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Development of the Reliability Assessment Process of the Hydraulic Pump for a 78 kW Tractor during Major Agricultural Operations

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Abstract: This study focuses on the development of the reliability test method for the hydraulic pump of a tractor during major agricultural operations (plow, rotary, baler, and wrapping) at various driving and PTO (power take-off) gear stages. The hydraulic-pressure-measurement system was installed on the tractor. The measured hydraulic pressure and engine rotational speed were converted to the equivalent pressure and engine speed for each agricultural operation using a mathematical formula. Additionally, the overall equivalent pressure and overall engine speed were calculated to determine the acceleration lifetime. The average equivalent pressure and engine speed for plow tillage were calculated at around 5.44 MPa and 1548.37 rpm, respectively, whereas the average equivalent pressure and engine speed for rotary tillage were almost 5.70 MPa and 2074.73 rpm, accordingly. In the case of baler and wrapping operations, the average equivalent pressure and engine speed were approximately 11.22 MPa and 2203.01 rpm, and 11.86 MPa and 913.76 rpm, respectively. The overall hydraulic pressure of the pump and the engine rotational speed were found to be around 10.07 MPa and 1512.93 rpm, respectively. The acceleration factor was calculated using the overall pressure and engine speed accounting for 336. In summary, the developed reliability test method was evaluated by RS-B-0063, which is the existing reliability evaluation standard for agricultural hydraulic gear pumps. The evaluation results proved that the developed reliability test method for the hydraulic pump of a tractor satisfied the standard criteria. Therefore, it could be said that the developed reliability test method could be applicable to the hydraulic pump of the tractor during agricultural field operations.

Keywords: tractor; reliability assessment; hydraulic pump; tillage; acceleration lifetime; agricultural operation

1. Introduction

Agricultural tractors deal with various agricultural operations, such as plows, rotary, and balers, by towing implements attached at PTO [1,2]. The demand for agricultural tractors is dramatically increasing due to the application of advanced technology [3]. According to Mordor Intelligence statistics [4], the global market of the agricultural tractor, which is an emerging market, has an expected annual growth rate of 4.02% in 2025 than that in 2020. The EconomyChosun [5] reported that the annual growth rate of the tractor market is comparatively higher than that of automobiles (6.8%) and heavy equipment

(1.0%). It also reported that the annual demand for global tractors is expected to grow from 2.55 million units in 2013 to 3.92 million units by 2023.

The EconomyChosun [5] again stated that the tractor market share of North America and Western Europe is gradually decreasing, whereas the Asia-Pacific regions, including China and India, are on trend to increase. Additionally, the tractor market size of Asia-Pacific was reported to be three times that of the Western European market. However, based on the EconomyChosun report, the global tractor market is dominated by John Deere (USA), CNH (UK), Kubota (Japan), and AGCO (USA), which are called the "Big 4", accounting for almost half of the tractor market. The latecomers, such as Korean, Chinese, and Indian companies, are competing for the rest of the market. To compete with the largest tractor manufacturing company in the global market, and to fulfill consumers' demands, Korean tractor-manufacturing companies are highly concerned with the development of various agricultural machinery with sophisticated technology, as well as the quality and durability of their agricultural machinery.

Recently, tractor power has been focused on hydraulic power, such as the hydraulic transmission, clutch, brake, steering, hydraulic pump, loader, PTO (power take-off), proportional valve, and so on [2,6], because it is highly precise, smooth, and comfortable for the driver [7]. However, Shin et al. [8] reported that the quality level of the hydraulic components of agricultural machinery in Korea was almost 68.4% in 2015, which indicated very low reliability. Therefore, the reliability test for the hydraulic system of agricultural machinery should be conducted.

The hydraulic pump is the crucial or core component, or heart, of the entire hydraulic system of a tractor. Zhonghai et al. [9] conducted the reliability analysis for highly reliable aircraft hydraulic systems, such as hydraulic pistons, hydraulic actuators, and landing gears. Additionally, he proposed a quick method, which was for the reliability estimation of hydraulic piston pumps, called the engineering-driven performance-degradation analysis method. Liu et al. [10] proposed the reliability test method of the hydraulic pump based on an acceleration life test. Tang et al. [11] stated that the hydraulic pump is the core power source of a hydraulic transmission system and developed a normalized convolutional neural network (NCNN) framework for fault identification. Further, he improved the model to tune automatically using the Bayesian algorithm, and the improved model was named BNCNN. Therefore, the hydraulic pump of the hydraulic system of a tractor was selected in this study for reliability analysis.

The reliability assessment process is generally adopted to access the span life, reliability level, and failure rate [12,13]. The two types of tests were also stated: one is a statistical-based reliability test (SRT), which requires engineering elements (failure mode and mechanism, test equipment and conditions, and cost limits); another is the engineering-based reliability test (ERT), which requires a big data set and statistical analysis. He further stated that both the SRT and ERT are combinedly used for the reliability test. Therefore, to ensure reliable and sustainable mechanization, it is high time to develop a reliability assessment technique for the hydraulic system of agricultural machinery.

