Analysis of Reaction Forces and Posture of a Bunch of Crop Stalks during Reel Operations of a Combine Harvester

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ABSTRACT

The purpose of the present study is to clarify reel operations appropriate to crop conditions, such as a crop's physico-mechanical properties and the extent of lodging, from the viewpoint of the mechanical interactions between the crops and a combine harvester reel. First, because the gathering processes by the reel involve mechanical operations of forced displacement, the horizontal and vertical reaction forces of a bunch of crop stalks (rice and wheat stalks) undergoing the forced displacement were measured. Further, a bunch of crop stalks, which has conventionally been complicated in dealing, was considered as a composition of a single crop stalk, and the reaction forces of crop stalks were analyzed numerically using a differential equation describing deflection, which was derived based on a mechanical model of a crop stalk.

As the results, the horizontal reaction forces increased linearly with the increment of forced displacement (deflection), while the vertical ones changed its direction and magnitude depending on relationship between crop posture and frictional force. The simulated results of the trends of the reaction forces agreed approximately with measured ones. This suggested that the analytical method of determining reaction forces based on the derived equation could be utilize for investigating reel-crop interactions. This paper also presents posture analysis of a bunch of crop stalks during gathering operations.

Keywords: combine harvester reel, gathering operation, mechanical model of a crop stalk, a bunch of crop stalks, reaction force, deflection characteristics

1. INTRODUCTION

In the field of agricultural machinery, machine tests are usually conducted in the field in order to assess performance including crop conditions, such as a crop's physico-mechanical properties and the extent of lodging. However, it would be advantageous to assess a machine's performance taking the crop conditions into account at the

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design stage, which would reduce development costs and shorten the development period. In order to improve the process of design and development, mechanical interactions between the machine and the crops, which are closely related to performance and are strongly affected by crop conditions, should be investigated by constructing analytical theories according to various operations of the harvesting machinery based on a mechanical model of the crop. In the present study, mechanical interactions between a combine harvester reel and the crop were investigated in order to clarify the gathering operations of the reel appropriate to specific crop conditions.

Several investigators have studied a variety of physico-mechanical properties of biological materials for the purpose of applying them to machine design, mechanical processes and lodging problems. O'Dogherty *et al.* (1995) examined the effects of wheat straw's maturity, stem internode position, and moisture content on physical (diameter and wall cross-sectional area) and mechanical (shear strength, tensile strength, Young's modulus, and modulus of rigidity) properties. Gawda (1978) measured the Young modulus of cereal stalks along the stalk's length during earing and at full maturity using an ultrasonic method. Gowin (1980) applied a measurement method involving holographic interferometry for determining the elasticity modulus of wheat stalks. Gowin (2000) proposed accurate methods for determining cereal stalk cross-sectional area and the moment of inertia of the stalk cross-section using a microscopic method and image analysis. Moustafa *et al.* (1968) discussed the stability of the wheat plant in terms of the buckling load and investigated the effect of maturity on the plant's elastic and visco-elastic parameters. Muller (1988) discussed the stability of the wheat-stalk based on the bending and torsional rigidity measured in each of its internodes. Szot and Skubisz (1984) evaluated winter wheat stalk elasticity including the influence of the root system, and investigated the effect of plant maturity on plant elasticity. As stated above, the mechanical characteristics and behaviors of biological material, which can be applied to the machine design, have been investigated, yet instances of their actual application to design are very few, and machine performance is still assessed based on field tests. One reason for the low number of real applications is the existence of very few studies focusing on the mechanical interactions between crops and the machine during actual operations. Namely, further studies regarding the mechanical behavior of biological materials involved in machine operations are indispensable to the application of the above investigations to machine design.

Gathering performance of the combine reel is affected by control parameters such as height and speed of the reel, and the location of the cutter bar in relation to the reel, and these parameters must be adjusted according to crop conditions. However, current operating manuals provides only a slight description of the adjustment points of these parameters, the performance depends mainly on the skill of operators. The clarification of effective reel operations can contribute to more effective control under specific crop conditions, to the development of a control system which provides stable performance, and also to reduction of the burden of the operators. Further, investigation of reel-crop interactions based on the mechanical model can lead to assessment of the performance from various aspects such as head loss, power requirement and smooth feed of cut stalk into the auger.

Previous studies focusing on reel operations have mainly shown the reel's geometric motion and the results of field tests. Esaki (1955) derived the equation describing the trajectory of the reel's motion and proposed a formula for determining the location of the cutter bar in relation to the reel. As well, Esaki reported the results of field tests under various velocity ratios, reel operating heights, and locations of the cutter bar. Sakai *et al.* (1993) derived a formula for determining the location of the cutter bar in relation to the reel under the condition of a standing single crop. Further, in order to determine a parameter necessary for utilizing the formula, Oduori *et al*. (1993) experimentally established a mathematical relationship between the ratio of rice stem deflection to the acting height of a deflecting force and a stem deflection angle. The above studies are valuable for determining the design parameters of a reel, yet they are applicable only to limited conditions due to an only slight theoretical consideration of the mechanical interactions between a combine reel and crops. Thus, the investigation of reel-crop interactions based on a mechanical model of a crop is indispensable.

The combine harvester reel feeds crop stalks into the auger while changing the location of its operation by its rotational motion. In this operation, reel-crop interactions, which involve the change of both external force of the reel (reaction force of the crop stalks) and crop posture, affect the behavior of the cut stalk; that is, these factors affect the operational performance of the reel. Thus, the authors (Inoue *et al*., 1998) applied a large deflection equation regarding an elastic beam to a rice stalk, and discussed the application to large deflection by the reel operations. Further, a mechanical model of a crop stalk with a heterogeneous cross-section based on bending theory regarding an elastic beam was proposed, and also a calculation method of flexural rigidity for materials with heterogeneous cross-section was inspected by deflection tests using piano wire (Hirai *et al.*, 2000). An extended model that takes into account the effect of a crop ear was proposed, and the relationships between the deflection and deflection force (horizontal force component) acting on a bunch of crop stalks during the reel operations were analyzed under a standing crop condition (Hirai *et al.*, 2002). It was suggested that the model was useful for investigating reel-crop interactions, and also that the analytical accuracy of the deflection force would be increased by considering the effect of the vertical force component and stalk's initial posture.

