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Load and Safety Analysis for Plow Operation in Dry Fields

Ju-Yeon Lee*, Ju-Seok Nam*,#
*Department of Biosystems Engineering, Kangwon National University

건답에서 쟁기작업의 부하특성 및 안전도 분석

이주연*, 남주석*,#
*강원대학교 바이오시스템기계공학과
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ABSTRACT

This study derives load characteristics and analyzes the safety of plowshares operating in dry fields. We mounted a three-blade, reversible plow on a 23.7 kW tractor and measured the plow's tractive force as well as the torque from the engine output shaft on the rear axle under various working speeds (L4, M1, M2, M3). We chose a Korean test site of Seomyeon, Chuncheon with sandy soil texture, as determined using the USDA method.

We constructed the load spectrum for torque and tractive force using measured data and derived the fatigue life of the plowshare from a stress-cycle (S-N) curve of the plow material. Our results show that the M3 gear maximizes the driving shaft torque loads and, applying the tractive force load spectrum, creates a cumulative damage sum of 4.14×10^{-5}. Considering sampling time, we estimate a fatigue life of 805 hours while using the M3 gear. When using the other working speeds, however, all of the stress levels fell within the endurance limits and, therefore, our model predicts infinite plowshare lifetimes. For this analysis, we used a yield strength of 1,079 MPa for the plowshare and static safety factors, analyzed using the maximum stress, between 6.83 and 8.63 under each working speed.

Key words : Load Spectrum(부하스펙트럼), Load Characteristic(부하 특성), Safety(안전도), Plow Operation(쟁기작업)

1. Introduction

The load generated during the agricultural operation, were varied by soil conditions, types of operation, etc. and these load characteristics affect the life and durability of the machine. Therefore, to establish the reliability of the domestic agricultural machine, load data should be constructed in various soil conditions and various types of operation.

Tillage operation makes the soil softening to suitable for crop cultivation by pulverizing and reversing it. Tillage consumed the most power among agricultural operation and represent more than 70% of the annual tractor-use hours[1]. It mostly proceed in order that, primary tillage with plow and secondary tillage with rotavator.

Reversible plow can reverse the soil right and left

Corresponding Author : njsg1218@kangwon.ac.kr
Tel: +82-33-250-6497, Fax: +82-33-259-5561

and consists of share, wing, landside. When the plowshare cuts the soil and pushes it to the wing, wing reverses the furrow. The landside supports the plow and keeps plow stable. Plowshare is worn out the most severe among the main parts. Accordingly it is necessary that design for considering plowshare durability and the measurement and analysis of the load during plow operation.

Han et al.[2] performed field tests and fatigue tests on the chisel component with strain gauges. Locations of strain gauges was selected with nCode software and carry out durability evaluation for the chisel. Kim et al.[3] performed plow operation on paddy and upland field and measured the loads for engine output shaft and driving shaft under each working speed. Kim et al.[4] surveyed the work of tractor user in the Jeollabuk-do and analyzed load spectrum of plow operation. Choi et al.[5] measured the torque on the front and rear wheel axles of a four – wheel drive tractor for plow and rotary operations.

The construction of the load characteristics database about the plow operation requires load measurements at various soil conditions and working conditions. In this study, loads of the plow operation were measured under various working speed in dry field. The load spectrum was analyzed by measuring

Fig. 1 A view of tractor used

the tractive force of the plow, and the torque of engine output shaft and rear axle. Based on this, fatigue life of the plowshare was predicted, and safety analysis was performed.

2. Materials and Methods

2.1 Test equipment

2.1.1 Tractor

The tractor used in the test was an agricultural tractor with rated output of 23.7 kW and rated rotational speed of 2600 rpm. The tractor had four main transmission gears (1, 2, 3, and 4), and three sub gears (L, M, and H). Minimum ground clearance is 345 mm, which has a high ground clearance and small size compared to products with the same output. Figure 1 and Table1 are the shape and specifications of the tractor used.

