,2,3]	35.9 ± 4.2^{Ba}	38.7 ± 4.7^{Ba}	105.0 ± 3.6^{Aa} (3.52)[4]	148.7 ± 3.7^{Ba} (4.14)	175.8 ± 4.2^{Ca} (4.54)
L2	43.5 ± 4.7^{Ab}	51.3 ± 3.3^{Bb}	58.5 ± 3.1^{Cb}	114.7 ± 3.9^{Ab} (2.64)	151.7 ± 4.1^{Ba} (2.95)	177.7 ± 3.4^{Ca} (3.03)
L3	64.9 ± 3.2^{Ac}	71.5 ± 3.5^{Bc}	82.1 ± 4.9^{Cc}	118.7 ± 4.0^{Ab} (1.83)	151.9 ± 3.8^{Ba} (2.12)	182.9 ± 4.2^{Cb} (2.23)

[1] Average ± standard deviation.
[2] Means with different superscript (A, B, C, D) in each row are significantly different at $p < 0.05$ by LSD's multiple range tests
[3] Means with different superscript (a, b, c, d) in each column are significantly different at $p < 0.05$ by LSD's multiple range tests.
[4] Values in the parentheses are the ratios of the torque on the PTO input shaft to the torque on the transmission input shaft at the speed combinations.

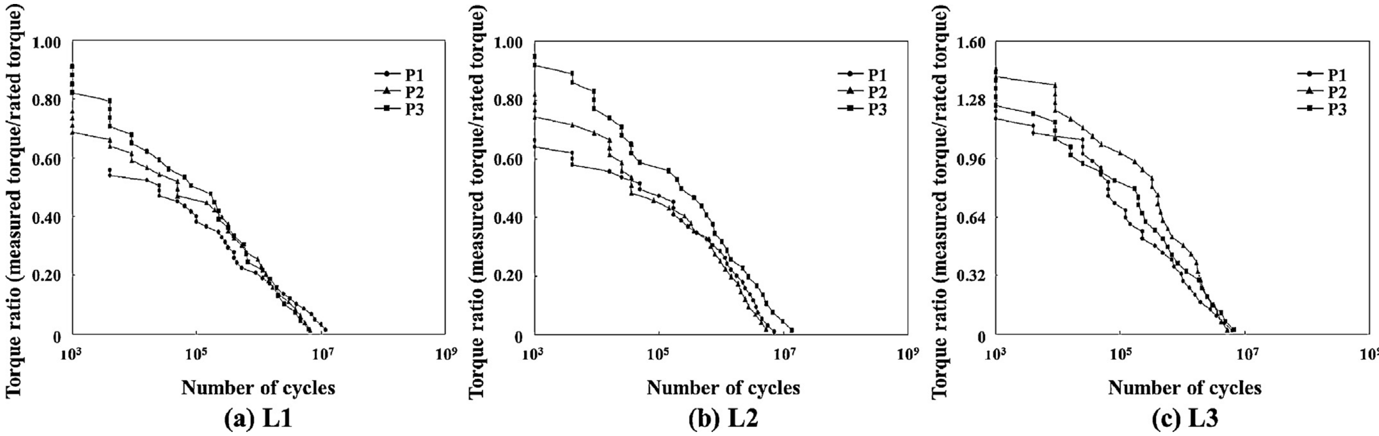

Fig. 4. Load spectra for the transmission input shaft at different gear settings during rotary tillage.