In the present study, the horizontal and vertical reaction forces of a bunch of crop stalks (rice and wheat stalks) undergoing forced displacement were measured through a series of experiments involving the gathering operations of a reel. Further, a differential equation describing deflection, which took into account the vertical force component, was derived based on the mechanical model of a crop stalk, and was used for numerical analysis of the reaction forces. In the analysis, the effect of friction was also considered. The simulated results of the trends of the reaction forces approximately coincided with the measurements. This suggested that the analytical method of determining reaction forces based on the derived equation could be utilized for investigating reel-crop interactions. This paper also presents posture analysis of a bunch of crop stalks during gathering operations.

Notation

D_j: flexural rigidity of the j^{th} internode, kN·mm^2
E: x coordinate at acting point of concentrated load, mm
E_l: length of an ear, mm
f: frictional force, N
F_x: horizontal reaction force, N
F_y: vertical reaction force, N
h_p: height at the loading point, mm
i: the number of crop stalks
L: length of a crop stalk, mm
M: bending moment acting on a crop stalk, N·mm
n: number of nodes or internodes from fixed end
N: total number of crop stalks
P: load acting on a crop stalk, N
P_n: normal force acting on a crop stalk, N
P_r: normal reaction force, N
P_t: tangential force acting on a crop stalk, N
W: weight of an ear, N
x_i, y_i, z_i: reference coordinates of crop stalks, mm
x_j, y_j: x, y coordinates at the j^{th} node, mm
x_p, y_p: x, y coordinates at loading point, mm
x_t, y_t: x, y coordinates at the tip of a stalk, mm
θ_p: deflection angle at loading point, rad
θ_t: deflection angle at the tip of a stalk, rad

2. Experimental system and method

2.1 Experimental system

Experimental system involving the reel operations is illustrated in Figure 1. This system is composed of an L-shaped sensor, oil-hydraulic apparatus, low pass filter (KYOWA, LF-303A), strain amplifier (KYOWA, DPM-612B), data-recorder (TEAC, DR-C1MK2), notebook computer (TOSHIBA, SA65C/4), digital video camera (SONY, DCR-VX1000), and tested material. The dimensions of the L-shaped sensor made in this experiment and the arrangement of strain gauges bonded to the steel body are shown in Figure 2. Four pieces of strain gauges were mounted on the body around each circular hole involving stress concentration. The bridge circuits were composed of each set of them, and voltage signals due to the change of strain was outputted. Thus, the L-shaped sensor is capable of sensing two mutual perpendicular force components. The L-shaped sensor attached to the rod of oil-hydraulic cylinder is controllable for horizontal motion and its speed by oil-hydraulic pump. The loading speed is measured by tracing reflector tape put on the cylinder rod using image data. The acting height of the sensor is adjustable using a stand. The material crop stalks tested comes in contact with the aluminum roller equipped with the tip of the sensor, while they are deflected by the horizontal motion of the sensor. At that time, high frequency signals due to a slight vibration during horizontal movement are removed from original electrical signals of the sensor by a low pass filter, and then the signals are amplified and recorded on a data recorder, which converted analog into digital data automatically. Data acquisition system is shown in Figure 3. The crop posture during the experiment is recorded by means of a digital video camera.

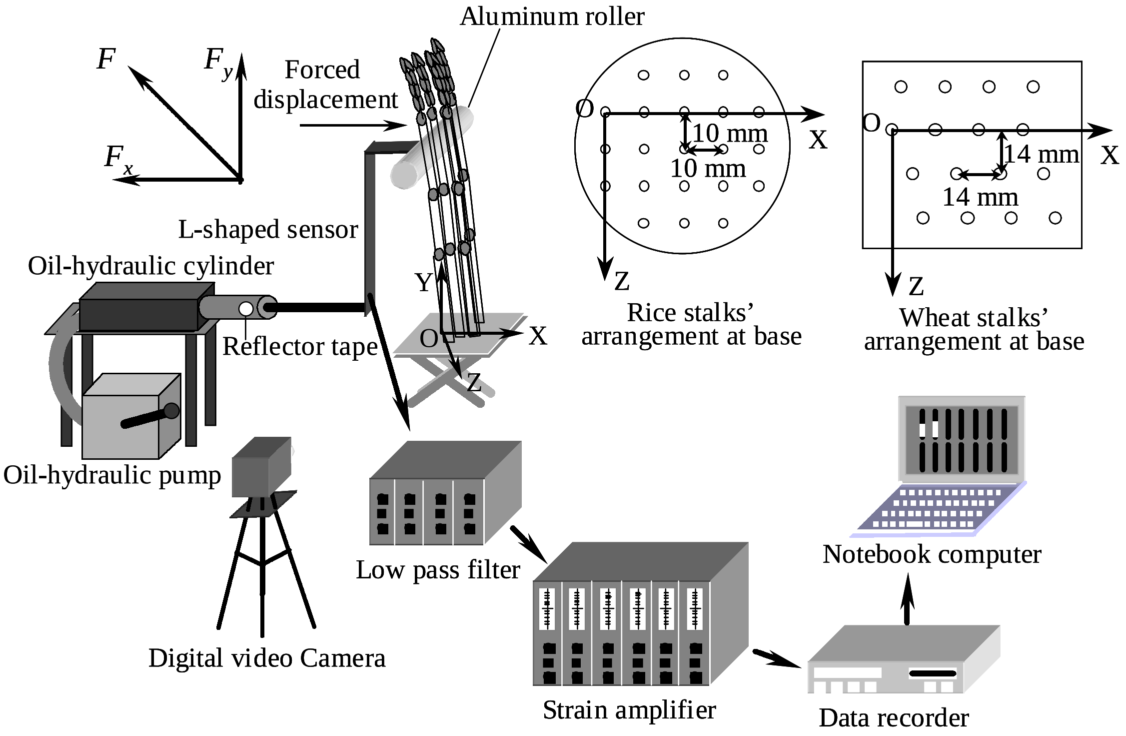


Figure 1. Experimental system involving reel operations and arrangement of a bunch of crop stalk