There are two types of SRT, which are the acceleration life test (ALT) and the accelerated degradation test (ADT) [14]. Between the two, the ALT is widely applied to practically assess product reliability because it is highly accurate, quick, and economical [15]. Chen et al. [12] presented an overview of the ALT and stated that ALT applications are recently increasing in the engineering research field with product reliability and the complexity of actual operational conditions. In addition, it is used as an engineering solution to improve the technical level of various instruments and equipment. Tkáč et al. [16] conducted the durability laboratory test, only for the hydrostatic pump of agricultural machinery, based on biodegradable oils. Tkáč et al. [17] also conducted the ALT in the indoor test of the hydrostatic pump for agricultural machinery. However, the actual field conditions were not considered in those studies. Therefore, this study approaches the reliability assessment techniques by considering the real field operations of a tractor.

This is a basic study on the development of a reliability assessment method for the hydraulic pump of agricultural machinery to ensure reliable and sustainable machinery performance. In this study, major agricultural operations (plow and rotary tillage, and bale and wrapping operations) were selected for the load measurements of the tractor. The acceleration factor was calculated using the equivalent load of the field experiments. The nobility of this research is the development of the reliability assessment method its verification, using the measured equivalent load of agricultural field operations. The specific objectives are as follows:

(i) To develop a load-measurement system for the agricultural tractor used in this study
(ii) To develop a reliability assessment method for the hydraulic pump of an agricultural tractor
(iii) To evaluate the developed reliability assessment method by the measured equivalent load during agricultural major operations
(iv) To estimate the lifetime of the hydraulic pump using the acceleration factor that represents the lifespan of a tractor

2. Materials and Methods

2.1. Tractor Configurations

In this study, a 78 kW MFWD (mechanical front wheel drive) tractor (07, TYM Co., Ltd., Gongju, Korea) was used to develop the reliability assessment method. The dimension of the tractor (Length × Width × Height) were 4225 × 2140 × 2830 mm, and the empty tractor weight was 3985 kg.

The engine-rated power and torque at the rotational speed of 2300 rpm were 78 kW and 324 Nm, respectively. The tractor transmission consisted of a total of 64 gear stages (32 forward and 32 reverse), including 4 mechanical synchromesh-type driving shifts (1, 2, 3, and 4), 2 power shifts (high and low), and 4 mechanical constant-type range shifts (C, L, M, and H). The maximum PTO (power take-off) power and torque were 69 kW at 2300 rpm and 360.7 Nm at 1400 rpm. The hydraulic pumps were specified with 24 cc/rev of the main pump, and 12 cc/rev of the auxiliary pump. The specifications of the tractor are listed in Table 1.

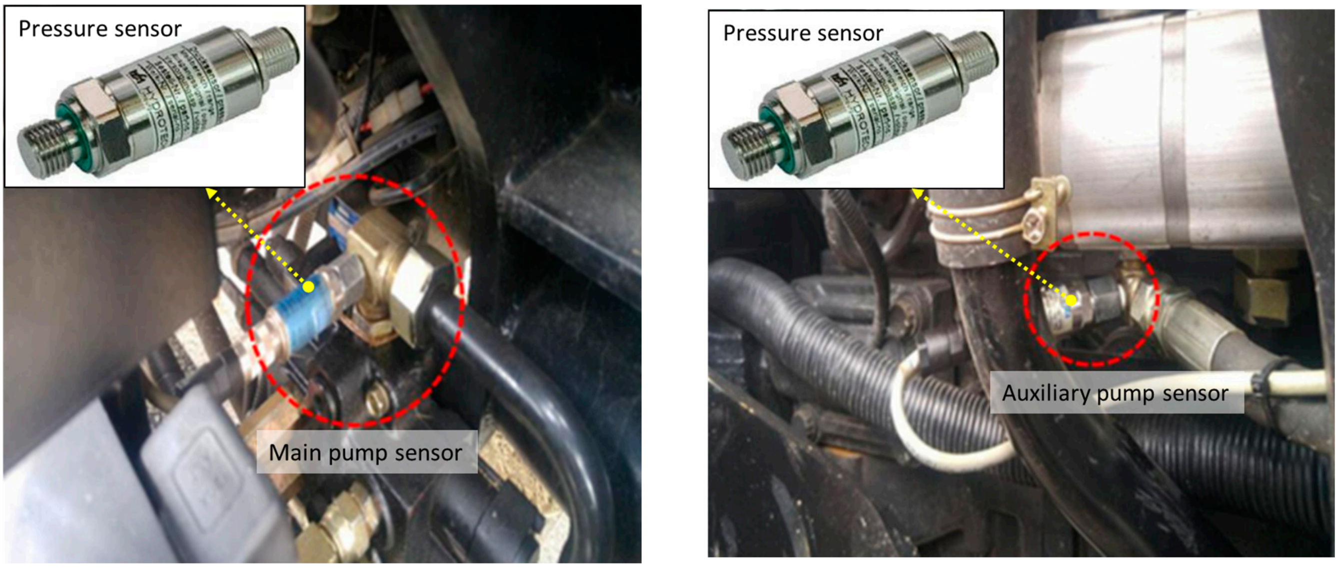
Table 1. The specifications of the tractor used in this study.