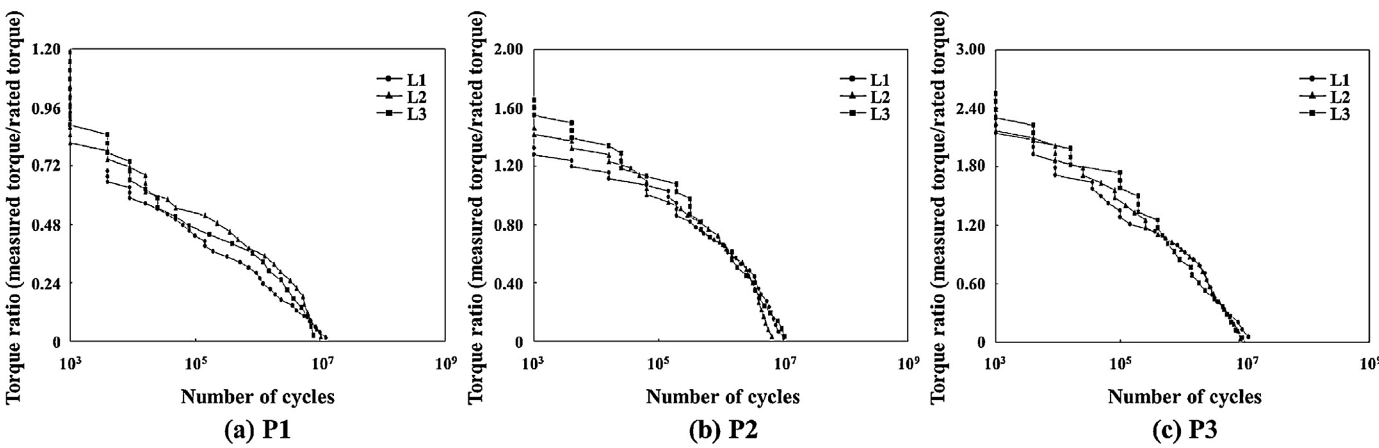

Fig. 5. Load spectra for the PTO input shaft at different gear settings during rotary tillage.

general, the torque ratio increased when the ground speed and PTO rotational speed increased. The greater ground speed and PTO rotational speed were during the rotary tillage, the greater loads on the PTO input shaft were. The torque ratios of the PTO input shaft were greater than those of the transmission input shaft as shown in Fig. 5. The range of the maximum torque ratio of the PTO input shaft was 0.8–2.5 and the greatest torque ratio was found also at L3P1, like for the transmission input shaft. The greater PTO rotational speed was, the greater load on the PTO input shaft was.

Fig. 6 shows evaluation of the severeness by the gear setting during the rotary tillage. The severeness for each gear setting was represented by ratio of the damage sum to the smallest damage sum among the speed combinations. Fig. 6(a) shows the severeness for the transmission input shaft. The smallest severeness was obtained at the lowest speed combination when the transmission was geared to L1 and the PTO gear was set to P1. The severeness increased when the combined speed increased, and the increasing amounts were greater when the ground speed increased. The severeness increased by 573–746% when the ground speed increased by 201% as the transmission gear was shifted from L1 to L3 at the same PTO rotational speed. At constant ground speeds, the severeness increased by 187 to 340% when the PTO rotational speed increased by 185% as the PTO gear was shifted from P1 to P3. There was no statistical difference when the average load

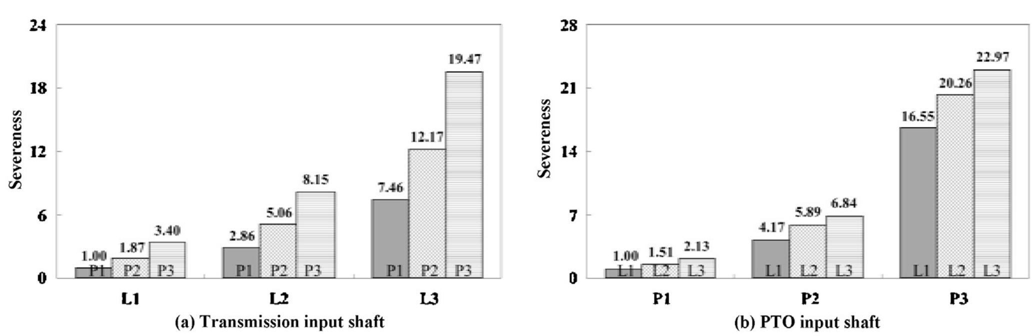

Fig. 6. Severeness evaluation for the tractor transmission (a) and PTO input shafts (b) at different gear settings during rotary tillage.

increased by only 11% (35.9–38.7 Nm) from L1P2 to L1P3, but the severeness increased by 182%. The results showed that greater gear setting of the transmission and PTO caused greater severeness on the transmission input shaft, which was different from the result of Kim et al. (2000) of only the greater PTO gear setting resulting in greater severeness of the transmission in rotary tillage. It may be attributed to that the ground speed (3.77 km h^{-1}) used by Kim et al. (2000) was relatively fast for rotary tillage. If the ground speed is too fast, the rotavator would likely walk on the soil, causing a decrease in transmission load as the ground speed was increased.

Fig. 6(b) shows the severeness of the PTO input shaft. The results were similar in the case of the transmission input shaft. The speed-combination of L1P1 resulted in the smallest severeness, and the severeness increased when the combined speed increased. It should be noted that the severeness increased significantly by 1078–1655% when the PTO rotational speed increased by 185% as the PTO gear was shifted from P1 to P3 at the same ground speed. The severeness increased by 139–213% when the ground speed increased by 201% as the transmission gear was shifted from L1 to L3 at the same PTO rotational speed. Also, the average load was not statistically different as the ground speed increased. The results showed that the load on the PTO input shaft was affected more significantly by the PTO rotational speed rather than by the ground speed.