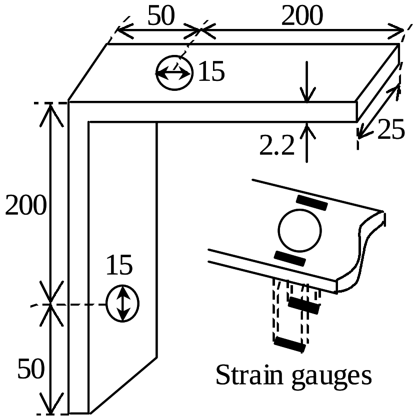


Figure 2. Dimensions of the L-shaped sensor and the arrangement of strain gauges (all dimensions are in mm)

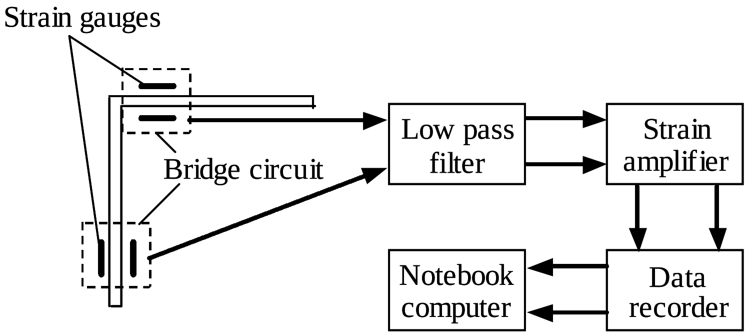


Figure 3. Data acquisition system

2.2 Experimental method

Measurements were made on 'Mineasahi' variety of rice stalks and 'Chikugoizumi' variety of wheat stalks. The specimens were selected randomly from 0.5 are area field of Kyushu University in Fukuoka, Japan. The roots were removed and a bunch of crop stalks (21 pieces of rice stalks and 16 pieces of wheat stalks) were fixed to a piece of wood at their base and arranged in the same manner as they would be in a field as shown in Figure 1. The base position closest to the sensor was defined as origin. Sampling was carried out in 2001 from 15 to 23 October and in 2001 from 29 May to 7 June for the rice and wheat, respectively. The acting height of the sensor was arranged according to the actual operational height of the reel, which was 70~80 % of the appearance height of the crop stalks. The crop stalks were deflected by the horizontal motion (forced displacement) of sensor, while at that moment two mutual perpendicular components of reaction forces were measured simultaneously. The tests were conducted twice for each material so that the material would not involve changes of the physical properties of the crop stalks such as fatigue and destruction, and each six materials of a bunch of rice and wheat was measured. Two sets of data were obtained for each material, and one data set among them was used for assessing the accuracy of this experiment. This experiment was conducted under a quasi-static condition; the speed of the sensor was about 10 mm s^{-1}. The reel acts dynamically on the crop stalks at a peripheral speed of about 1.5 m s^{-1} under standard operations, though the basic operation of the reel is the operation, which deflects the crop stalks. Thus, it is indispensable to establish an equation which expresses the relationship between the load acting on the crop stalk and the deflection (differential equation describing deflection), and to examine the application range of the equation. In a future study, the range will be discussed through comparison with experimental results under dynamic conditions, and the motion equation will be derived from a differential equation describing deflection. Following this experiment, a deflection test for determining the flexural rigidity of each crop stalk composing the bunch was carried out.

2.3 Deflection test

An illustration of the measurement system for deflection test is provided in Figure 4. This system is composed of markers, a line-shift camera (COSMO SYSTEM, LCIID-5000B), an image-processing apparatus (FAST, CSC901b), a monochromatic monitor, halogen lamps, and a personal computer (NEC, PC9801). The line-shift camera provides an image in two dimensions by driving the CCD elements through a stepping motor. The image-processing apparatus converts the image into gray tones and can control the range of gray tones in order to distinguish an object. The personal computer collects data regarding the makers' center coordinates, which are recognized by image processing, through a RC-232C interface.

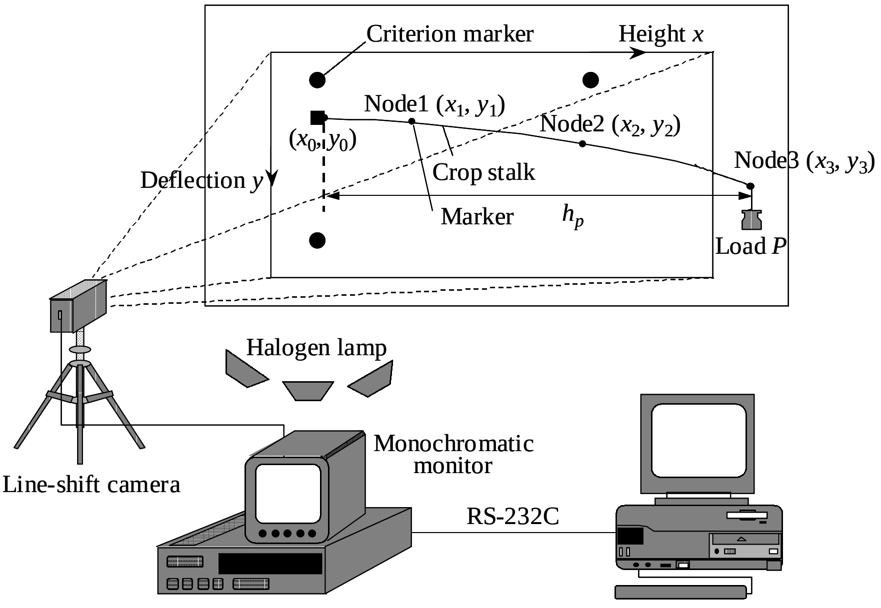


Figure 4. Measurement system for deflection test

In this measurement, the theory of segmentation, in which images are segmented into either white (0) or black (1) values, was applied in order to recognize the markers digitally. Images segmented were analyzed by using a program made of C language. The markers' center coordinates were calculated based on the geometrical moment of the recognized area of the markers. The deflection of a stalk was calculated by the displacement from the criterion marker to each marker bonded to the stalk, and the height was calculated based on the distance between each marker. The deflection and height of each stalk node was measured while the load was acted on the tip of the stalk. The flexural rigidities of each internode and an average value were calculated using Eqn (1) employing data obtained from the deflection test.