Parameters			Specifications
Model, Company			S07, TYM Co., Ltd., Gongju, Korea
Dimension (Length × Width × Height) (mm)			4225 × 2140 × 2830
Weight (kg)			3985
Engine	Rated power (kW) at speed (rpm)		78 at 2300
	Rated torque (Nm) at speed (rpm)		324 at 2300
	Max. torque (Nm) at speed (rpm)		430 at 1400
Transmission	Main transmission	Type	Mechanical (synchromesh)
		No. of ear stages	64 (32 forward and 32 reverse)
		Power shift	2 (high and low)
		Driving shift	4 (1, 2, 3, and 4)
	Sub-transmission	Type	Mechanical (constant)
		Range shift	4 (C, L, M, and H)
PTO	Max. power (kW) at speed (rpm)		69 at 2300
	Max. toque (Nm) at speed (rpm)		360.7 at 1400
Hydraulic pump	Main pump (cc/rev)		24
	Auxiliary pump (cc/rev)		12

2.2. Load-Measurement System

2.2.1. Hydraulic System

The tractor hydraulic system included two hydraulic pumps (main and auxiliary). The hydraulic pressure sensors were installed in the tractor to measure pressure generated by the hydraulic pump (main and auxiliary). The main pump (Figure 1a) was performed to operate the implements, and the auxiliary pump (Figure 1b) was performed for the hydraulic steering used to turn the tractor. The pressure sensors installed in the input and output pipe of the pump are shown in Figure 1.



(**a**) Main pump pressure sensor (**b**) Auxiliary pump pressure sensor

Figure 1. Pressure sensors installed in the experimental tractor.

The pressure sensor (HySense PR 130, HYDROTECHNIK, Germany) was configured with the range of 0~250 bar, and it measured the relative pressure using the piezo-resistive method. The details of the specifications of the pressure sensors are listed in Table 2.

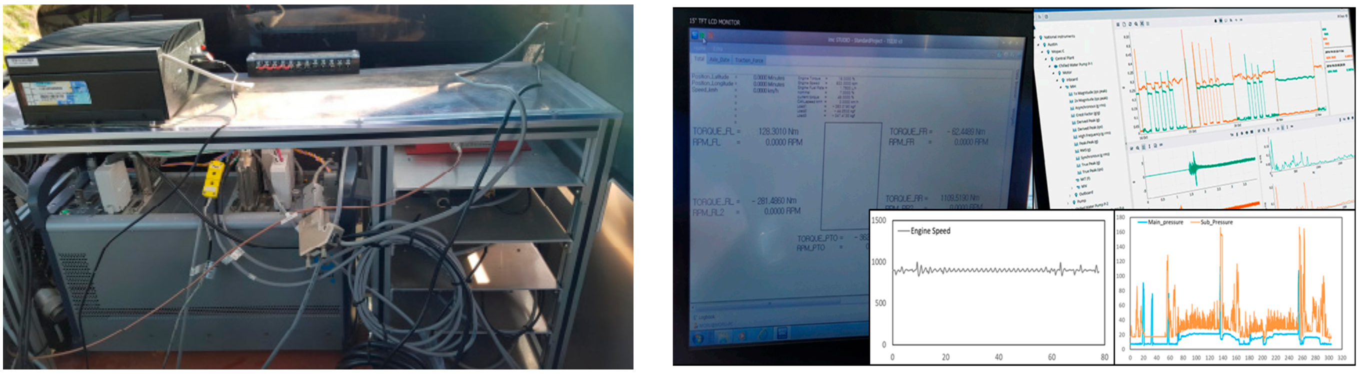
Table 2. The specifications of the pressure sensors installed in the tractor.

Parameters	Specifications
Model, Company	HySense PR 130, HYDROTECHNIK, Germany
Measuring principle	Piezo-resistive
Pressure type	Relative pressure
Pressure range (bar)	0~250
Input power (VDC)	10~30
Output (VDC)	0~10

2.2.2. Data-Acquisition System (DAQ)

The data-acquisition system (DAQ) was installed in the test tractor to read the pressure data of the main and auxiliary pumps during major agricultural operations. CRONOS compact CRC−400−11, IMC, Germany was used in this study, which is shown in Figure 2a. A data-monitoring system was also installed in the tractor cabin to monitor the real-time load data generated by the hydraulic pump during agricultural operations in the field, which is shown in Figure 2b. The data-monitoring system was capable of displaying and storing the real-time data during the turning of the tractor or lifting implements at the same time.

The dimensions (length × width × height) of the DAQ system were 353 × 155 × 264 mm, and the weight of the device was 10.5 kg, which was configured with a sampling rate of 400 kS, and the maximum module slots were 11. The engine rotational speed was collected using CAN data, and the hydraulic pressure of the pump was measured using the pressure sensors installed in the test tractor. The details of the specifications of the DAQ system are listed in Table 3.



(**a**) Data–acquisition system (**b**) Data–monitoring system

Figure 2. The data−acquisition system installed in the tractor.

Table 3. The specifications of the data−acquisition system used in this study.

Parameters	Specifications
Model, Company	CRONOS compact CRC–400–11, IMC, Germany
Dimension (Length × Width × Height) (mm)	353 × 155 × 264
Weight (kg)	10.5
Max. module slots	11
Max. aggregate sampling rate (kS/s)	400
DC power supply (VDC)	10~32
Operating temperature (°C)	−40~+85

2.3. Experimental Conditions

2.3.1. Operational Conditions

In this study, the tractor was operated by an experienced operator using a conventional method to improve the reliability of the tractor. The plow and rotary tillage operations were conducted at 150~200 mm of the tillage depth, which is commonly used in Korea, especially in paddy fields [18–22]. Additionally, according to the moldboard specifications, the maximum working depth was 200 cm. Wang et al. [23] also stated that plow tillage was conventionally conducted at a depth of 15~18 cm. The moldboard plow specifications are listed in Table 4.

Table 4. The specifications of the moldboard plow used in this study.

