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REVIEW

Development of a Torque Measurement Device for a Head-feeding Combine Harvester Engine Output Shaft

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Abstract

A torque-measuring device for measuring the engine output shaft on head-feeding combine harvesters was developed to investigate engine working load, an essential element in studies of fuel consumption and exhaust gas emissions. On most head-feeding combine harvesters, a pulley is fastened to an engine flywheel without a shaft. The power loss caused by the belt means engine torque should be measured between the flywheel and pulley. However, there is insufficient space to install conventional torque-measuring equipment. The torque-measuring device we developed was designed to be mounted between the flywheel and pulley. To make the device more compact, it was designed as a double-cylinder structure, with the deformation of the two torque-transmitting beams translated into a torque value. This device does not require irreversible alterations to be made to combines, and is designed to measure torque without any power loss. In static torque measurements, the margin of error of this device proved less than 6%, while the data measured during harvesting operations correlated with that of prior studies. Our results indicate that this device has good potential for use in further studies.

Discipline: Agricultural machinery
Additional key words: emissions, fuel consumption, strain, working load

Introduction

The degree of environmental impact of agricultural machinery, including commonly used head-feeding combine harvesters (hereinafter referred to as “combines”), is increasingly important in their evaluation in Japan. Fuel consumption and exhaust gas emissions are crucial indices for evaluating the environmental impact of combines.

Emissions generated by combines allowed to drive on public roads have been regulated since 2003[6]. Under these regulations, test engine emissions are certificated in ISO 8178-4:2007, using a test cycle defined as the C1 cycle. In this method, the emissions are measured for eight different load states and three different engine speeds[3]. However, Hanson *et al.* have pointed out that the C1 cycle is not suited to the actual operational conditions of agricultural machinery[2]. For emissions caused by tractors, Seki *et al.* have shown the need to develop an evaluation method based on actual operational conditions[9]. However, to investigate this question, the following series of processes is required, since the emissions concerned are only obtained on the test bench. Firstly, the actual loads experienced by the engine output shaft on combines needs to be measured. The obtained loads should then be reproduced using the test bench dynamometer for measuring emissions.

According to the Japanese national test code, fuel consumption of combines should be calculated using the total volume of fuel during the operation from start to end[5]. However, this method is not reproducible, due to the varying influence of the crop and soil conditions. As an alternative, the fuel consumption rate (mass of fuel consumed per load) can be obtained after a diesel engine performance test. This rate depends on engine speed and load, and is represented as a contour chart[7]. It is clear that fuel consumption can be calculated realistically if the actual load and engine speed can be obtained. Therefore, it should be possible to establish a reproducible test method of fuel consumption by measuring the actual load and engine output shaft rpm, and building a general load model from the results obtained.

These facts indicate that it is necessary to investigate engine actual loads to be able to practically evaluate the

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environmental impact of a combine. However, to date, no practical methods have been devised to measure the torque of an engine output shaft during operation.

In this study, prompted by the need for methods to evaluate emissions and fuel consumption, we developed a torque-measuring device for use on a combine's engine output shaft. This device can be mounted on test combines, eliminating the need for irreversible alterations, to measure the torque on the output shaft required to obtain the engine operating loads.

Overview of a prototype torque measurement device

1. Structure of the combine power train

To determine the specifications of the measurement device, the structure of the power train near the engine and the surrounding space was investigated. Three combines, with rated engine output ranging from 20.6 - 51.5 kW, were measured. In these combines, the power from the engine output shaft is transmitted through the belt, and the pulley is fastened to the flywheel with bolts (hereinafter referred to as the "engine pulley") (Fig. 1). The diameter of the engine pulley varies from 110 - 230 mm and the rated torque from 78 - 257 Nm. Space exists between the engine pulley and the structures located on the opposite side of the engine in an axial direction. The minimum dimensions of this space are about 25 mm in the axial direction and about 140 mm in the radial direction.