$$
\begin{aligned}
&\text{(I) } n = 1 \\
&\quad \frac{dy}{dx} = f(x, D_n) \\
&\text{(II) } n \geq 2 \; (x_{n-1} \leq x \leq x_n) \\
&\quad \frac{dy}{dx} = f(x, D_n) + \sum_{j=1}^{n-1} \left\{ f(x_j, D_j) - f(x_j, D_{j+1}) \right\}
\end{aligned}
\qquad (1)
$$

where, $f(x, D) = \dfrac{h_p x - \dfrac{x^2}{2}}{\sqrt{\left(\dfrac{D}{P}\right)^2 - \left(h_p x - \dfrac{x^2}{2}\right)^2}}$

and: D_j is the flexural rigidity of the j^{th} internode; h_p is the height at the loading point; n is number of nodes or internodes from fixed end; P is the load acting on a crop stalk; x_j, y_j are the x, y coordinates at the j^{th} node. Now, the Eqn (1) is a differential equation for the deflection angle. To calculate the deflection using this equation, the Runge-Kutta Method was applied. The data regarding rice and wheat stalk flexural rigidity, length, weight, and moisture content are shown in Table 1. In Table 1, the figures in parentheses represent the standard deviation. The flexural rigidity and length of the stalks were measured for all stalks composing the bunch, and the standard deviation was calculated. The weight, length of the ear, and moisture content were expressed as the average values obtained from five samples of the bunch.

Table 1 Data regarding rice and wheat stalk flexural rigidity, length, weight and moisture content

Rice stalk No.1	***Internode1***	***Internode2***	***Internode3***	***Whole***	***Ear***
Flexural Rigidity, kN·mm^2	41.2 (12.9)	43.3 (21.9)	12.1 (3.4)	30.1 (9.2)	-
Length, mm	175 (48)	232 (65)	368 (40)	775 (50)	187
Weight, N	-	-	-	0.044	0.039
Moisture Content, % w.b.	-	-	-	61.0	24.3
Rice stalk No.2	***Internode1***	***Internode2***	***Internode3***	***Whole***	***Ear***
Flexural Rigidity, kN·mm^2	32.7 (10.3)	25.3 (10.6)	9.2 (1.7)	22.9 (5.2)	-
Length, mm	208 (46)	187 (10)	326 (22)	720 (40)	169
Weight, N	-	-	-	0.036	0.028
Moisture Content, % w.b.	-	-	-	59.3	28.1
Wheat stalk No.1	***Internode1***	***Internode2***	***Internode3***	***Whole***	***Ear***
Flexural Rigidity, kN·mm^2	28.9 (9.2)	48.8 (20.6)	16.4 (5.3)	28.8 (8.1)	-
Length, mm	198 (46)	244 (12)	336 (29)	778 (49)	84
Weight, N	-	-	-	0.022	0.021
Moisture Content, % w.b.	-	-	-	46.7	12.8
Wheat stalk No.2	***Internode1***	***Internode2***	***Internode3***	***Whole***	***Ear***
Flexural Rigidity, kN·mm^2	34.5 (12.1)	56.6 (34.4)	20.2 (6.5)	31.1 (11.6)	-
Length, mm	174 (47)	238 (10)	347 (35)	759 (44)	89
Weight, N	-	-	-	0.021	0.02
Moisture Content, % w.b.	-	-	-	51.3	15.2

NOTE: Figures in parentheses represent standard deviation, the number of internode indicate order from the base.

3. Analysis of reaction forces

3.1 Mechanical model of a crop stalk and differential equation describing deflection

The differential equation describing deflection was derived based on the mechanical model of a crop stalk as shown in Figure 5. In this model, a sectional heterogeneity of a stalk was expressed as the different flexural rigidity D_j of each internode (subscript j is the number of internode), and the effect of an ear was considered to be a load concentrated at the tip of the stalk. In the present study, the flexural rigidity D was expressed as one parameter, while it was generally expressed as the product of the modulus of the stalk's elasticity and its moment of inertia. The center of the ear length was assumed to be the acting point of the concentrated load. The resultant force acting on a crop stalk undergoing forced displacement is composed of normal force P_n and tangential force P_t. The tangential force P_t gives the elongation on the crop surface at its loading point, but the effect on the bending was considered to be very slight. Thus, only the bending moment due to the normal force and concentrated load was considered, and a differential equation describing deflection was derived. The bending moment acting on the crop stalk is obtained as follows.

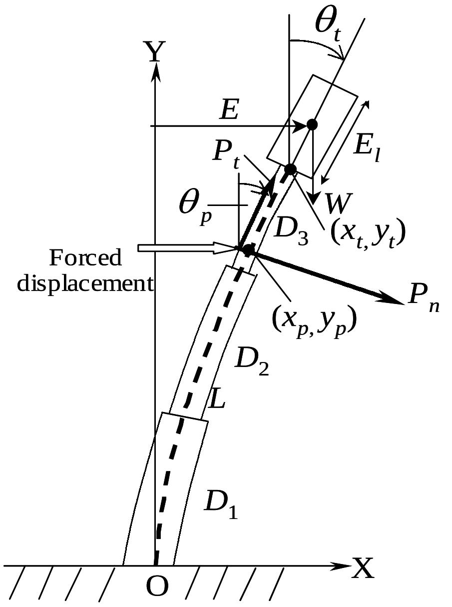


Figure 5. Mechanical model of a crop stalk undergoing forced displacement

$$\begin{aligned}
&\text{(I) } 0 \le y \le y_p \\
&\quad M = P_n \cos\theta_p (y_p - y) + P_n \sin\theta_p (x_p - x) + W(E - x) \\
&\text{(II) } y_p \le y \le y_t \\
&\quad M = W(E - x)
\end{aligned} \tag{2}$$

