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Analysis of the Reaction Force of a Bunch of Rice Stalks Undergoing Forced Displacement

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The analytical method for the reaction force of crop stalks undergoing forced displacement, which has been verified for a bunch of wheat stalks, was applied to analysis of a bunch of rice stalks. The reaction forces of the rice stalk's bunches with various initial shapes were analyzed, and the accuracy was assessed by experimental results. The analytical results involved a certain amount of error, depending on the accuracy of the simulated initial shape, but were reasonably close. It was demonstrated that the reaction force according to the initial shape could be predicted utilizing the previous analytical method in the case of the bunch of rice stalks as well.

INTRODUCTION

In the field of agricultural machines, it would be advantageous to assess a performance of the machine taking the crop properties into account at the design stage instead of through actual machine tests, especially from the viewpoints of cost reduction, shortening of the development period, and clarification of optimum machine operations according to crop conditions. In order to improve the process of design and development, investigations of physico–mechanical properties and behavior of crops caused by machine operations are important.

A variety of physico–mechanical properties of biological materials have been investigated for the purpose of applying them to machine design, mechanical processes and lodging problems (Moustafa *et al.*, 1968; Muller, 1988; O'Dogherty *et al.*, 1995; Szot and Skubisz, 1984). On the other hand, instances of their application to machine design are very few, and machine performance is still assessed by field tests. One reason for the low number of real applications is the existence of very few studies focusing on the mechanical response of the crop stalk during actual machine operations. Thus, the authors have investigated deflection response (characteristics) related to gathering operations of a combine harvester reel based on a mechanical model of a crop stalk. A mechanical model of a crop stalk with a heterogeneous cross–section was proposed, based on bending theory regarding an elastic beam (Timoshenko, 1958), and also a calculation method of

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flexural rigidity for materials with a heterogeneous cross-section was verified 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 were analyzed under a standing crop condition (Hirai *et al.*, 2002a). The effects of frictional force and the vertical force component were considered, and horizontal and vertical reaction forces on a bunch of crop stalks were analyzed (Hirai *et al.*, 2002b).

Currently, the analytical method for the reaction force, taking into account the initial shape of crop stalks, has been developed, and the validity of the application has been shown under conditions of a single wheat stalk (Hirai *et al.*, 2003a), a bunch of wheat stalks (Hirai *et al.*, 2003b) and a single rice stalk (Hirai *et al.*, 2003c). In the present study, the analytical method is applied to a bunch of rice stalks. Reaction forces are measured under various initial shapes of the rice stalks and are compared with the analytical ones. The analytical results involve a certain amount of error, depending on the initial shape of the rice stalk's bunch, but are reasonably close. It is demonstrated that the reaction force according to the initial shape can be predicted utilizing the previous analytical method in the case of the bunch of rice stalks as well.

EXPERIMENTAL SYSTEM AND METHOD

Experimental system

Reaction forces of a bunch of rice stalks undergoing forced displacement were measured using the experimental system as shown in Fig. 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), criterion makers and subject test material (21 pieces of rice stalks). The specifications of the L-shaped sensor are shown in the previous paper (Hirai *et al.*, 2002a). The L-shaped sensor is capable of detecting two mutual perpendicular force components by using bridge circuits composed of strain gauges, which are mounted on the body of sensor. The L-shaped sensor is attached to the rod of the oil-hydraulic cylinder. The horizontal movement and speed of the sensor can be controlled by oil-hydraulic pump. The height of the material being tested is adjustable using stand to vary the acting height of the sensor. The height of the sensor is arranged in 70~80% of the appearance height of the rice stalks. The material is deflected by the horizontal motion of the sensor, while at that moment horizontal and vertical reaction forces are measured simultaneously. High frequency signals, caused by a slight vibration during horizontal movement, are removed from original electrical signals of the sensor by a low pass filter. The signals are then amplified and recorded on a data recorder, which converts analog data into digital data automatically. The deflection shape of the rice stalks during the experiment is recorded by means of a digital video camera. The data of coordinates of the shape are obtained by processing image data utilising commercial software (Library, MOVE-TR32/2D).

Experimental method

Measurements were made on 'Mineasahi' variety of rice stalks. The roots and leaves