Items	Specifications
Model	WJSP-8, WOONGJIN MACHINERY, Gimje, Korea
Mass (kg)	790
Length × width × height (mm)	2800 × 2150 × 1250
Required power (kW)	67~89
Maximum working depth (mm)	200
Working speed (km/h)	5~8
Share type	Gunnel-type/Plain coulter with spring

The plow tillage was performed at gear stages of M2 high and M3 low, whereas the rotary tillage was conducted using the gear stages of L3 low and L3 high, and the PTO gear stages were selected at P1 and P2. In the case of the baler operation, the pressures were measured for the M2 low-gear stage, whereas the PTO gear stages were selected at P1 and P2. However, the wrapping operation was conducted at the driving gear stage of M4 low, and was replicated 3 times. The field operation conditions, with the tractor speed, are listed in Table 5.

Table 5. The specifications of the pressure sensors installed in the tractor.

Field Operations	Depth (cm)	Gears Stages	
		Transmission	PTO
Plow tillage	15~20	M2 high (5.99 km/h) M3 low (7.05 km/h)	-
Rotary tillage	15~20	L3 high (2.82 km/h) L3 low (2.37 km/h)	P1 (540 rpm) P2 (750 rpm) P1 (540 rpm)
Baler	-	M2 low (5.05 km/h)	P1 (540 rpm) P2 (750 rpm)
Wrapping	-	M4 low (9.21 km/h)	-

2.3.2. Soil Conditions

To experiment with the measurements of the hydraulic pressure of the hydraulic pump used in the tractor, two experimental sites (Seosan and Gongju, Republic of Korea) were selected. The soil samples from the selected experimental sites were collected, and the soil texture was analyzed using the USDA soil texture triangle, physical, and mechanical properties to determine the field condition. The water content, hardness (cone index, CI), shear force, electrical conductivity (EC), and temperature of the soil were measured. The soil samples were collected, and physical and mechanical properties were measured, randomly at 10 points of each experimental site. The soil analysis results for both fields are listed in Table 6.

Table 6. The soil analysis of the experimental field.

Parameters	Experimental Sites	
	Seosan	Gongju
Soil type	Gravel loamy sand	Gravel sand
Soil water content (%)	33.79	8.3 *
Cone index (kPa)	738.07	1275
Shear force (Nm)	17.59	-
Electric conductivity (dS/m)	0.77	-
Temperature (°C)	18.87	-

* The water content of the rice straw was measured during the baler operation.

2.4. Equivalent Load Estimation

In agricultural operations, the load is an irregular shape due to uneven fields, variable soil hardness with stones and crop straw, tractor vibrations, and so on. However, the unique load that represents the agricultural work is required to develop the reliability evaluation criteria. In this study, the equivalent load of the hydraulic pump during agricultural operations could be expressed as an equivalent pressure. The Palmgren–Miner rule, based on cumulative damage, is usually used to estimate the equivalent load for each agricultural operation [24]. The Palmgren–Miner rule equation is shown in Equations (1) and (2).

$$P_{ei}= \left(\sum h_i P_i^{\lambda}\right)^{\frac{1}{\lambda}}, \tag{1}$$

$$P_e = \frac{P_{e1}^{\lambda}t_1 + P_{e2}^{\lambda}t_2 + P_{e3}^{\lambda}t_3 + \ldots\ldots\ldots\ldots\ldots + P_{ei}^{\lambda}t_i}{t_1 + t_2 + t_3 + \ldots\ldots\ldots\ldots\ldots + t_i}, \tag{2}$$

where P_{ei} is the equivalent pressure of ith operation (MPa); P_e is the equivalent pressure of the hydraulic pump (MPa); h_i is the ratio of ith relevant frequency of the pressure to the total frequencies of the pressure; P_i is the pressure (MPa) for ith operation; t_i is the annual usage time (h) for ith operation; and λ is the coefficient of fatigue damage. The fatigue-damage coefficient was considered to be 8 [13].

In the case of the rotational speed, the equivalent rotational speed was estimated using Equations (3) and (4).

$$n_{ei} = \frac{1}{P_{ei}^{\lambda}} \sum h_i n_i P_i^{\lambda}, \tag{3}$$

$$n_e = \frac{P_{e1}^{\lambda} n_1 t_1 + P_{e2}^{\lambda} n_2 t_2 + P_{e3}^{\lambda} n_3 t_3 + \ldots\ldots\ldots\ldots\ldots + P_{ei}^{\lambda} n_i t_i}{P_e^{\lambda} t_t}, \tag{4}$$

where n_{ei} is the equivalent rotational speed (rpm) for ith operation; n_i is the rotational speed (rpm) for ith operation; n_e is the equivalent rotational speed (rpm); and t_t is the total usage time (h).

2.5. Acceleration Life Test (ALT)

The acceleration life test (ALT) is comparatively a time-consuming and costly experiment, especially for agricultural machinery such as tractors, during field operations. To solve this issue, the strategy of a failure-free lifetime test applying a high-stress acceleration method was adopted for the reliability assessment of the hydraulic pump of a tractor. This adopted test method can estimate the acceleration test time using the calculated equivalent hydraulic pressure of the hydraulic pump.