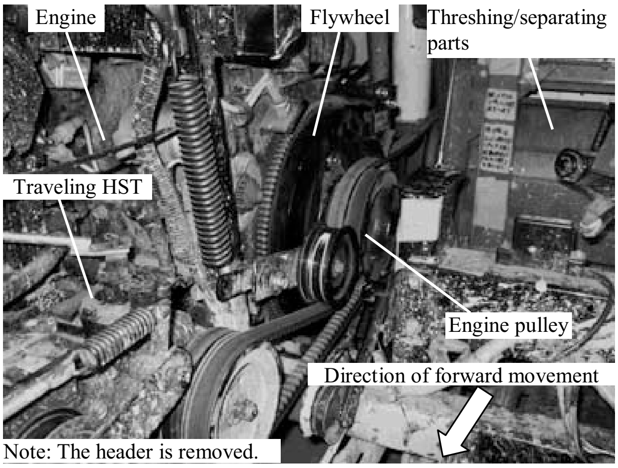

Fig. 1. View of the power transmission part of a head-feeding combine

2. Determining the applicability of existing methods

In a combine, the torque of the engine output shaft needs to be measured before the belt to avoid power losses caused by slipping. These measurements can be done on the engine pulley, but the space available for mounting a measuring device is less than 25 mm in the axial direction.

We investigated previous studies using torque-measuring devices implemented in compact spaces in the axial direction. Some possibly usable and compact devices were found that comprised a magnetostrictive sensor or strain gauges and a transmitter [8,10]. However, they would have been difficult to apply without modification for the purposes of this study. We thus concluded that there was a need to develop a new measuring device optimized to the structure we were investigating.

3. Structure and power transmitting method of the developed measuring device

In this study, a torque-measuring device suited to the structure of combines was developed. The diameter of the flywheel and pulley of combines can vary depending on their type. Accordingly, we developed a measurement device that could be adapted to various types of combines with different flywheels and pulleys.

The structure was designed such that the engine torque is transmitted to the pulley through the measuring device. The pulley was first disconnected from the flywheel and a drive shaft and roller ball bearings were added to support the pulley without transmitting torque. One end of the drive shaft was fixed to the flywheel and the other was joined to an inner boss on the measuring device. The outer flange of the measuring device was fixed to the outer end of the pulley (Fig. 2). The drive shaft and measuring device were joined with an agricultural 35-mm spline as specified in JIS D 6702-1976[4].

The maximum torque of the measuring device was determined as 255 Nm, based on the study result for the rated torque in combines. The diameter of the drive shaft and the bearing were determined according to the rated torque of the tested combines. In this study, we set the target to the combines with a rated torque of about 100 Nm to design the shaft.

4. Structure of the measuring device

The measuring device was designed to measure torque and transmit the resulting data outside the rotary body while being installed in the limited space between the pulley and other structures. It was considered feasible to make the double cylinder structure used in a former study[12] more compact in the axial direction while providing high sensitivity. This structure consists of inner and outer cylinders and interconnecting beams. The torque is sensed as deflection of the beams.

A prototype of a measuring device using this structure was produced (Fig. 3), consisting of an inner boss, an outer flange, two beams, and measuring devices. The inner boss is splined so as to receive power from the engine, while the outer flange is joined with the pulley with bolts. To sense the deflection of beams, four strain gauges are attached to