Table 1 Specifications of a prime mover tractor

Item	Specification
Model/Company/Nation	C320/Tongyang Moolsan/Korea
Weight (kN)	14.2
Weight distribution ratio (front axle : rear axle, %)	43.2:56.8
Length×Width×Height (mm)	3010×1390×2560
Minimum ground clearance (mm)	345
Rated engine power (kW) /speed (rpm)	23.7/2600

Fig. 2 A view of plow used

Table 2 Specifications of the plow

Item	Specification
Model/Company/Nation	YP3-75H-C/Youngjin Machinery/Korea
Weight (kN)	2.2
Length×Width×Height (mm)	1780×1000×1220
Applicable tractor power (kW)	23.5 ~ 31.6
Nominal tilling width (mm)	750
Nominal tilling depth (mm)	200
Share size ⓐ×ⓑ×ⓒ (mm)	290×280×280

2.1.2 Plow

The used plow was 3-blades reversible plow, which is mainly used by farmers in Chuncheon, Gangwon-do. The plow used in the test is a hydraulic reversible plow which can reverse the soil right and left and had wide tilling width. Figure 2 and Table 2 show the shape and specifications of the plow.

2.2 Measuring system

In order to construct the load spectrum of the plow operation, measuring system was composed to measure the engine output shaft torque, the rear axle torque, and the tractive force of plow. Figures 3 and 4 show the overall configuration of a measuring system mounted on a tractor.

The electronic control unit (ECU) is an electronic control device for controlling engine, automatic transmission, etc. with a computer. Speed and torque

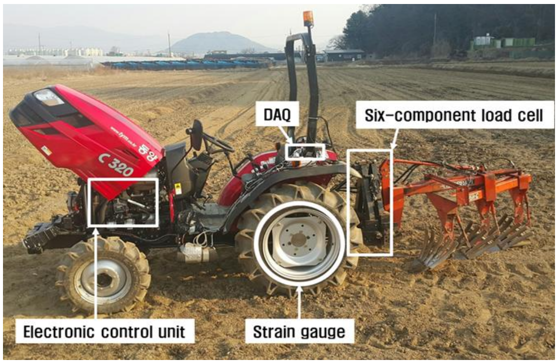

Fig. 3 A view of measuring instruments on tractor

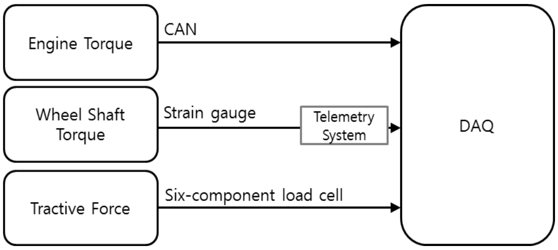

Fig. 4 Schematic diagram of data logging system

of engine output shaft were acquired from the ECU through controller area network (CAN) communication.

To measure the torque of driving axle, strain gauge was attached to the rear axle. The torque generated from the rear axle was measured by using a two-element 90 ° rosette strain gauge (CEA-06-062 UV-350, Micro Measurements Co., USA) which is suitable for torque measurement. The strain gage signals were calibrated using a twist tester (215.45C, MTS Inc., USA) as in Nam et al.[6]. Strain gauges were attached to the left and right rear wheel axles to measure the torques of the left and right axles. The total axle torque was obtained by adding the left and right axle torques. The signal of the strain gage was transmitted to the data acquisition device (DAQ) through the telemetry system. Figure 5 shows the measurement equipment mounted on the rear wheel axle.

The tractive force was measured by six-component load cell which mounted between 3 point hitch and the plow[7]. The six-component load cell used in the test has 6 load cell and measured tractive force with

Fig. 5 Strain gauge and telemetry system for rear wheel torque measurement.

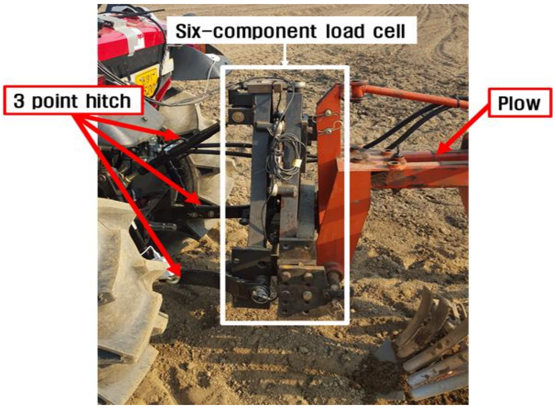

Fig. 6 A six-component load cell for tractive force measurement.

an error rate less than 1.5%. The measured signals from six-component load cell are transmitted to the data acquisition device via a wired cable. Figure 6 is a six-component load cell mounted on tractor.