However, no evaluation standard or method can apply the equivalent pressure of the hydraulic pump. In 2008, the Korean Agency for Technology and Standards introduced the RS-B-0063 for the gear pump of agricultural machinery. This standard stands to evaluate the performance and reliability test methods of gear pumps for agricultural machinery, especially for the actual operations of the agricultural machinery. According to this standard, the ALT was performed for 10 samples up to 1000 h at B_{10}, and the lifespan of 1900 h was guaranteed, where it reached 80% of the confidence level [25]. The evaluation test conditions of the standard are as below:

I. At the maximum input rotational speed, hold on for 5 s under the no-load condition, and then 5 s at the maximum load condition.
II. Perform comprehensive performance tests before and after the ALT is completed.
III. Perform representative performance tests at 50% of the total life test time.

The evaluation criteria of the standard are as follows: (i) both the comprehensive and representative performance must satisfy the evaluation criteria; and (ii) all samples should have no failure and satisfy the evaluation criteria of the comprehensive performance test after the ALT. Therefore, the RS-B-0063 was used in this study to evaluate the ALT of the hydraulic pump of the tractor.

The failure-free lifetime of the hydraulic pump of a tractor during field operations was estimated using Equation (5).

$$T = B_x \left(\frac{\ln(1 - CL)}{N.\ln(R_x)} \right)^{\frac{1}{\beta}}, \tag{5}$$

where T is the failure-free test time (h) of the hydraulic pump of a tractor; B_x is the lifespan of the hydraulic pump (h); CL is the confidence level; N is the number of the test sample (h); R_x is the reliability ($R_x < 1$); and β is the shape parameter, which is considered to be 2.0 [26].

In this study, the failure-free test time (T) was set as 3122 h when the number of the sample (N) was 1. The test time was calculated to be almost 14,549 h based on the lifespan (B_{10}) at 90% of the confidence level (CL) [27,28]. B_{10} means that 10% of the hydraulic pump may be damaged within the warranty period. As the ALT is a time-consuming test using an indoor test device, the acceleration factor was estimated using Equations (6) and (7).

$$AF = \left(\frac{P_t}{P_e} \right)^{\lambda} \times \left(\frac{n_t}{n_e} \right), \tag{6}$$

$$T_a = \left(\frac{T}{AF}\right), \tag{7}$$

where AF is the acceleration factor of the hydraulic pump of a tractor; P_t is the hydraulic pressure (MPa) at test conditions; T_a is the acceleration test time (h) of the hydraulic pump; and n_t is the rotational speed (rpm) at test conditions.

In this study, the harshness pressure of the hydraulic pump was set at 20 MPa and the rotational speed was set at 2100 rpm, which is the engine-rated speed to determine the acceleration factor of the hydraulic pump of the tractor.

2.6. Analysis Method

In this study, statistical approaches were used to analyze the hydraulic pressure and engine rotational speed measured for various gear stages and major agricultural operations. A one-way ANOVA (analysis of variance) test and Duncan's multiple-range test (DMRT) were performed to analyze the significance of the hydraulic pressure and engine speed to the gear stages for each agricultural operation. The software used for the statistical analysis was IBM SPSS Statistics (SPSS 25, SPSS Inc., New York, NY, USA).