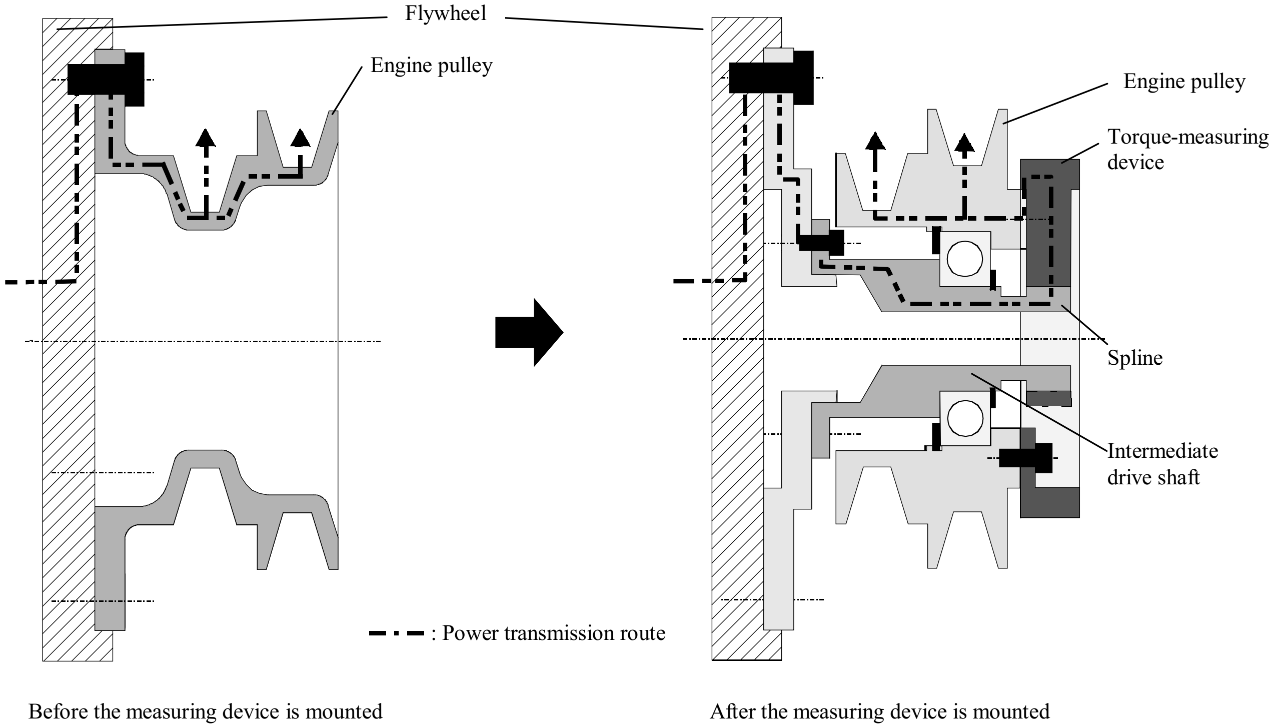

Fig. 2. Overview of torque-measuring device structure

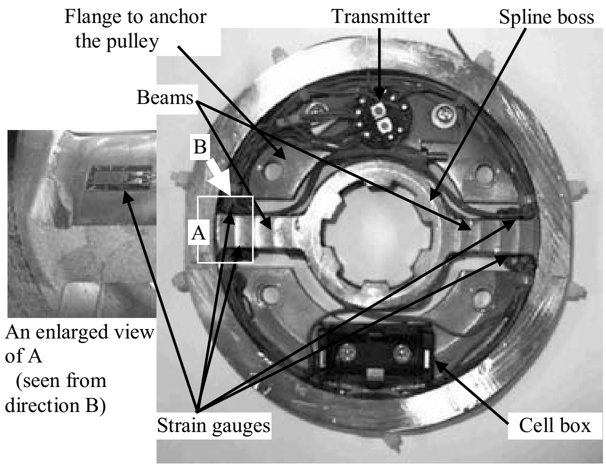

Fig. 3. Overview of the measuring part (seen from the right in Fig. 2)

both surfaces of the two beams. The data was exported via an MRT-300A transmitter (Kyowa Electronic Instruments Co., Ltd.). It contains a bridge box and modulates the potential difference across the bridge into a single FM wavelength band. The transmitting antenna is mounted on the perimeter and the power source is a CR2 lithium battery. The measuring device was made of SS400 steel due to its strength, ease of processing, and low cost.