Here, $E = x_t + (E_l \sin\theta_t / 2)$

Further, the differential equation describing deflection of a crop stalk is derived from relation between curvature and bending moment as follows.

$$\frac{d^2x}{dy^2} = \frac{M}{D_j}\left\{1 + \left(\frac{dx}{dy}\right)^2\right\}^{3/2} \tag{3}$$

where: E is the x coordinate at acting point of concentrated load; E_l is the length of an ear; L is the length of a crop stalk; M is the bending moment acting on a crop stalk; P_n is the normal force acting on a crop stalk; P_t is the tangential force acting on a crop stalk; W is the weight of an ear; x_p, y_p are x, y coordinates at loading point; x_t, y_t are x, y coordinates at the tip of a stalk; θ_p is the deflection angle at loading point; θ_t is the deflection angle at the tip of a stalk

3.2 Calculation method of reaction forces using the differential equation

The reaction force of a crop stalk undergoing forced displacement is composed of normal reaction force P_r and frictional force f. The normal reaction force P_r, which is balanced with normal force P_n, was calculated using Eqns (2) and (3). The frictional force, which was the resistance force against tangential force P_t, was assumed to be equal to maximum static frictional force, and the frictional force was calculated by means of $f = \mu P_r$ using the coefficient of static friction μ. The frictional force *f* was considered positive upward along the tangential direction, and the direction of the reaction force was taken to be positive following arrow illustrated in Fig.1. Thus, reaction forces F_x, F_y in horizontal and vertical directions are obtained as follows.

$$\begin{cases} F_x = P_r \cos\theta_p - f \sin\theta_p \\ F_y = P_r \sin\theta_p + f \cos\theta_p \end{cases} \tag{4}$$

The flow chart for calculation of the reaction forces is shown in Figure 6. First, data regarding physical property of each crop stalk, the reference coordinates of the i^{th} crop stalk (x_i, y_i, z_i), total number of crop stalk N, loading point (x_p, y_p) (location of the sensor) are inputted. Next, the current deflection of the i^{th} crop stalk x_{pi}^{cur} is calculated based on the relationship between the location of the sensor and reference coordinate of the crop stalk. In this calculation, a standing condition of the crop stalk was assumed. Namely, distribution of crop stalks at acting height of the sensor is assumed to be the same as that at base, and deflection of each crop stalk was calculated from difference of *x* coordinate between at the sensor's height and at the base.

Further, the normal force P_n is calculated using three initial values of both deflection and deflection angle at the tip of a stalk x_t^{ini}, θ_t^{ini} and an initial value of deflection angle at loading point θ_p^{ini}. Namely, the initial value of P_n^{ini} is renewed repeatedly until the calculated deflection x_{pi}^{cal} approaches to current deflection x_{pi}^{cur} to a sufficient extent while crop's shape is assumed to have deflection and deflection angle given initially (three initial values). Therefore, in the next step, the validity of the crop's shape assumed initially (given three initial values) must be determined. The given three initial values x_t^{ini}, θ_t^{ini}, θ_p^{ini} must be close to x_t^{cal}, θ_t^{cal}, θ_p^{cal} calculated under converged P_n^{ini} to a sufficient extent. Thus, normal forced P_n and deflection angle at loading point θ_p are determined, and each component of reaction forces of one crop stalk is calculated at an arbitrary sensor displacement (location). This series of calculations was conducted for each crop stalk composing the bunch. The reaction forces of the bunch of crop stalks at each sensor displacement were calculated from the summation of the reaction forces of all crop stalks. The displacement of the sensor was defined as the horizontal displacement from the base of the crop stalk closest to the sensor. The differential equation was solved by means of the Runge-Kutta Method, and the initial values were renewed by means of the Gauss-Newton Method. The calculation of the deflection by the Runge-Kutta method has been verified through deflection tests using a cantilever piano wire shown in figure 4 (Inoue et al. 1998). In this analysis, interactions between the crop stalks were not considered. Considering the contact surface of the aluminum roller used in this experiment, a coefficient of static friction 0.4 (material: rice stalk, surface: steel sheet) and 0.3 (material: wheat stalk, surface: galvanized steel sheet) were cited for rice and wheat stalks, respectively (Esaki, 1986). In his measurement, the material is held in a container loaded with weight, and its surface is mounted on the steel sheet. The contact surface between the material and the steel sheet is drawn by weight through a pulley. The weight is measured at the moment when the surface slides, and the static frictional coefficient is determined.

