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# An Evaluation Method for Threshing Operations Using a Rod–shaped Threshing Tooth Acting on a Single Rice

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A threshing unit consumes about 40% of power required by a Japanese head feeding combine. Thus, the unit has a major impact on efficiency and energy consumption during harvest. The threshing capacity can be improved by increasing an engine output, while threshing operations should be studied to lower energy consumption. The objectives of this study were to evaluate threshing operations under different acting speeds, locations, and angles of a rod–shaped threshing tooth (hereafter, threshing tooth), and to investigate an evaluation method for threshing operations, which considered energy efficiency. We evaluated percentage of detached grains, energy efficiency, and the grain number of the largest broken panicle (GNLBP) under different rotational speeds (300 rpm, peripheral velocity: 9.4 m/sec; 500 rpm, peripheral velocity: 15.7 m/sec), acting locations of a threshing tooth on a single rice (upper stem, neck node of a panicle, center of a panicle), and acting angles (10°, 30°). The largest PDG was 80% when the threshing tooth acted on a rice with 10° at the neck node of a panicle under 500 rpm. Percentage of detached grains decreased when GNLBP increased. Energy efficiency ranged from 4–42%, and was the highest when the threshing tooth acted on a rice with 10° at the neck node of a panicle under 300 rpm. The acting locations of upper stem (10° and 30°) and neck node of a panicle (30°) suffered large energy loss, because a stem or a panicle was broken. Moreover, energy loss was assumed to be large due to work required for accelerated motion of a panicle, which increased under 500 rpm. In conclusion, the evaluation method in this study effectively identified threshing operations, which lowered energy efficiency.

**Key words**: Combine, Energy efficiency, Percentage of detached grains, Power requirement, Threshing performance

## INTRODUCTION

Japanese head feeding combines feed only head part of crop in threshing unit, whereas combines used in Europe and America feed the whole crop. The way of feeding only head part can reduce load during threshing crop and increase threshing efficiency. Thus, Japanese head feeding combine can increase operation speed and lower energy consumed during harvest.

A threshing unit consumes about 40% of power required by a Japanese head feeding combine (Esaki, 1986). In the threshing unit, teeth mounted on a threshing cylinder hit panicles. Grains are detached when pedicels of a panicle involve tensile, bending, and shear stress by threshing teeth. Meanwhile, power transmission is complex when grains are detached, which might increase energy loss during the threshing operation. Thus, an evaluation method for threshing operations needs to be developed considering energy efficiency to improve threshing performance with reduced energy consumption.

Umeda (1992) measured force and energy consumption when a single rice was threshed with a rod–shaped threshing tooth. On the other hand, this study did not evaluate energy efficiency during the threshing operations. In addition, threshing conditions including acting locations and angles of a threshing tooth were not evaluated. Therefore, the objectives of this study were to evaluate threshing operations under different acting speeds, locations, and angles of a rod–shaped threshing tooth, and to investigate an evaluation method for threshing operations, which considered energy efficiency.

## MATERIALS AND METHODS

### Experimental system

An experimental system for evaluating threshing operations consists of a servo motor (GYS502D5–HC2, Fuji Electric), a servo amplifier (RYT502D5–VS–2, Fuji Electric), a programmable logic controller (PLC) (NP1W1606T, Fuji Electric), a rod–shaped threshing tooth, a dynamic strainmeter (TMR–281, Tokyo Measuring Instruments Lab.), high–speed cameras (Fastcam 1024PCI–2CH, Photron), and halogen lamps (Fig. 1). The rod–shaped threshing tooth (hereafter, threshing tooth) made of stainless steel was fixed to a coupling installed on the axis of the servo motor. The rotational speed of the threshing tooth was controlled by