2.3 Work conditions

The test site was located in Seomyeon, Chuncheon. The soil properties were analysed by soil samples randomly collected at 5 points of the site. The moisture content of the soil was determined using oven method[8] and the soil texture was determined using the U.S. Department of Agriculture (USDA) method. As the results of the soil properties analysis, the soil texture was sandy with 90.9% of sand, 6.0% of silt and 3.1% of clay and the moisture content ranged from 19.5 to 24.2%.

The transmission gears were determined to L4, M1, M2 and M3 considering actual working speed of local farmers[9]. The engine speed was fixed at the rated speed during plow operation, and the working length was 30 ~ 50 m. The rated working speed of the tractor under each gear condition is shown in Table 3, and Figure 7 shows an actual plow operation. Plow operation was repeated 3 times at the same condition and the data were analyzed using average values.

Table 3 Work conditions for field test

Gear of tractor	Rated working speed (km/h)
L4	1.99
M1	2.57
M2	3.53
M3	4.54

Fig. 7 A view of actual plow operations

2.4 Analysis of load data

Figure 8 shows measured torque of engine output shaft at L4 gear. The measured load data was expressed in time domain. Filtering was performed using a moving average method, since the time-torque curve includes high-frequency noise components from uneven field condition and explosion stroke of the engine, etc. Preliminary analysis was performed to find the condition that

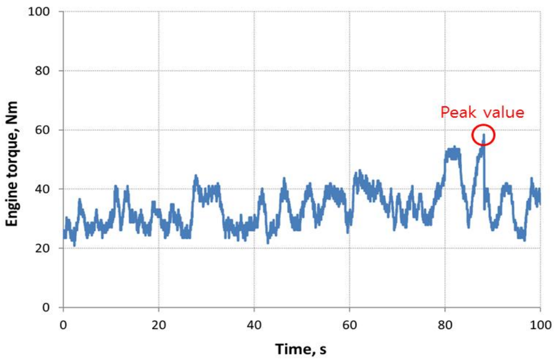

Fig. 8 Measured torque of engine output shaft at L4 gear

peak value is appeared in data and the high frequency noise components are effectively removed. As a result of preliminary analysis, the number of data averaged was set to 10. Thus, the load spectrum was constructed using 10-point moving averaged data. Static safety was analyzed using the peak value in the time-load curve.

To construct a load spectrum, the load must be expressed in frequency domain. It is required that the frequency of a certain load should be counted accurately. Plow operation generate aperiodic load due to various factors such as test site conditions, types of operation. The maximum value of the measured load was divided into 32 bins and the number of cycles in each bin was counted. Also, the load must be converted to equivalent completely reversed load to determine fatigue life. The load spectrum of equivalent completely reversed load was constructed using Smith-Watson-Topper equation. (Equation (1))

$$P_e = \sqrt{P_a(P_a + P_m)} \tag{1}$$

Where,
P_e = Equivalent completely reversed load (N or Nm)
P_a = Average load (N or Nm)
P_m = Load amplitude (N or Nm)

For analyzing the torque of the engine output shaft and the driving shaft, the relative level is more important than the absolute value[10-11]. Therefore, the load spectrum of engine output shaft and rear axle is constructed by torque ratio of the measured torque to the rated torque. The rated torque of the engine output shaft and the rear axle are calculated using Equations (2) and (3). The gear ratio from the engine to the rear axle was obtained by rotational speed as shown in Equation (4). At this time, the power transmission efficiency from the engine to the axle is assumed to be 1.0. For each working speed, rated rotational speed of the rear axle is decided by dynamic radius of rear wheel (KS B ISO 4251-1) and rated working speed of tractor at rated engine speed.