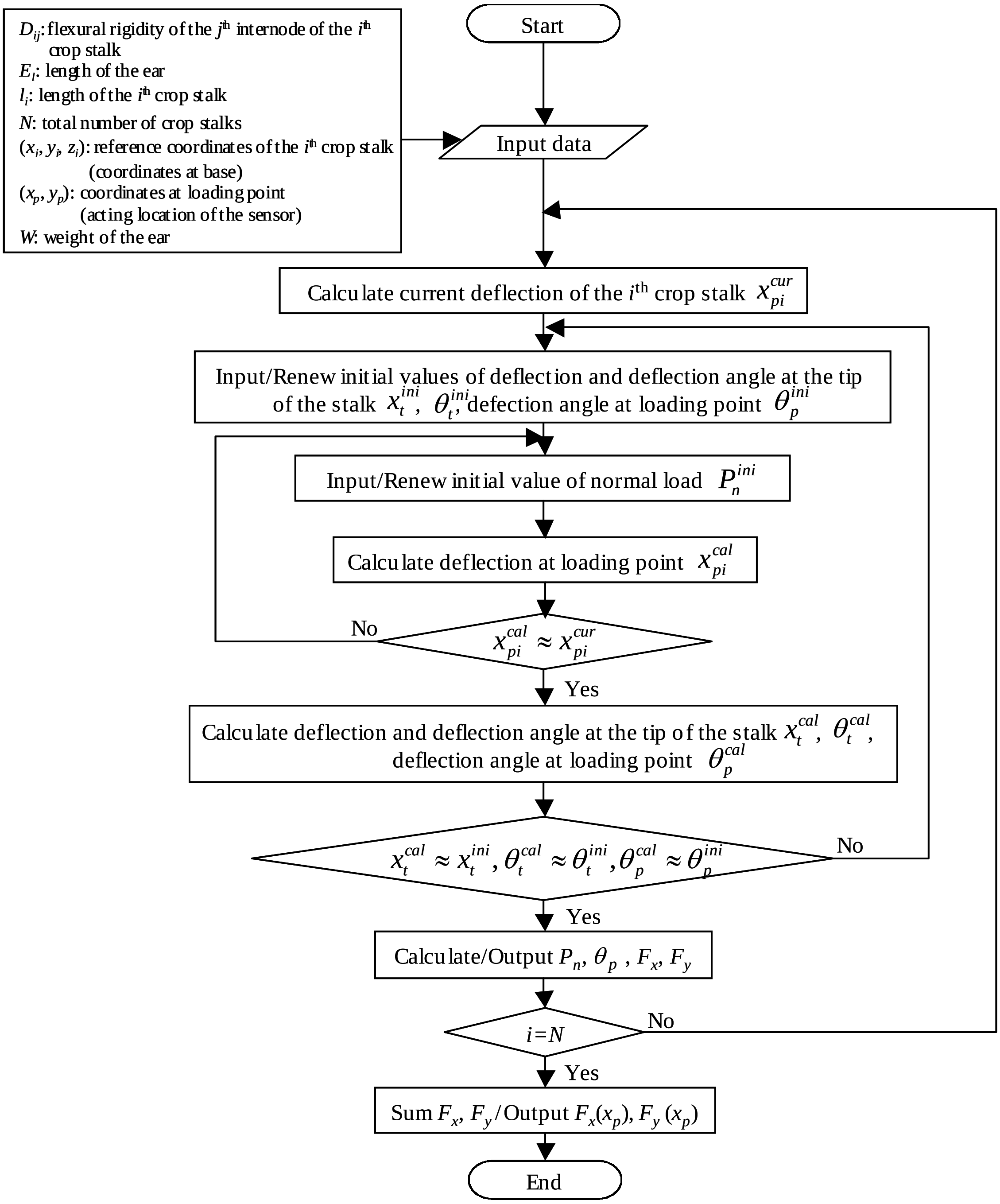


Figure 6. The flow chart for calculation of reaction forces

4. Results and discussion

4.1 Comparison between numerical analysis and measurement results of reaction forces

Comparison between numerical analysis and measurements of horizontal and vertical reaction forces are shown in Figures 7 and 8. The "deflection" of the horizontal axis in the figures represents the horizontal displacement of the sensor from the base of the crop stalk closest to the sensor (the origin was defined as shown figure 1). The materials tested were not completely standing crops (having some initial posture), and at the origin some force components were measured since the initial posture inclined toward the negative direction on the X axis. Because relationships between deflection and reaction forces from the origin were examined in the present study, the effect before the origin (the effect at negative x) was not considered; the force components measured before the origin were removed, and reaction forces at the origin were regarded as 0. The direction of each reaction force was taken to be positive following arrow illustrated in Figure 1. The crop's Number in Figure (e.g., rice stalk No.1) corresponds to crop's number in Table1.

At first, measurement results are examined. The horizontal reaction forces linearly increased along with the increment of the sensor's displacement, while the vertical reaction forces showed one negative peak, and then increased linearly. The measurement results of the vertical reaction forces are explained as follows. At the range of approximately 0 to 100 mm, the vertical forces take negative values because the vertical component of the frictional force directed downward along the tangential direction is larger than the vertical component of the normal reaction force. Also, the sensor's displacement, at which the vertical reaction forces shift from negative to positive values, was the location where the vertical component of the normal reaction force was beyond that of the frictional force because of the stalk's posture (large curvature). The linear increment of the horizontal forces in the range from 0 to 40 mm in which the crop stalks were arranged, was considered to be caused mainly by the interactions between the crops and the difference of distribution between the loading point and the base due to the crop's initial posture. Namely, the crops are pushed together due to the interactions between the crop stalks, and the sensor already acts on some crop stalks at the origin due to the initial posture of the crops. Consequently, the horizontal reaction forces changed linearly regardless of the arrangement of the crop stalks at the base.

Next, comparison results with numerical analysis are shown. Referring to results of rice stalk shown in Figure 7, simulated results of horizontal component were low values in comparison with the measurements especially in the range of the sensor's displacement from 0 to 40 mm in which a bunch of crop stalks was arranged at the base. The main reason is that analysis of reaction force was conducted under a standing condition of crop stalks though the crops stalks have actually some initial posture. Namely, the distribution of the crop stalks at loading point was assumed to be same manner as that of base and the reaction force was calculated based on difference between coordinate at base and the sensor's displacement, thus the simulated values had a certain amount of error. The results of vertical component comparatively had a tendency to coincide with measurements. Simulated results for wheat stalks shown in figure 8 reduced the error with measurements compared with the case of rice stalk. In case of No.1 wheat stalk as shown in left side of figure 8, the horizontal value had a certain amount of error throughout, but the increment coincided considerably with measurement. Some error due to initial posture at the beginning of simulation only keeps until end of simulation, and the analytical accuracy would be increased by considering the effect of initial posture. In case of No.2 wheat stalk, simulated result had good consistence with measurement because initial posture was close to a standing condition.

As demonstrated by the above results, analytical method used in the present study requires further development in terms of the effect of initial posture, but could approximately predict valid reaction forces of the bunch of crop stalk. This suggested that the analytical method of determining reaction forces based on the derived equation was useful for investigating reel-crop interactions.

