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Analysis of the PTO load of a 75 kW agricultural tractor during rotary tillage and baler operation in Korean upland fields

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Abstract

In this paper, the PTO severeness of an agricultural tractor during rotary tillage and baler operation was analyzed. The S–N curves of the PTO driving gears were obtained through fatigue life test. To obtain the S–N curves of the PTO driving gears, the breakage time and rotational speed of the gears were measured through observation of the bending stress with changing torque. The torque acting on the PTO was measured and analyzed during rotary tillage and baler operation. Rotary tillage and baler operation were conducted at two ground speeds and two PTO rotational speeds at upland field sites with similar soil conditions, respectively. The load data were inverted to a load spectrum using rain-flow counting and SWT equations. Modified Miner's rule was used to calculate the partial damage sum. The severeness was defined as the relative ratio of the damage sum. The results showed that the damage of the PTO increased when the ground speed or the PTO rotational speed increased. The effect of the PTO rotational speed on the severeness of the PTO was more significant than that of the ground speed. The severeness of the PTO of rotary tillage was greater than that of baler operation.

Keywords: Agricultural tractor; PTO; Severeness; Rotary tillage; Baler operation

1. Introduction

Tractor production reached 40,449 units in 2011, accounting for 57% of major agricultural machinery (tractor, combine, and rice transplanter) for field operations in Korea. The utilization ratio of the tractor in field operations increased to 85.7% in 2011 (KAMICO and KSAM, 2014).

Analysis of the load on the major parts of the tractor power drive line during field operations is critical for the optimum design of a tractor (Han et al., 1999). Load analysis has been studied mostly on the transmission because it makes up approximately 30% of the total tractor costs (Kim, 1998). Gerlach (1966) measured the transmission loads of an agricultural tractor under plow tillage, and the peak torque was approximately 2.5 times the rated engine torque. Kim et al. (2001) measured and analyzed the torque load acting on the transmission and driving axle shafts of an agricultural tractor during plow tillage operations in Korea. The torque measurements were made under five field conditions and at two speed levels. The results showed that the load increased with plowing speed in both

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the input shaft and final drive shaft in every field condition. Especially, the effect of the plowing speed on the load spectrum was more significant at the input shaft of the transmission than at the final drive shaft.

Recently, research for improving the major components of an agricultural tractor, including the transmission, has been accelerated for tractor localization (Kim et al., 2013), and research on PTO driven tractor implements is an important topic. Kim et al. (2011a) analyzed the power requirements of agricultural tractors during plow tillage, rotary tillage, and loader operations. They conducted a survey to obtain the annual usage ratio of the tractor. The annual usage ratio of rotary tillage was approximately 45%, indicating that rotary tillage was the greatest energy requiring operation. According to the results of their study, PTO required the greatest amount of power among the major components during rotary tillage; thus, further studies on load analysis for the tractor PTO were needed. Kim et al. (2011b) analyzed the major components (transmission input shaft, PTO input shaft, main hydraulic pump, and auxiliary hydraulic pump) at two PTO gear levels during baler operation for a forage harvest using a tractor with a rated engine power of 71 kW. The results showed that PTO required the greatest amount of power, as in rotary tillage operation, and the power consumption of the components increased when the PTO gear was shifted from P1 (585 rpm) to P2 (756 rpm). The utilization ratios of the engine power were greater than 50% (50–75%) for all PTO gear levels. Summarizing the findings above, a considerable amount of the load was applied on the PTO shaft during rotary tillage and baler operation. However, there has been no research focused on the load of PTO; therefore, more research analyzing the load on the PTO shaft during rotary tillage and baler operation is needed.

Procedures to analyze the tractor load vary, depending on the purpose. Because the load causes damages to the tractor, the fatigue of the tractor parts needs to be investigated. In this study, severeness, a method of load representation proposed by Kim et al. (1998, 2000), was used to analyze the PTO load. Severeness is defined as the ratio of the damage sum, which is the cumulative fatigue damage of material caused by stress cycles. The severeness was obtained by normalized magnitudes of the damage sum for each operation. The normalization was calculated by the lowest magnitude, which was selected among the damage sum for all operations. Severeness indicated which operation was more unfavorable to the tractor and had a proportional relationship with fatigue life; thus, a higher severeness results in lower fatigue life. Kim et al. (1998) measured the loads acting on the input shaft of the transmission and analyzed the load severeness during the most common agriculture tractor operations, such as plow tillage, rotary tillage, and transportation operations. They found that the load severeness during transportation operation was similar to that during plow tillage, but the severeness during rotary tillage was approximately 63 times greater than during the transportation operation. Kim et al. (2000) analyzed the severeness of the transmission input shaft during rotary tillage at four combinations of tractor ground speeds (2.9 km/h and 4.1 km/h) and PTO rotational speeds (588 and 704 rpm) using a tractor with a rated engine power of 30 kW. The results showed that the severeness increased by 2.3–2.6 times when the PTO speed increased at the same ground speed. In contrast, the severeness decreased by 0.2–0.3 times when the ground speed increased at the same PTO speed.

The primary goal of this study was to provide useful information for the optimum design of a tractor PTO considering field load data. The purpose of this study was to analyze the load severeness of the PTO of a 75 kW agricultural tractor during major PTO operations, such as rotary tillage and baler operation. Specific objectives were (1) to obtain the S–N (stress vs. number of cycle) curves of the PTO driving gears through the test for fatigue life using a PTO dynamometer, (2) to measure and analyze the loads acting on the PTO during the operation, and (3) to evaluate the PTO load severeness during rotary tillage and baler operation.

2. Materials and methods

2.1. Fatigue life of PTO driving gears

The S–N curves are well-known in the ASTM standard code, having some differences with the actual fatigue of the materials (Nguyen et al., 2011). Thus, the S–N curves of PTO were obtained through the test for fatigue life using a PTO dynamometer. PTO driving gears were used as test gears for the fatigue life of the PTO, and the test gears were made of SCM 420H (Litvin and Fuentes, 2004). The fatigue life tests of the PTO driving gears were conducted using a diesel engine with 75 kW rated power, a PTO dynamometer with 200 kW rated power, and the PTO 1st (P1) and PTO 2nd (P2) driving gears. Because the test for the fatigue life of PTO driving gears requires significant time for gear breakage, accelerating the test was necessary. In this study, the acted torque on the PTO driving gear was changed to obtain bending stress (Lee and Hur, 1990; Douglas et al., 1980). Bending stress was calculated by torque (2000, 2500, 3000, 3500, 4000, 4500, and 5000 Nm) using the Lewis Eq. (1) Shigley et al., 2004 within the maximum capacity of the PTO dynamometer (5000 Nm). The circular pitch, face width and Lewis form factor of the P1 and P2 driving gears are 8.93 mm, 22 mm, and 0.71, and 9.12 mm, 17 mm, and 0.70, respectively. The tangential force on the end of the gear tooth was calculated using Eq. (2), which is a general equation for torque and force. The breakage time and the rotational speed of the gears were measured to calculate the number of cycles. The linear S–N curves were determined according to ASTM E739-80 standard (ASTM, 2004).

$$\sigma(\mathrm{MPa}) = \frac{W_t}{F \times p \times y} \tag{1}$$