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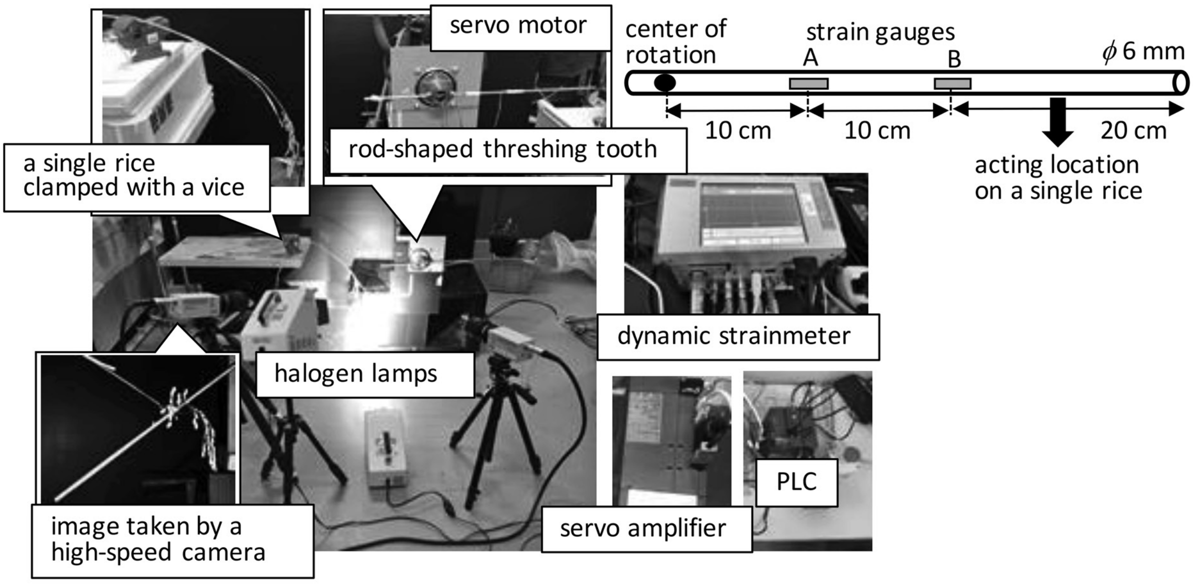


**Fig. 1.** An experimental system for evaluating threshing operations.

**Table 1.** Experimental conditions

| Control parameter | Conditions |
|---|---|
| Rotational speed (rpm) | 300 (peripheral velocity: 9.4 m/sec), |
| | 500 (peripheral velocity: 15.7 m/sec) |
| Acting location | upper stem, neck node of panicle, center of panicle |
| Acting angle (°) | 10, 30 |

the PLC. The rotational angle was measured by counting pulse signals emitted from an encoder. The threshing tooth allowed to measure bending moment of the rod on which two strain gauges were glued as shown in Fig. 1.

**Experimental procedure**

The experiment started with the setting of the rotational speed. Then, bending moment acted on the threshing tooth was measured while the tooth was idling. Next, we adjusted an acting location and angle of a threshing tooth on a single rice of which base was clumped with a vice. Table 1 lists the experimental conditions. The acting location was around 10 cm from the tip of the rod (30 cm from the center of rotation). We used naturally dried rice (cultivar: Nikomaru) of which leaves were removed in the experiment. Before evaluating threshing performance, we counted the number of rough rice per panicle and selected test samples, which had 80 to 100 of rough rice per panicle.

The rotation of the threshing tooth started from the opposite side of the location where the base of rice was clumped. The threshing tooth acted on a rice at the rotational angle of approximately 180° and then stopped at 360°. Figure 2 shows strain measured along a rotation of the threshing tooth while idling and acting on a rice. The circle in the figure corresponds to the location where the threshing tooth acted on a rice. Net strain generated by the reaction force of a rice was obtained by