4. Summary and conclusions

This study was conducted to analyze effects of the gear selection on load acting on the transmission and PTO input shafts of a 75 kW agricultural tractor during rotary tillage. First, the loads acting on the transmission and PTO input shafts were measured during rotary tillage. Rotary tillage was conducted at three ground speeds and three PTO rotational speeds under upland field sites with the same soil conditions. Second, loads on the transmission and PTO input shafts were evaluated. The results showed that the average torque on the transmission input shaft increased significantly as the ground speed increased from L1 to L3 at the same PTO rotational speed. Also, the average torque on the PTO input shaft increased as the PTO rotational speed increased at the same ground speed.

Finally, load severeness of the transmission and PTO input shafts were evaluated. Severeness levels of the transmission and PTO input shafts increased as both the ground speed and PTO rotational speed increased. The severeness of the transmission input shaft increased by 573–746% when the ground speed increased by 201% as the transmission gear was shifted from L1 to L3 at the same PTO rotational speed. At the same ground speed, the severeness increased by 187–340% when the PTO rotational speed increased by 185% as the PTO gear was shifted from P1 to P3. The fatigue life of the transmission input shaft decreased when the combined speed increased, and effects of the ground speed were more significant. The severeness of the PTO shaft increased significantly by 1078–1655% when the PTO rotational speed increased by 185% as the PTO gear was shifted from P1 to P3 at the constant ground speed. The severeness increased by 139–213% when the ground speed increased by 201% as the transmission gear was shifted from L1 to L3 at the same PTO rotational speed. The fatigue life of the PTO shaft was similar in the case of the transmission input shaft.

Farmers tend to conduct rotary tillage operation at greater travel speeds for greater field efficiency (i.e., less time) and greater PTO rotational speeds for finer tilth. Greater travel and PTO speeds, however, would cause greater loads on and shorter fatigue life of the input shafts. Furthermore, greater speeds may cause unfavorable soil conditions after the tillage operation. For example, improper fast travel speeds may lead to coarser soil conditions, while too fast PTO rotational speeds may lead to finer soil conditions, than favorable tilth for better crop growth and less environmental concerns such as soil erosion. Farmers need to select an optimum gear setting for their crop and soil conditions, considering not only field efficiency but load severeness of the major power transmission parts.

Acknowledgement

This research was supported by Bio-industry Technology Development Program, Ministry for Food, Agriculture, Forestry and Fisheries, Republic of Korea.

References

ASTM, 2004. Statistical Analysis of Linear or Linearized Stress-Life (S–N) and Strain-Life (ε-N) Fatigue Data. In: ASTM standard E739-91. American Society for Testing and Materials, Pittsburgh.

Dowling, N.E., 1972. Fatigue failure predictions for complicated stress–strain histories. Journal of Materials 7, 71–87.

Fatemi, A., Yang, L., 1998. Cumulative fatigue damage and life prediction histories; a survey of the state of the art for homogenous materials. International Journal of Fatigue 20 (1) 9–34.

Gerlach, A., 1966. Field measurement of tractor transmission forces. Transactions of the ASAE 9 (5) 707–712.

Glinka, G., Kam, J.C.P., 1987. Rainflow counting algorithm for very long stress histories. International Journal of Fatigue 9 (4) 223–228.

Graham, J.A., Berns, D.K., Olberts, D.R., 1962. Cumulative damage used to analyze tractor final drives. Transaction of the ASAE 5 (2) 139–146.

Han, K.H., Kim, K.U., Wu, Y.G., 1999. Severeness of transmission loads of agricultural tractor for rotary operations in poorly drained paddy field. Journal of Biosystems Engineering 24 (4) 293–300.

Hong, N., 1991. A modified rainflow counting method. International Journal of Fatigue 13 (6) 465–469.

KAMICO, KSAM, 2010. Agricultural Machinery Yearbook in Republic of Korea. Korea Agricultural Machinery Industry Cooperative and Korean Society for Agricultural Machinery, Seoul.

Kichler, C.M., Fulton, J.P., Raper, R.L., McDonald, T.P., Zech, W.C., 2011. Effects of transmission gear selection on tractor performance and fuel costs during deep tillage operations. Soil and Tillage Research 113 (2) 105–111.

Kim, D.C., Ryu, I.H., Kim, K.U., 2001. Analysis of tractor transmission and driving axle loads. Transactions of the ASABE 44 (4) 751–757.