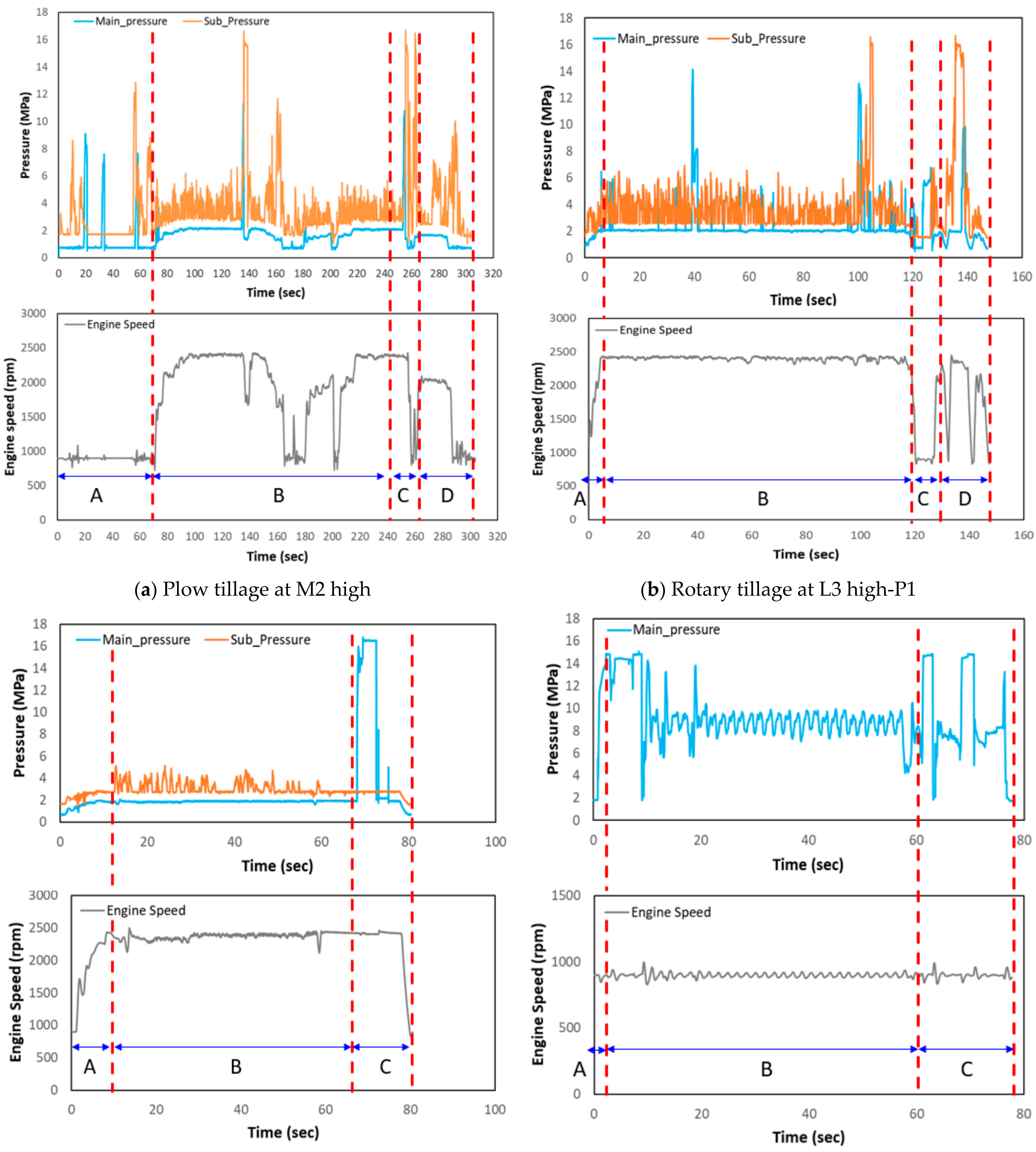
3. Results

3.1. Hydraulic Pressure and Engine Rotational Speed Analysis

In this study, the hydraulic pressure of the pump and engine rotational speed were measured by field tests using the target tractor. The major agricultural operations, such as plow, rotary, baler, and wrapping, were conducted for various gear stages to evaluate the reliability assessment of the tractor's hydraulic pump. The measured pressures of both the main and auxiliary pumps, as well as the engine's rotational speed at one gear stage, for each operation are shown in Figure 3.

Plow tillage was carried out for the M2 high- and M3 low-gear stages, and Figure 3a shows the M2 high plow tillage. Figure 3b shows the hydraulic pressure and engine speed for the rotary tillage operation at L3 high, where the PTO gear stage was used at P1 (540 rpm). In the case of the plow and rotary tillage, the total data set was divided into four sections: (A) preparation time; (B) operation time; (C) lifting of the three-point hitch; and (D) steering and moving. During the rotary tillage, the PTO power was turned on at preparation time and turned off at lifting time of the three-point hitch. It was noticed that the main and auxiliary pump pressures for both operations fluctuated during the preparation and operation time because of the controlling of the three-point hitch of the tractor to maintain the tillage depth. Additionally, the fluctuation was observed to lift the three-point hitch at section C.

On the other hand, the baler and wrapping operations data sets were divided into three sections: (A) preparation (PTO on); (B) operation; and (C) discharge (PTO off). The baler operation was performed for the M2 low driving gear stage and P1 PTO gear stage, which is shown in Figure 3c. It was observed that the baling pressure rose to the peak during the discharge of the bale. In the case of the wrapping operation, the field test was conducted for M4 low, which is shown in Figure 3d. During the wrapping operation, the pressure graph shows that there were oscillations at the bale discharge period after wrapping.



(**a**) Plow tillage at M2 high (**b**) Rotary tillage at L3 high-P1

(**c**) Baler operation at M2 low-P1 (**d**) Wrapping operation M4 low-1

Figure 3. The pressure and engine rotational speed for major agricultural operations.

The maximum and minimum pressure for the main and auxiliary pump during plow tillage at M2 high were 11.34 and 0.35 MPa, and 16.65 and 1.13 MPa, respectively. In the case of M3 low, the maximum and minimum pressure for both the main and auxiliary pumps were 12.09 and 0.36 MPa, and 16.97 and 1.39 Mpa, respectively. The statistical analysis showed that, in the pressure of the main and auxiliary pumps during plow tillage, there was a significant difference for M2 high- and M3 low-gear stages. The analysis of the rotary tillage, baler, and wrapping operations showed that the pressure of both the main and auxiliary pump also had a significant difference between all gear stages. The statistical analysis of the pressure of the hydraulic pump for both the main and auxiliary pumps during agricultural major operations is listed in Table 7.

Table 7. The statistical analysis of pressure of the hydraulic pump of a tractor during agricultural major operations.

Operations	Gear Stages	The Pressure of the Hydraulic Pump (MPa)					
		Main Pump			Auxiliary Pump		
		Maximum	Minimum	Avg. ± S.D. *	Maximum	Minimum	Avg. ± S.D. *
Plow tillage	M2 high	11.34	0.35	1.35 ± 1.05 [a]	16.65	1.13	2.96 ± 2.07 [c]
	M3 low	12.09	0.36	1.51 ± 1.04 [b]	16.97	1.39	3.22 ± 2.38 [d]
Rotary tillage	L3 high-P1	14.15	0.50	2.07 ± 1.48 [e]	16.68	0.99	3.56 ± 2.32 [h]
	L3 high-P2	13.26	0.66	1.79 ± 0.96 [f]	16.53	0.89	3.37 ± 2.49 [i]
	L3 low-P1	8.30	0.65	1.99 ± 0.74 [g]	16.84	0.99	3.57 ± 2.57 [j]
Baler	M2 low-P1	16.79	0.65	2.59 ± 3.21 [k]	5.15	1.46	2.93 ± 0.53 [m]
	M2 low-P2	16.74	0.64	2.39 ± 3.19 [l]	10.62	1.13	3.08 ± 1.13 [n]
Wrapping	M4 low-1	15.09	1.70	9.10 ± 2.79 [o]			
	M4 low-2	15.25	1.72	7.38 ± 4.88 [p]		-	
	M4 low-3	14.95	1.72	8.84 ± 2.82 [q]			

[a,b,c,d,e,f,g,h,i,j,k,l,m,n,o,p,q] Means within each column for same operation with the same lettering are not significantly different at $p < 0.05$ according to Duncan's multiple-range test. * Avg. ± S.D. is average ± standard deviation.