The external diameter and axial dimension of the measuring device were set at 120 and 20 mm, respectively. The connecting beams were linked to form a quadrangular prism and arranged point-symmetrically about the axis of rotation. The dimensions of the cross section of the beams and the arrangement of strain gauges were determined according to an estimation based on theory and the results of preparatory experiments. The estimation showed the observed strain peaked near the shaft center, but it was concluded to be difficult to attach strain gauges sufficiently securely at this point, due to the fillet and the roughness of the processed surface. The strain gauges were therefore attached to the outermost area that had the next highest sensitivity after that at the shaft center and stable shape. Because the degree of deflection declines rapidly with increasing distance from the center, smaller strain gauges were more suitable for achieving increased sensitivity. KFG-3-350-C1-11 strain gauges (Kyowa Electronic Instruments Co., Ltd.), which are 3 mm in diameter, were used, with their centers set 44 mm from the shaft center. The margin of error in positioning the strain gauges was within 0.5 mm. The dimensions of the cross-section were set at 10 mm high and 15 mm wide, producing a strain of about 100×10^{-6} around the gauge center when a torque of 100 Nm was applied.

Performance of the measuring devices

1. Test methods

The accuracy of the prototype measuring device was evaluated via calibration. For this process, the outer flange was fixed and torque was applied to the inner boss through the spline shaft. The torque was varied from 0 to 255 Nm according to the specifications, applied by hanging weights from a horizontal arm attached to the spline shaft. The length of the arm from the shaft center to the load point was 1 m. The loaded torque was recorded with the slope of the arm in each measurement. The measured torque was calculated by determining the primary regression equation obtained from the measured strain and load torque using the least-square method. A Kyowa Electronic Instruments MRT-301A was used as the demodulator and amplifier. The cut-off frequency of low-pass filter which is equipped in the amplifier was set at 10Hz. Measurements were performed with high and low loads, clockwise and anti-clockwise, to observe the effects of the direction of rotation and hysteresis. The total number of measurements was 91.

The prototype was then mounted on a three-row combine (Yanmar GC328 with a rated engine speed of 2,800 rpm and rated torque of 75 Nm) to investigate the variations in measured strain on applying tension to the belt as instructed in the operation manual.

At the same time, the ease of mounting was evaluated and it was confirmed that no irreversible alterations were required.

2. Results and discussion

The measured torque shows good correlation with the load (Fig. 4), since the standard error was 4.3 (Nm). The margin of error was less than 6%, nonlinearity was within 3% and hysteresis was within 2%. The effect of radial loads caused by belt tension was below the margin of error.

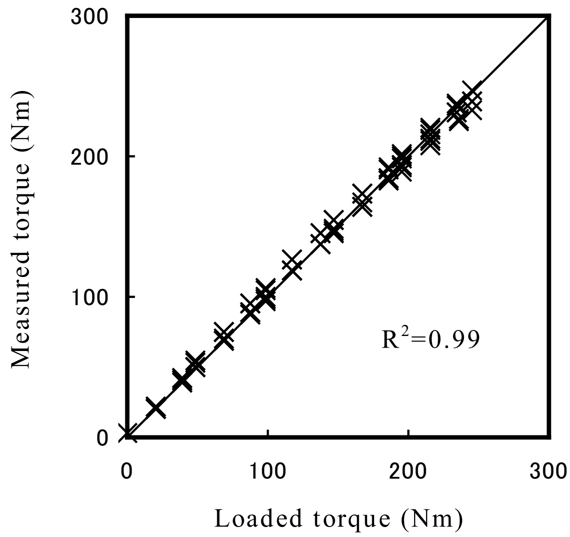

Fig. 4. Relationship between statically loaded and measured torque

To determine the overall adaptability of the measuring device, including the pulley and drive shaft, the torque loss and rigidity of the entire assembly had to be considered. This loss proved negligible, however, since there were no elements causing a substantial loss. The rigidity of the entire measuring device was not the same as that of the original pulley, meaning that the dynamic behavior could vary over a scale of up to a second. However, this could be ignored in practice, since the analyses lasted longer than several seconds.

The entire device could be mounted on the test combine in about 1 hour by removing the header and belt guides, which were reversible alterations.

The performance of the entire developed measuring device was thus sufficient to investigate the actual load on the engine in combines.

Validation of the developed measurement device in field tests

1. Test methods

As mentioned above, the measuring device was developed and tested in static situations. However, to put the device into practical use, its performance had to be validated, since problems such as sharp fluctuations in torque and vibration experienced by combines during harvesting risked degrading the performance of the measuring device.