Kim, J.H., 1998. Analysis of Mission and Transmission Loads of Agricultural Tractors. Seoul National University, Seoul, Republic of Korea (Unpublished MS Thesis).

Kim, J.H., Kim, K.U., Choi, C.W., Wu, Y.G., 1998. Severeness of transmission loads of agricultural tractors. Journal of Biosystems Engineering 23 (5) 417–426.

Kim, J.H., Kim, K.U., Wu, Y.G., 2000. Analysis of transmission load of agricultural tractors. Journal of Terramechanics 37, 113–125.

Kim, Y.J., Chung, S.O., Park, S.J., Choi, C.H., 2011a. Analysis of power requirement of agricultural tractor by major field operation. Journal of Biosystems Engineering 36 (2) 79–88.

Kim, Y.J., Lee, D.H., Chung, S.O., Park, S.J., Choi, C.H., 2011b. Analysis of power requirement of agricultural tractor during baler operation. Journal of Biosystems Engineering 36 (4) 243–251.

Lampman, S.R., 1997. ASM Handbook 19: Fatigue and Fracture. ASM International, Ohio.

Lee, D.H., 2011. Analysis of Power Requirements of Tractor for Field Operations. Sungkyunkwan University, Suwon, Republic of Korea (MS Thesis).

Mao, W., 2010. Fatigue Assessment and Extreme Response Prediction of Ship Structures. Chalmers University of Technology and University of Gothenburg, Sweden (PhD Dissertation).

Miner, M.A., 1945. Cumulative damage in fatigue. Journal of Applied Mechanics 12 (3) 159–164.

Nahmgung, M.J., 2001. Load Analysis of Driving Axles and Life Evaluation of Driving Gear of PTO on Tractors. Sungkyunkwan University, Suwon, Republic of Korea (PhD Dissertation).

Nguyen, N.T., Chu, Q.T., Kim, S.E., 2011. Fatigue analysis of a pre-fabricated orthotropic steel deck for light-weight vehicles. Journal of Constructional Steel Research 67 (4) 647–655.

Park, S.H., Kim, Y.J., Im, D.H., Kim, C.K., Jang, Y., Kim, S.S., 2010a. Analysis of factors affecting fuel consumption of agricultural tractor. Journal of Biosystems Engineering 35 (3) 151–157.

Park, S.H., Kim, Y.J., Im, D.H., Kim, C.K., Jung, S.C., Kim, H.J., Jang, Y., Kim, S.S., 2010b. Development of eco driving system for agricultural tractor. Journal of Biosystems Engineering 35 (2) 77–84.

Park, S.H., Kim, Y.J., Im, D.H., Kim, C.K., Jung, S.C., Kim, H.J., Lee, J.S., Kim, S.S., 2010c. Characteristics of tractor PTO power and workloads. Journal of Biosystems Engineering 35 (1) 15–20.

Petracconi, C.L., Ferreira, S.E., Palma, E.S., 2010. Fatigue life simulation of a rear tow hook assembly of a passenger car. Engineering Failure Analysis 17 (2) 455–463.

Rahama, O.A., Chancellor, W.J., 1994. Peak and average loads on tractor structures. Transactions of the ASAE 37 (6) 1733–1740.

Renius, K.T., 1977. Application of cumulative damage theory to agricultural tractor design elements. Konstrucktion 29 (3) 85–93.

Robson, J.D., 1964. An Introduction to Random Vibration. Edinburgh University Press, Edinburgh.

Rotz, A., Bowers, W., 1991. Repair and Maintenance Cost Data for Agricultural Equipment. In: ASAE Report No. 911531. American Society for Agricultural Engineers, St. Joseph, MI.

Simens, J.C., Bowers, W., 1999. Machinery Management: How to Select Machinery to Fit the Real Needs of Farm Managers, Farm Business Management (FMB) Series. John Deere Publishing, East Moline, IL.

Van, N.N., Matsuo, T., Koumoto, T., Inaba, S., 2009. Transducers for measuring dynamic axle load of farm tractor. Bulletin of the Faculty of Agriculture, Saga University 94, 23–35.

Wannenburg, J., Heyns, P.S., Raath, A.D., 2009. Application of fatigue equivalent static load methodology for the numerical durability assessment of heavy vehicle structures. International Journal of Fatigue 31 (10) 1541–1549.

Xiong, J.J., Shenoi, R.A., 2005. A reliability-based data treatment system for actual load history. Fatigue and Fracture of Engineering Materials and Structures 28 (10) 875–889.