The engine rotational speed at various gear stages during plow, rotary, baler, and wrapping operations were analyzed statistically. It was observed that there was a significant difference between the engine speed among the gear stages of each agricultural operation. The statistical analysis results of the engine rotational speed with respect to gear stages for each operation are listed in Table 8.

Table 8. The statistical analysis of engine rotational speed of a tractor during agricultural major operations.

Operations	Gear Stages	Engine Rotational Speed (rpm)		
		Maximum	Minimum	Avg. ± S.D. *
Plow tillage	M2 high	2432.00	722.50	1436.30 ± 644.30 [a]
	M3 low	2444.00	781.80	1679.40 ± 596.20 [b]
Rotary tillage	L3 high-P1	2458.00	826.80	2053.70 ± 596.40 [c]
	L3 high-P2	2472.00	814.00	1974.60 ± 645.20 [d]
	L3 low-P1	2465.00	817.50	2226.50 ± 506.90 [e]
Baler	M2 low-P1	2498.0	823.30	2289.30 ± 303.00 [f]
	M2 low-P2	2469.00	811.00	2118.70 ± 382.70 [g]
Wrapping	M4 low-1	997.50	828.30	898.30 ± 19.20 [h]
	M4 low-2	1214.00	818.80	943.90 ± 95.90 [i]
	M4 low-3	996.30	832.30	898.50 ± 17.80 [j]

[a,b,c,d,e,f,g,h,i,j] Means within each column for same operation with the same lettering are not significantly different at $p < 0.05$ according to Duncan's multiple-range test. * Avg. ± S.D. is the average ± standard deviation.

3.2. Equivalent Pressure and Engine Rotational Speed Analysis

In this study, the measured pressure of the pumps (main and auxiliary), and the engine rotational speed, were converted to the equivalent pressure and equivalent rotational speed using equations to estimate the reliability of the tractor hydraulic pump. The total measured data of the pressure and engine speed for each operation at each driving or PTO gear stage were divided into eight sections. The average equivalent pressure and engine speed for plow tillage were calculated at around 5.44 MPa and 1548.37 rpm, respectively, whereas the average equivalent pressure and engine speed for rotary tillage were almost 5.70 MPa and 2074.73 rpm, accordingly. In the case of baler and wrapping operations, the average equivalent pressure and engine speed were approximately 11.22 MPa and 2203.01 rpm, and 11.86 MPa and 913.76 rpm, respectively. The equivalent hydraulic pressure and engine speed for each agricultural operation are listed in Table 9.

Table 9. The estimation of the equivalent pressure and engine rotational speed for each operation.

Operations	Gear Stages	P_e (MPa)	n_e (rpm)
Plow tillage	M2 high	5.38	1418.15
	M3 low	5.49	1678.59
	Average	5.44	1548.37
Rotary tillage	L3 high-P1	7.06	2070.44
	L3 high-P2	6.12	1950.52
	L3 low-P1	3.92	2203.24
	Average	5.70	2074.73
Baler	M2 low-P1	11.21	2286.01
	M2 low-P2	11.23	2120.01
	Average	11.22	2203.01
Wrapping	M4 low-1	11.55	898.28
	M4 low-2	12.62	944.06
	M4 low-3	11.39	898.93
	Average	11.86	913.76

The overall equivalent hydraulic pressure of the tractor and engine rotational speed were calculated using usage time and the equivalent pressure and engine speed of each operation [29]. The usage times of the plow tillage, rotary tillage, baler, and wrapping operations were 86, 102, 55, and 41 h, respectively. The overall equivalent hydraulic pressure and engine speed are listed in Table 10.

Table 10. The overall equivalent pressure and engine rotational speed for major agricultural operations.

Item	Plow Tillage		Rotary Tillage		Baler		Wrapping	
	Equivalent Value	Usage Time (h)	Equivalent Value	Usage Time (h)	Equivalent Value	Usage Time (h)	Equivalent Value	Usage Time (h)
Pressure (MPa)	5.44	86	5.50	102	11.22	55	11.86	100.70
Rotational speed (rpm)	1548.37		2074.73		2203.01		913.76	

3.3. Acceleration Life Test (ALT) Analysis and Comparison

In this study, the hydraulic pressure of the tractor was set at 20 MPa, and the engine rotational speed was set at 2100 rpm as the engine-rated speed, whereas the equivalent pressure and engine speed were calculated at around 10.07 MPa and 1512.93 rpm, respectively. The acceleration factor was 336, which is shown in Table 11.

Table 11. The acceleration factor calculation.