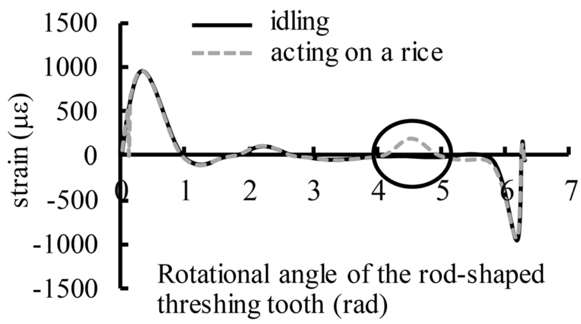


**Fig. 2.** Strain measured along a rotation of the rod–shaped threshing tooth while idling and acting on a rice (300 rpm, acting location: neck node of a panicle, acting angle: 10°)

subtracting strain measured while idling. The reaction force and its acting location of the threshing tooth were calculated by strain measured by points A and B shown in Fig. 1.

We took images of a rice response with high–speed cameras in order to investigate panicles broken by the threshing operation. The frame rate and shutter speed of the high–speed cameras were 1000 fps and 1/8000 sec., respectively. We counted the number of a single grain detached from a panicle. We also counted the grain number of the largest broken panicle (GNLBP).

### Calculation of total work and energy efficiency

Total work by the threshing tooth was calculated by the Eq. (1).

$$W=\int_{\theta_s}^{\theta_p} T \; d\theta \tag{1}$$

where $W$ is the total work by the threshing tooth (J), $T$ is the axial torque of the motor (Nm), $\theta$ is the rotational angle of the threshing tooth (rad), $\theta_s$ is the rotational angle when the threshing tooth started acting on a rice (rad), and $\theta_p$ is the rotational angle when the axis torque of the motor reached the peak value (rad). The rod–shaped threshing tooth returned to the original shape after its deformation caused by bending became peak. Thus, we assumed that work after the peak value of the axial torque was measured because of response of the rod returning to the original shape. This was the reason for setting $\theta_p$ as the larger limit of integration in Eq. (1). Moreover, energy efficiency (EF) was calculated by Eq. (2).

EF (%) = Work required for detaching grains from a panicle /Total work by the threshing tooth×100 (2)

Here, the numerator in Eq. (2) was calculated by the product of the number of detached grains from a panicle and work required to detach a single grain from a pedicel, which was measured by a tensile test. The percentage of detached grains (PDG) was calculated by the following Eq. (3).

PDG (%) = Number of grains detached from a panicle /Total number of grains ×100 (3)

## RESULTS AND DISCUSSION

For the operations under 300 rpm, PDG (65%) was significantly higher than other operations when the threshing tooth acted on a rice with 10° at the neck node of a panicle (Fig. 3(a)). In this operation, EF (42%) was significantly higher than the operations where the threshing tooth acted on a rice at the upper stem. In general, PDG and EF were largest for the operations at the neck node of a panicle, followed by at the center of a panicle, and the upper stem. Moreover, PDG and EF had a large difference between 10° and 30° at the neck node of a panicle. For the operations under 500 rpm, PDG and EF had similar trends with those under 300 rpm (Fig. 3(b)). On the other hand, PDG increased to 80%, while EF decreased to 34% for the operation with 10° at the neck node of panicle.

PDG was low for the acting locations of upper stem (10° and 30°) and the neck node of a panicle (30°) because GNLBP was large. The GNLBP increased when a panicle was broken around the neck node of a panicle. For the acting location of the upper stem, GNLBP increased because a stem was easily broken for smaller shear strength when dried rice was used in the experiment.