$$T_e = \frac{P_e \times 60 \times 1000}{2\pi \times N_e} \tag{2}$$

Where,
T_e = Rated torque of engine (Nm)
P_e = Rated power of engine (kW)
N_e = Rated rotational speed of engine (rpm)

$$T_r = T_e \cdot \rho \tag{3}$$

Where,
T_r = Rated torque of driving axle (Nm)
T_e = Rated torque of engine (Nm)
ρ = Gear ratio of engine to driving shaft

$$\rho = \frac{N_e}{N_r} \tag{4}$$

Where,
ρ = Gear ratio of engine to driving shaft
N_e = Rated rotational speed of engine (rpm)
N_r = Rated rotational speed of driving shaft (rpm)

Table 4 Material and modifying factors of plowshare

Item	SUP10
Ultimate strength (MPa)	1226
Fatigue strength (MPa)	613
Surface factor	0.580
Size factor	0.876
Load factor	0.72/0.577
Temperature factor	1.000
Miscellaneous-effects factor	0.753

Load spectrum of tractive force was constructed using measured tractive force from six-component load cell and the fatigue life of the plowshare was predicted under each working speed. In S-N curve, strengths for 10^3 cycle and 10^6 cycle were calculated by equation (5), and S-N line of the plowshare was drawn using linear relationship[12]. The material of plowshare used in test is SUP10, and ultimate strength is 1226 MPa according to JIS-G4801[13]. Since the ultimate strength is less than 1400 MPa, the fatigue strength was determined to be 613 MPa which is 0.5 times the ultimate strength. Table 4 shows the ultimate strength of the plow and the factors used in equation (5). The factors were determined by related researches[14-15].

$$S_e = k_a k_b k_c k_d k_e S_e' \tag{5}$$

Where,

S_e = Strength of material (Pa)

S_e' = Strength of test specimen (Pa)

k_a = Surface factor

k_b = Size factor

k_c = Load factor

k_d = Temperature factor

k_e = Miscellaneous-effects factor

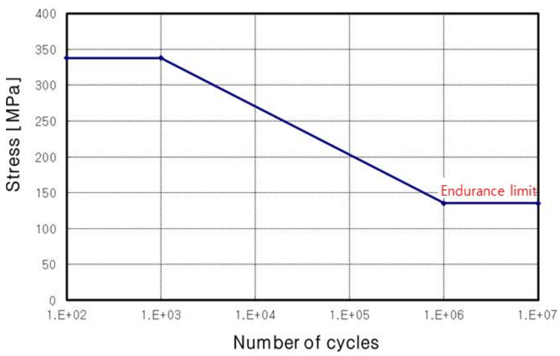

Fig. 9 A S-N Curve for SUP10

The calculated strengths for 10^3 cycle and 10^6 cycle were 337 MPa and 135 MPa. Figure 9 shows S-N diagram of SUP10.

The cumulative damage sum was acquired from load spectrum of tractive force, using Palmgren-Miner rule. In the cumulative damage theory, it is assumed that the total damage is derived from sum of partial damage caused by all the loads acting on it. The fatigue failure is occurred when the total damage is reached to 1.0. In this study, stress spectrum was derived from the load spectrum of equivalent completely reversed load. And partial damage was calculated by the ratio of actual number of cycles at each stress and the number of cycles corresponding to the stress in the S-N curve. However, fatigue failure does not occur regardless of frequency at stresses less than the endurance limit. The partial damage was 0 when calculated stress less than 135 MPa which is the endurance limit of plowshare. The fatigue life using the damage sum is calculated as equation (7) considering working time. The average work time for each working condition in this study was 120 seconds.

$$D = \sum_{i=1}^{32} \frac{N_i'}{N_i} \tag{6}$$

Where,

D = Cumulative damage sum

N_i' = Fatigue life for stress i

N_i = Actual number of cycles for stress i

$$L_f = \frac{1}{D} \times t \tag{7}$$

Where,

L_f = Fatigue life (s)

t = Working time which generate damage sum (s)