Due to a lack of precedent for torque measurements of engine output in combines, validation was applied in comparison with former studies on the required power of the driving or threshing part. In previous studies, Ezaki has described how the power consumed by the running gears of combines increases with rising operation speed[1]. Umeda reports that, with head-feeding threshers, the threshing units of which resemble those of combines, the power required by the threshing part increases with increased feeding rate or threshing depth[11].

Based on these findings, trials were performed in which traveling speed and threshing depth were valid. The prototype was mounted on the three-row combine used in the previous section and the torque and rotating speed of the engine output shaft during rice harvesting were measured. The traveling speed was set at one of two levels: “low” or “high”. In the high-speed trials, the threshing depth was set to three levels: shallow, average or deep (Table 1). Every trial was repeated three times. The test track was about 40 m long and the test area began after a 10-m approach run. The engine was operated at the rated speed. The test field was owned by BRAIN, and the test crop was cv. *Sainokagayaki* rice. An MRT-301A, a demodulator and amplifier manufactured by Kyowa Electronic Instruments, and an Omron ZR-RX20 data logger, were installed in a dustproof case that was mounted on the combine. The sampling frequency was set at 100 milliseconds and the data was recorded from start to end to observe any changes during the trial. The average for the test area was also calculated.

Table 1. Test conditions

Travel speed	Low (target speed: 0.55 m/s) High (target speed: 1.0 m/s)
Threshing depth	Average, shallow or deep (at high travel speed only)
Setting of chaff sieve	Average
Setting of resistance plate	Average
Crop used in test	Rice, cv. *Sainokagayaki*
Average length (cm)	99
Average stand angle (°)	84
Average rice moisture content (%)	15.9
Average yield (t/ha)	5.2
Average depth penetrated by rectangular plate* (mm)	44

*: The depth of penetration of a rectangular plate with an area of 4 cm^2 pressed into the ground surface with a force of 294 N through an SR-2 soil resistance-measuring device

Table 2. Average torque and power in test area

Travel speed	Low	High	High	High
Threshing depth	Standard	Standard	Shallow	Deep
Travel speed (m/s)	0.55	0.95	0.97	0.95
Engine speed (rpm)	2837	2799	2826	2789
Torque (Nm)	37.2ab	45.6b	40.5	47.4a
Power (kW)	11.1ab	13.4b	12.0	13.9a

a: Significant difference at the 5 % level.
b: Significant difference at the 10 % level.

2. Results and discussion

(1) Average torque in the test area

The device successfully measured the torque of the engine output shaft in all the trials. The torque averages in the test area were about 60% of the rated value, which were considered reasonable, since the crop and field were in good condition (Table 2). The average torque and power requirement increased at higher operation speeds and increased combing depth. The difference between “low” and “high” traveling speed was significant at the 10% level. The engine output, in terms of torque, increased with increased threshing depth at each repetition, but the difference was insignificant in the context of the larger differences due to repetition. These results coincide with the abovementioned previous studies.

(2) Fluctuation of torque during the trials

The patterns of fluctuation of the measured torque during the trials were similar for all test conditions. Figure 5 shows an example.

The measured torque of the engine output shaft peaked during engine startup. The average torque before harvesting was about 15 Nm without cutting and threshing clutch engagement and about 20 Nm with engagement. During the initial harvesting stages, torque increased with progress, while about 10 s after the start of harvesting, the torque leveled off. The torque measured without the cutting and threshing clutch being engaged is considered due to the load from the HST pump, which is constantly engaged in the test combine. The increased torque at the initial harvesting stage was caused by the acceleration of the combine and the increasing mass of the processed crop inside it. The observed phenomena also coincide with those obtained in