For the acting location of the neck node of a panicle with 10°, PDG was high because the operation did not involve large broken panicles, and grains were detached when pedicels were broken by tensile, bending, and shear stress, which were caused by inertia force of a panicle. Larger inertia force of a panicle under 500 rpm likely increased PDG for the acting location of the neck node of a panicle with 10°. On the other hand, PDG was low for the acting location of the center of a panicle because increased number of grains remained undetached. This indicated that inertia force of a panicle was small because the acting location of a threshing tooth

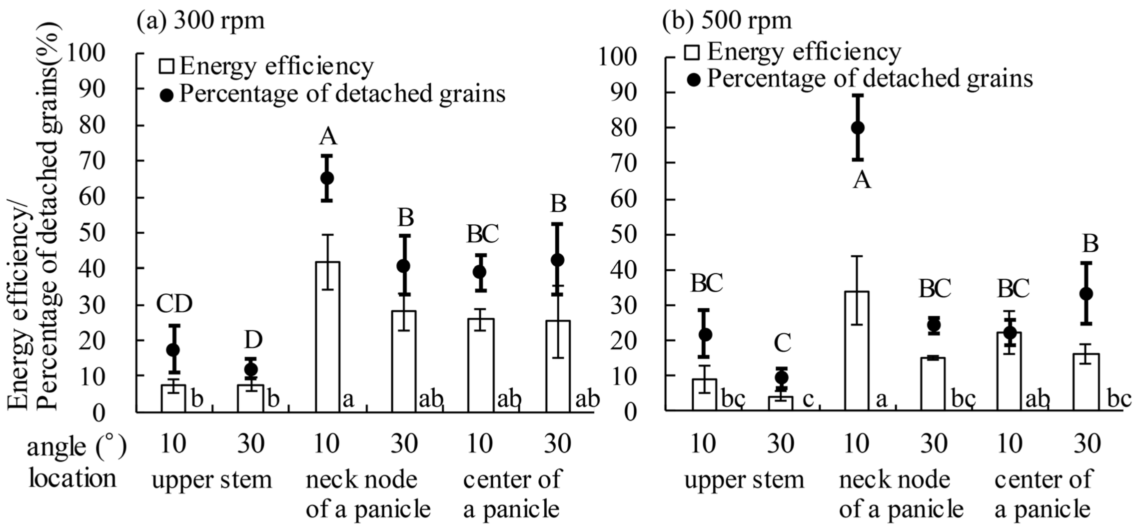


**Fig. 3.** Energy efficiency and percentage of detached grains.
*Different alphabets (small letter: energy efficiency, capital letter: percentage of detached grains) in the graphs indicate that mean values among experimental conditions are significantly different ($p < 0.05$) according to the Tukey's method. n=3

approached the tip of a panicle.

For the acting location of the neck node of a panicle with 10°, PDG was higher under 500 rpm than that under 300 rpm, while EF was lower under 500 rpm. This was probably because work required during the threshing operation increased due to increase in inertia force of a panicle under 500 rpm. Larger inertia force of a panicle probably increased PDG, whereas it can involve reduced EF.

From the above results, threshing performance can be improved when large broken panicle was reduced and a rice does not involve unnecessary acceleration motion. Thus, the threshing tooth should be acted near the neck node of a panicle with a smaller angle under an appropriate rotational speed.

## CONCLUSIONS

The objectives of this study were to evaluate threshing operations under different acting speeds, locations, and angles of a rod–shaped threshing tooth, and to investigate an evaluation method for threshing operations, which considered energy efficiency. The following conclusions were drawn:

1. The percentage of detached grains was largest for the acting location of the neck node of a panicle with 10°. Energy efficiency lowered when the rotational speed increased from 300 rpm to 500 rpm.
2. Energy efficiency markedly lowered for the acting location of the upper stem because the grain number of the largest broken panicle increased.
3. Energy efficiency ranged from 4–42%, which indicated large energy loss occurred when a stem or a panicle was broken and a rice involved large acceleration motion.
4. The evaluation method in this study effectively identified threshing operations, which lowered energy efficiency.

## AUTHOR CONTRIBUTIONS

Y. Hirai designed the study, analyzed the data, and wrote the paper. D. Furukawa conducted experiments, analyzed the data, and wrote the paper partly. E. Inoue, T. Okayasu, and M. Mitsuoka offered advices on the experiments and data analysis. All authors assisted in editing of the manuscript and approved the final version.

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