3. Results and Discussion

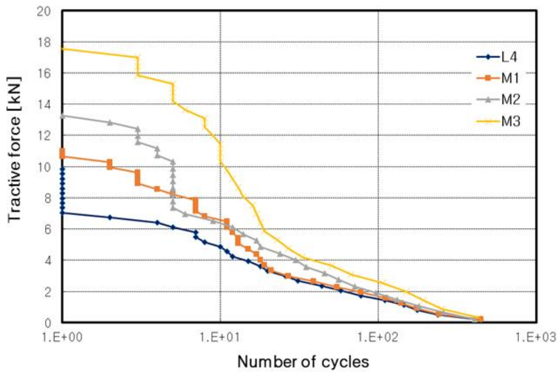

Fig. 10 Load spectrum of tractive force of the plow

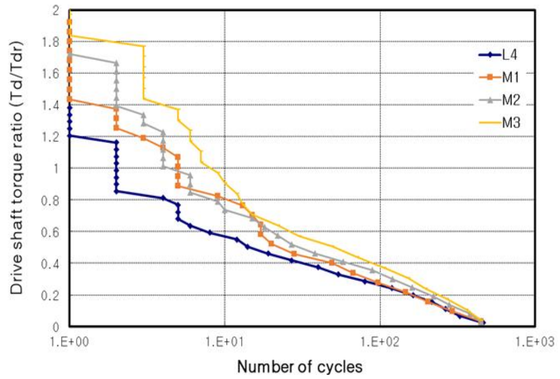

Fig. 11 Load spectrum of rear axle

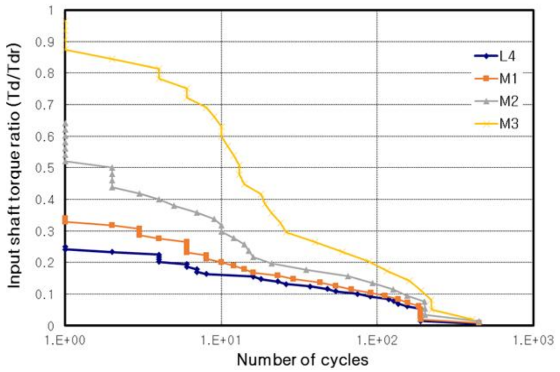

Fig. 12 Load spectrum of engine output shaft

Figures 10 to 12 show the load spectrum of tractive force of the plow, the rear axle and engine output shaft under each working speed condition (L4, M1, M2, M3). The maximum tractive forces were 9.85, 10.99, 13.256, and 17.534 kN under the working speed L4, M1, M2 and M3, respectively. The tractive force increased as the working speed. This is consistent with the known trend that the tractive force of the plow is proportional to the square of the working speed[16].

As the tractive force of the plow increases, the soil thrust to support the tractive force increases and the torque of the driving axle also increases[17]. Therefore, the torque of the engine output shaft and the driving axle show a tendency to increase as the working speed increases. The max-min torque ratio at number of cycles 0 was 1.33 for the rear axle and 3.87 for the engine output shaft. The max-min torque ratio of engine output shaft is larger than rear axle. Kim et al.[3] analyzed max-min torque ratio for rear axle and engine output shaft in two level of working speed. This study verified the load variation on the engine output shaft is larger than that on the rear axle as well as in various working speed conditions.

Measured tractive force data were generated from three plowshares. Considering the number and size of plowshare, tractive force was converted into the stress to calculate the cumulative damage sum for a plowshare. Tables 5 to 8 show stress spectrum of a plowshare derived from spectrum of tractive force.

The cumulative damage sum of plowshare at M3 gear was 4.14×10^{-5} and estimated fatigue life was 805 hours. In the other working speed conditions, all the stress levels were less than the endurance limit and cumulative damage sum was 0. Therefore, it shown infinite lifetime except gear M3 condition.