Items	Pressure (MPa) a	Rotational Speed (rpm) b	Acceleration Factor (a × b)
Test value (A)	20	2100	-
Equivalent value (B)	10.07	1512.93	
Exponent of inverse power model (λ)	8	-	
$\left[\frac{A}{B}\right]^{\lambda}$	242.10	1.38	336

The warranty lifetime of the hydraulic pump of the tractor was calculated at around 3112 h, which is 90% of the confidence level (B_{10}). In addition, it was found that the fault-free test time of the hydraulic pump was 44 h. In addition, the reliability test results were compared to the RS-B-0063, which is the existing reliability evaluation standard for agricultural gear pumps. The acceleration factor, warranty lifetime, and fault-free test time were different, which are listed in Table 12.

Table 12. The comparison of the reliability life test with the standard.

Items	RS-B-0063		Developed Method	
	Pressure (MPa)	Rotational Speed (rpm)	Pressure (MPa)	Rotational Speed (rpm)
Test value	21	2400	20	2100
Equivalent value	19	2200	10.07	1512.93
Acceleration factor	2.24		336	
No. of samples	10		1	
Warranty lifetime (h) (Confidence level)	1900 (80%)		3112 (90%)	
Fault-free test time (h)	1000		44	

4. Discussion

In this study, the hydraulic pressure and engine rotational speed of the tractor were measured for various driving and PTO gear stages during major agricultural operations. The measured hydraulic pressure and engine speed were converted to the equivalent pressure and equivalent engine speed to develop the reliability assessment process of the hydraulic pump of a tractor. The results of this study are discussed below:

(1) The hydraulic pressure of the pump and engine rotational speed were measured for plow tillage, rotary tillage, as well as baler and wrapping operations. The measured hydraulic pressure and engine speed were statistically analyzed. The statistical analysis (DMRT) proved that there was a significant difference between the pressures measured at different gear stages for the same operation. Zhonghai et al. [9] stated that one pressure and one engine speed are required to develop the reliability test method. Therefore, the equivalent hydraulic pressure and equivalent engine speed for each operation were estimated using the mathematical formula.

(2) The average equivalent pressure and engine speed for plow tillage were calculated at around 5.44 MPa and 1548.37 rpm, respectively, whereas the average equivalent pressure and engine speed for rotary tillage were almost 5.70 MPa and 2074.73 rpm, accordingly. In the case of baler and wrapping operations, the average equivalent pressure and engine speed were approximately 11.22 MPa and 2203.01 rpm, and 11.86 MPa and 913.76 rpm, respectively. It was observed that the highest hydraulic powers were used for baler and wrapping operations. The hydraulic power was only used to ascend or descend the implements during plow and rotary tillage when the tractor needs to turn. On the other hand, the cylinder was actuated by the hydraulic power during baler operations. In the case of wrapping operations, all works were conducted by hydraulic power.

(3) The overall equivalent hydraulic pressure and engine speed were calculated at around 10.07 MPa and 1512.93 rpm, respectively, where the acceleration factor was 336. The warranty lifetime was 3112 h with a confidence level of 90%, whereas the fault-free test time was 44 h. However, the manufacturer recommended that the maximum warranty lifetime was almost 14,549 h. The acceleration life test was evaluated using the RS-B-0063 standard. It was found that the equivalent pressure, engine speed, warranty lifetime, and fault-free test time using the developed method were higher than the standard results. This indicates that the developed reliability assessment method can satisfy the existing reliability evaluation standard for agricultural gear pumps.

In summary, the developed reliability assessment method is evaluated by the standard. The evaluation results prove that the developed method satisfied the standard criteria. This indicates that this reliability test method could be applicable to shorten the test time during field operations.

5. Conclusions

This study emphasized the development of the reliability test method for the hydraulic pump of a tractor during major agricultural operations (plow, rotary, baler, and wrapping) at various driving and PTO gear stages. In this study, the hydraulic pressure for both the main and auxiliary pump, as well as the engine rotational speed, were measured and converted to the equivalent pressure and engine speed for each agricultural operation using a mathematical formula. However, the statistical analysis showed that there is a significant difference between various gear stages for the same agricultural operation. Therefore, the overall equivalent pressure and overall engine speed were calculated to determine the acceleration lifetime. The developed reliability test method was evaluated by RS-B-0063, which is the existing reliability evaluation standard for agricultural hydraulic gear pumps. The major findings of this study are listed below:

(i). The average equivalent pressure and engine speed for plow tillage were calculated at around 5.44 MPa and 1548.37 rpm, respectively, whereas the average equivalent pressure and engine speed for rotary tillage were almost 5.70 MPa and 2074.73 rpm, accordingly. In the case of baler and wrapping operations, the average equivalent pressure and engine speed were approximately 11.22 MPa and 2203.01 rpm, and 11.86 MPa and 913.76 rpm, respectively.

(ii). The overall hydraulic pressure of the pump and the engine rotational speed were found around 10.07 MPa and 1512.93 rpm, respectively. The acceleration factor was calculated using the overall pressure and engine speed accounting for 336. Additionally, the fault-free test time was calculated 44 h for the hydraulic pump of the tractor.

In summary, it was observed that the warranty lifetime was increased by 1.64 times at 90% of the confidence level than that 80% of the confidence level. The evaluation results proved that the developed reliability test method for the hydraulic pump of a tractor satisfied the standard criteria. In addition, this approach was an efficient, cost-effective, and time-saving technique to assess the reliability of the hydraulic pump of a tractor. We also believe that this technique contributes to the literature, especially regarding the reliability assessment of the off-road vehicle. Therefore, it could be said that the developed reliability test method could be applicable to the hydraulic pump of the tractor during agricultural field operations.

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