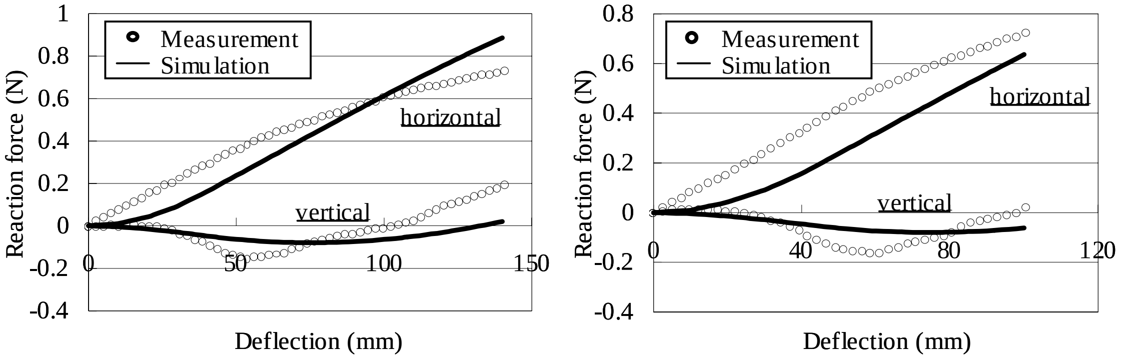


Figure 7. Comparison results between measurement and simulation of rice stalk: left figure: rice stalk No.1 (sensor acting height: 592 mm), right figure: rice stalk No.2 (sensor acting height: 550 mm)

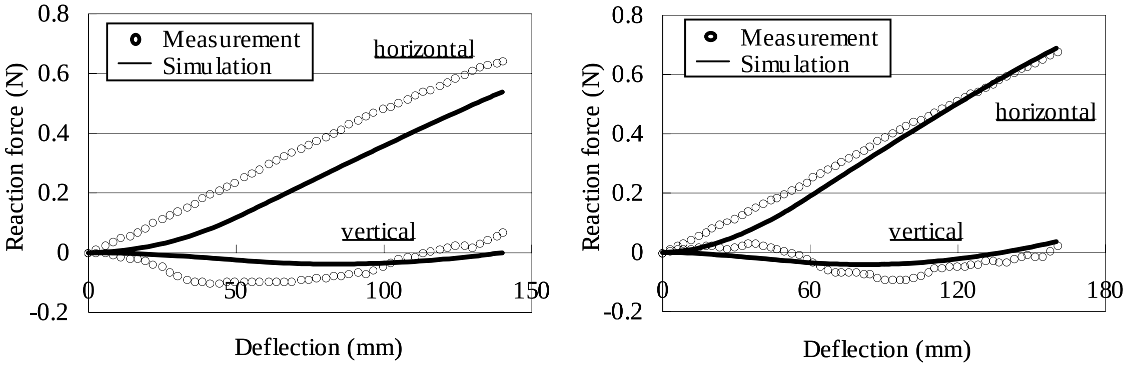


Figure 8. Comparison results between measurement and simulation of wheat stalk: left figure: wheat stalk No.1 (sensor acting height: 630 mm), right figure: wheat stalk No.2 (sensor acting height: 630 mm)

4.2 Posture analysis of a bunch of crop stalks

From comparison results of previous section, it was suggested that differential equation describing deflection was useful for investigating reel-crop interactions. In this session, posture analysis of a bunch of crop stalk was conducted using predicted normal force by Eqns (2) and (3). The purpose of the posture analysis was to obtain data regarding the crop stalk's center of gravity that changes due to the combine's reel operations during harvesting. The center of gravity of the crop stalk is data indispensable to the clarification of the behavior of the cut stalk and to the investigation of the timing for cutting the stalk. The results of the analysis are shown in Figures 9 and 10. Figure 9 shows results of posture analysis for No.1 rice stalk under an acting sensor height of 592 mm and deflections (displacement of sensor) of 30, 60, and 90 mm. Figure 10 shows results of posture analysis for No.1 wheat stalk under an acting sensor height of 630 mm and deflections (displacement of sensor) of 30, 60, and 90 mm. The difference in crop posture in terms of each physical property of the crop stalks and operating conditions was visualized in three-dimensions. In a future study, the simulated crop posture will be evaluated by comparing actual images. Also, the change of a crop stalk's center of gravity and relationship between the center of gravity and the location of the cutter bar will be investigated based on the results of the posture analysis.

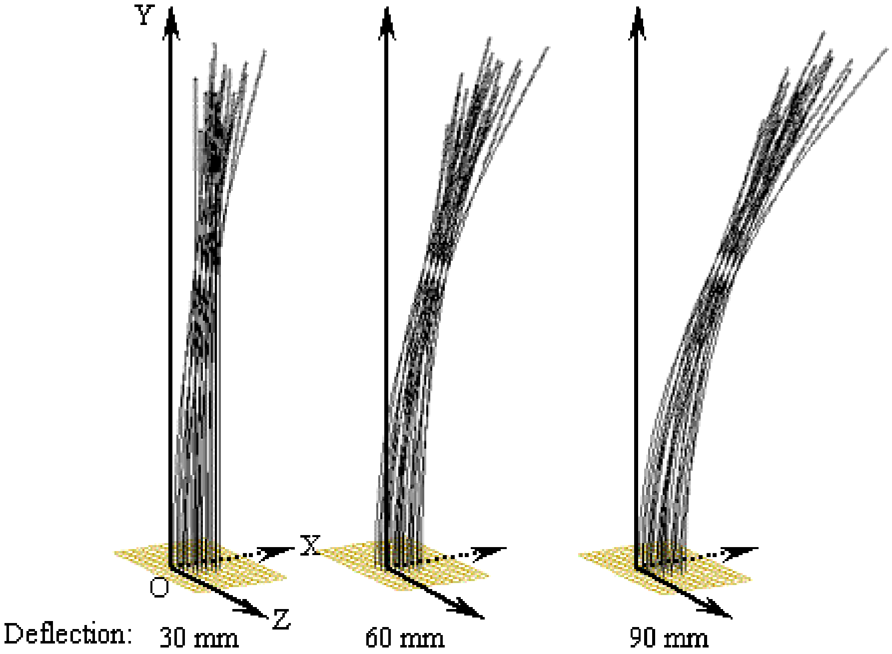
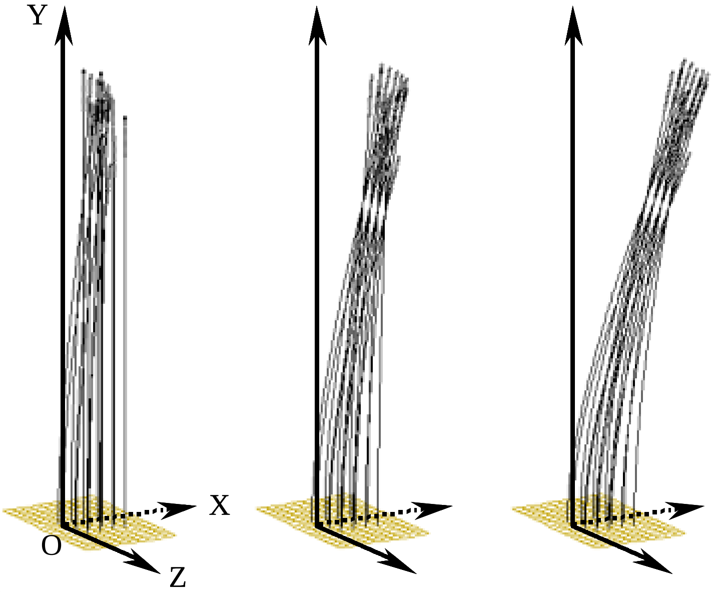