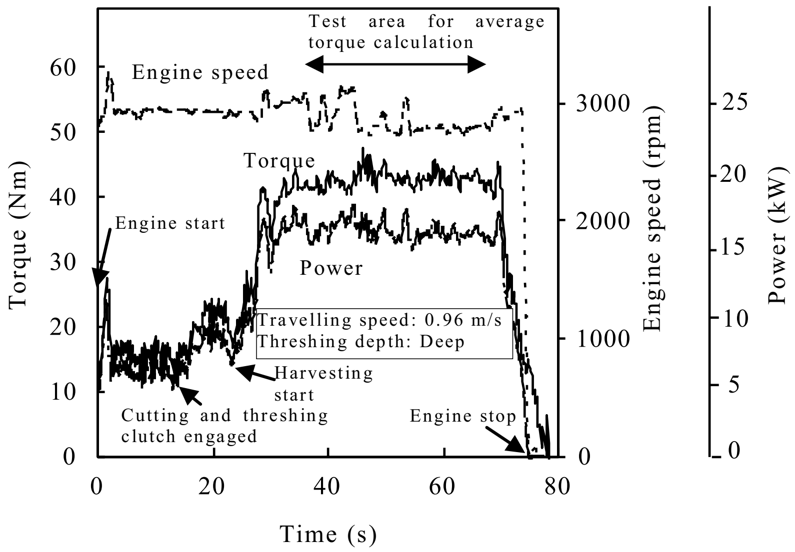

Fig. 5. Fluctuation of torque during harvesting operation

the former studies mentioned above.

Conclusions

These results validated the performance of the developed device in both static situations and during harvesting. There were also no special problems related to the appropriateness of the surrounding environment or the effects on the device of continuous running time, dust and heat, etc. We therefore conclude that the device can be practically implemented for measuring the engine output shaft torque during rice harvesting.

We plan to use the developed device in further studies on actual loads in combines, to enable the influence of crop and field conditions and machinery settings to be investigated.

References

1. Ezaki, H. (1986) *Grain Harvesters.* Isebu Co. Ltd., Ibaraki, 113–116 [In Japanese].
2. Hanson, P-A. et al. (2001) A comparison between different methods of calculating average engine emissions for agricultural tractors. *J. Agric. Engineer. Res.*, **80**, 37–43.
3. ISO (2007) *ISO 8178-4:2007.* ISO, Geneva, 1–18
4. JIS (2001) *JIS D 6702: Power Take-off for Agricultural Tractors.* Japanese Standards Association, Tokyo, 1–3 [In Japanese].
5. Ministry of Agriculture, Forestry and Fisheries (2005) National test code for combine harvesters. *Kanpo (Gazette)*, **4099**, 11 [In Japanese].
6. Ministry of Land, Infrastructure, Transport and Tourism (2009) *Shin Doro-unsosharyo no Hoankijun* (*Revised Safety Regulations for Road Transport Vehicles)*. Kobunsha Co. Ltd., Tokyo, **2**, 1082–1113 [In Japanese].
7. Miyashita, N. & Kuroki, H. (1994) *Jidosha-yo Diesel Engine (Diesel Engines for Road Vehicles)*. Sankaido Co. Ltd., Tokyo, 18–22 [In Japanese].
8. Nishibe, Y. et al. (1996) Magnetostrictive torque sensor for automobile engines. *Toyota chuo-kenkyusho R&D revue (R&D revue of Toyota Central R&D Labs.)*, **31**, 61–70 [In Japanese with English summary].
9. Seki, E. et al. (2006). Evaluation of exhaust gas emissions for agricultural tractors based on actual operations. *Nogyo kikai gakkaishi (Journal of JSAM)*, **68**, 130–137 [In Japanese with English summary].
10. Shimada, N. & Sato, Y. (2000) Torque sensor for bicycles. Jpn. Pat. P2000–193540A [In Japanese].
11. Umeda, M. (1992) Analysis of threshing mechanism of head feeding thresher (Part 4). *Nogyo kikai gakkaishi (Journal of JSAM)*, **54**, 49–57 [In Japanese with English summary].
12. Yoneyama, T. (1993) *Kikaisekkei no Kisochishiki (Basic Knowledge for Machine Design)*. Nikkan-kougyo Shinbunsha Co. Ltd., Tokyo, 361–366 [In Japanese].