Table 5 Stress of a share for L4 gear

Number of cycle	Stress [MPa]	Number of cycle	Stress [MPa]
448	1.737	8	49.608
238	4.731	7	52.603
177	7.726	7	55.597
145	10.711	5	58.582
110	13.705	4	61.576
78	16.699	2	64.571
58	19.694	1	67.565
44	22.678	1	70.550
31	25.673	1	73.544
26	28.667	1	76.538
20	31.661	1	79.533
18	34.646	1	82.518
15	37.641	1	85.512
12	40.635	1	88.506
11	43.629	1	91.501
10	46.614	1	94.495

Table 6 Stress of a share for M1 gear

Number of cycle	Stress [MPa]	Number of cycle	Stress [MPa]
448	1.910	12	55.367
243	5.250	11	58.707
176	8.590	11	62.047
140	11.929	8	65.396
111	15.269	7	68.736
78	18.619	7	72.076
55	21.959	7	75.416
39	25.298	5	78.755
27	28.638	4	82.095
21	31.978	3	85.435
19	35.318	3	88.785
18	38.658	3	92.124
17	42.007	2	95.464
15	45.347	2	98.804
13	48.687	1	102.144
13	52.027	1	105.484

Table 7 Stress of a share for M2 gear

Number of cycle	Stress [MPa]	Number of cycle	Stress [MPa]
408	2.083	6	66.672
259	6.123	5	70.713
181	10.164	5	74.744
132	14.194	5	78.784
97	18.235	5	82.815
71	22.266	5	86.856
56	26.306	5	90.896
46	30.347	5	94.927
35	34.378	5	98.967
30	38.418	4	102.998
24	42.449	4	107.039
18	46.489	3	111.079
17	50.530	3	115.110
14	54.561	3	119.150
12	58.601	2	123.191
9	62.632	1	127.222

Table 8 Stress of a share for M3 gear

Number of cycle	Stress [MPa]	Number of cycle	Stress [MPa]
434	2.918	12	88.266
253	8.244	11	93.593
194	13.580	10	98.929
150	18.916	10	104.265
107	24.252	10	109.601
67	29.588	9	114.937
51	34.915	8	120.264
33	40.251	8	125.600
27	45.587	6	130.936
23	50.923	5	136.272
19	56.259	5	141.608
18	61.595	5	146.935
17	66.922	3	152.271
16	72.258	3	157.607
14	77.594	3	162.943
13	82.930	1	168.279

Kim et al.[18] surveyed the use of agricultural machinery in 1500 farmhouses at 11 provinces, and the plow operation time with tractor was 21.1 hours/year. Kim et al.[9] surveyed the work of tractor user in the Jeollabuk-do and the plow operation time was 105 hours/year. Considering the annual plow operation time, the fatigue life of the plowshare was estimated to 38 years based on Kim et al.[18] and 8 years based on Kim et al.[9].

The yield strength of SUP 10 which is the material of plowshare was 1,079 MPa. The maximum tractive force was driven from peak value in the time-load relationship of tractive force. Table 9 shows the maximum load and static safety factor for each working speed. The static safety factor under each working speed was 8.23, 6.88, 8.63, 6.83, and it was estimated statically safe under every conditions.

Table 9 Static safety factor under each working speed

Gear of tractor	Yield strength (MPa)	Maximum stress of a share (MPa)	Static safety factor
L4	1079	130.99	8.23
M1		156.92	6.88
M2		124.99	8.63
M3		157.89	6.83

4. Conclusions

This study analyzed the tractive force of plow and torque of engine output shaft and rear axle during plow operation in Seomyeon, Chuncheon. Test site has moisture content from 19.5 to 24.2% and it was sandy with 90.9% of sand, 6.0% of silt and 3.1% of clay. 3-blades reversible plow was mounted on a tractor with 23.7 kW of rated power to perform the plow operation. Tractive force and torque of engine output shaft and rear axle were measured under various working speed condition (L4, M1, M2, M3). The working speed was determined by the actual working speed of local farmers.

The main results of this study are as follows:

1. The maximum traction forces were 9.85, 10.99, 13.256 and 17.534 kN under working speed L4, M1, M2 and M3, respectively. The tractive force increased as the working speed.
2. The max-min torque ratio at number of cycles 0 was 1.33 for the rear axle and 3.87 for the engine output shaft. It shows the load variation on the engine output shaft is larger than that on the rear axle.
3. The cumulative damage sum of plowshare at M3 gear was 4.14×10^{-5} and estimated fatigue life was 805 hours. In the other working speed conditions, all the stress levels were less than the endurance limit and cumulative damage sum was 0.
4. Considering the annual plow operation time, the fatigue life of the plowshare was estimated to 38 years based on Kim et al.[18] and 8 years based on Kim et al.[9].

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