Figure 9. Posture analysis of a bunch of rice stalk (No.1)



Deflection: 30 mm 60 mm 90 mm

Figure 10. Posture analysis of a bunch of wheat stalk (No.1)

5. Conclusions

In the present study, mechanical interactions between a combine harvester reel and crop stalks (rice and wheat stalks) were investigated based on a mechanical model of a crop stalk. The following conclusions were drawn from this study.

(1) The reaction forces of a bunch of crop stalks undergoing forced displacement were measured through a series of experiments involving reel operations. As the results, the horizontal reaction force increased with increment of the sensor's displacement, while the vertical reaction forces changed both its direction and magnitude due to relationship between frictional force and crop posture.

(2) The reaction forces of crop stalks undergoing forced displacement were analyzed numerically utilizing the differential equation describing deflection based on the mechanical model of a crop stalk. Simulated results had a certain amount of error depending on initial posture of a crop stalk, but their trends approximately coincided with the measurement. Especially, the case of wheat stalk had good agreement with the measurement because its initial posture was close to a standing condition. This suggested that the analytical method of determining reaction forces based on the derived equation could be utilize for investigating reel-crop interactions. Further, the analytical accuracy of the reaction forces would be increased by considering the effect of initial posture of the crop stalk.

(3) The difference in crop posture in terms of each physical property of the crop stalks and operating conditions was visualized by means of the crop model. In a future study, the simulated crop posture will be evaluated by comparing actual images, and also the change of the crop stalk's center of gravity due to the reel operations, and relationship between the center of gravity and the location of cutter bar will be investigated based on the results of the posture analysis.

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References

Esaki H. 1955. Studies on harvesting machines (X): Some data for the design of reel. Journal of the Japanese Society of Agricultural Machinery, 17(1): 21-25. (In Japanese)

Esaki H. 1986. Grain harvester. 184-194. Japan: Isebu. (In Japanese)

Gawda H. 1978. Attempt at Applying the Ultrasonic Method for Determining the Young Modulus of Cereal Stalk. ZESZYTY PROBLEMOWE POSTEPOW NAUK ROLNICZYCH, z. 203: 145-152. Warszawa.

Gowin J. 1980. Determination of Wheat Stalk Modulus of Elasticity by means of Holographic Interferometry. In Proc. II. Int. Conf. On Physical Properties of Agricultural Materials, 1-8. Godolo, Hungary. 26-28 August.

Gowin J. 2000. Geometry of Cereal Stalk Cross-Section. International Agrophysics, 14: 33-36.

Hirai Y., E. Inoue, K. Hashiguchi, Y. K. Kim, S. Inaba and K. Tashiro. 2000. Examination of Calculation Method for Flexural Rigidity of Crop Stalks. In Proc. 3rd Int. Conf. on Agricultural Machinery Engineering (Korean Society for Agricultural Machinery), Vol. II: 287-294. Seoul, Korea. 13-16 November.

Hirai Y., E. Inoue, K. Mori and K. Hashiguchi. 2001. Investigation of Mechanical Interaction between a Combine Harvester Reel and Crop Stalks. Biosystems Engineering, 83(3): 307-317.

Inoue E., Y. K. Kim, K. Hashiguchi, T. Okayasu and J. Kashima. 1998. Mechanical Characteristics of Rice Stalk. Journal of the Japanese Society of Agricultural Machinery, 60(2): 145-150. (In Japanese)

Moustafa S. M. A., B. A. Stout and W. A. Bradley. 1968. Elastic and Inelastic Stability of a Biological Structure. Journal of Agricultural Engineering Research, 13(1): 64-82.

Muller Z. 1988. An Investigation on Mechanical and Geometrical Properties Influencing the Stability of Wheat-Stalk. Physical Properties of Agricultural Material and Products, Edited by R. Reznicek, 199-204. Washington: Hemisphere Publishing Corporation.

Oduori M. F., J. Sakai and E. Inoue. 1993. Combine Harvester Reel Stagger-II: Empirical Study on Crop Stem Deflection and Application of the Results for Reel Stagger Determination. Agricultural Mechanization in Asia, Africa and Latin America, 24(4): 35-39.

O'Dogherty M. J., J. A. Huber and C. J. Marshall. 1995. A Study of the Physical and Mechanical Properties of Wheat Straw. Journal of Agricultural Engineering Research, 62: 133-142.

Sakai J., E. Inoue and M. F. Oduori. 1993. Combine Harvester Reel Stagger-I: Principle of Determination of Reel Stagger Based on Reel Kinematics and Crop Stem Deflection. Agricultural Mechanization in Asia, Africa and Latin America, 24(2): 27-32.

Szot B. and G. Skubisz. 1984. Characteristics of Winter Wheat Stalk Elasticity on the Basis of Measurements in Field Conditions. ZESZYTY PROBLEMOWE POSTEPOW NAUK ROLNICZYCH, z. 243: 175-186. Warszawa.