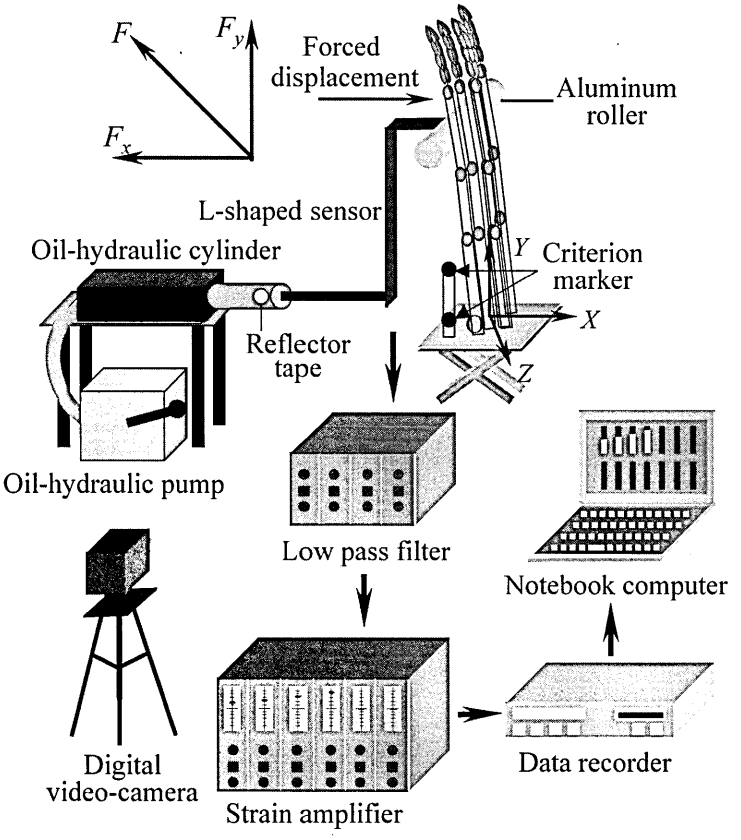

Fig. 1. Composition of experimental system

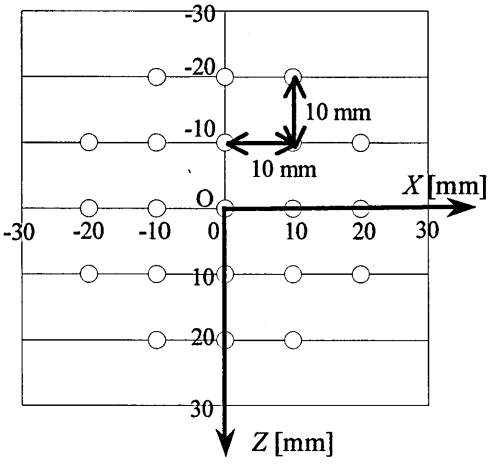

Fig. 2. Basal arrangement of a bunch of rice stalks

were removed and 21 pieces of rice stalks (a bunch of rice stalks) were fixed to a piece of wood using a quick-drying glue at the base. The arrangement of the rice stalks is shown Fig. 2. The rice stalk's samples used in this experiment were consisted of 6 bunches taken in 2001 from 18 to 23 October. Each was used twice, to avoid adverse effects on results from the use of fatigued or damaged stalks. One data set 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. Following this experiment, a deflection test (Hirai *et al.*, 2000) for calculating the flexural rigidity of each rice stalk composing the bunch was carried out. Data regarding flexural rigidity, length, weight and moisture content are shown in Table 1.

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

Material and location	Flexural rigidity (kN mm^2)	Length (mm)	Weight (N)	Moisture content (%)
Rice stalk No. 1				
Internode 1	41.2 (12.9)	175 (48)	–	–
Internode 2	43.3 (21.9)	232 (65)	–	–
Internode 3	12.1 (3.4)	368 (40)	–	–
Whole stalk	30.1 (9.2)	775 (50)	0.044	61.0
Ear	–	187	0.039	24.3
Rice stalk No. 2				
Internode 1	28.0 (10.1)	231 (55)	–	–
Internode 2	26.4 (15.0)	203 (27)	–	–
Internode 3	8.1 (2.1)	333 (23)	–	–
Whole stalk	19.8 (5.5)	767 (43)	0.04	65.9
Ear	–	184	0.028	24.7

* Figures in parentheses represent standard deviation

SIMULATION OF THE INITIAL SHAPE OF A BUNCH OF RICE STALKS

Assessment parameter of the initial shape and the equation of curvature describing the initial bending

Two instances of actual images of the initial shape are shown in Figures 3 (a) and 4 (a), and their initial shapes plotted are shown in Figures 3 (b) and 4 (b). Commercial software (Library, MOVE-TR32/2D) was used for processing the images. Also, because it was difficult to distinguish each individual rice stalks composing a bunch from image data, the features of the initial shape were formed by plotting the outline of the bunch. In the present study, a type of the initial shape shown in Fig. 3 (No. 1) was defined as "negative shape" and the shape shown in Fig. 4 (No. 2) was defined as "positive shape".

The initial shape of a bunch of rice stalk was calculated by the same procedure as the case of wheat stalk's bunch previously proposed (Hirai *et al.* 2003b). First, using four sets of coordinate data (x_{BL}, 0), (x_{BR}, 0), (x_{TL}, y_{TL}), (x_{TR}, y_{TR}), left and right lodging angles

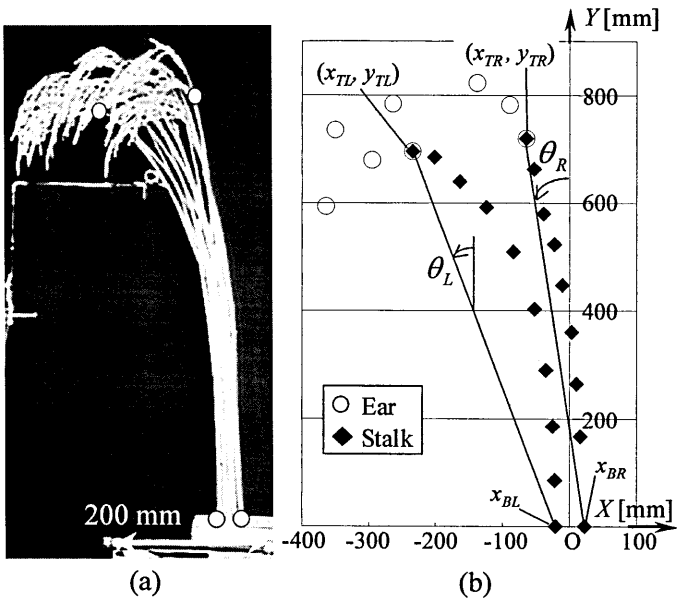

Fig. 3. Initial shape of a bunch of rice stalk (No. 1)

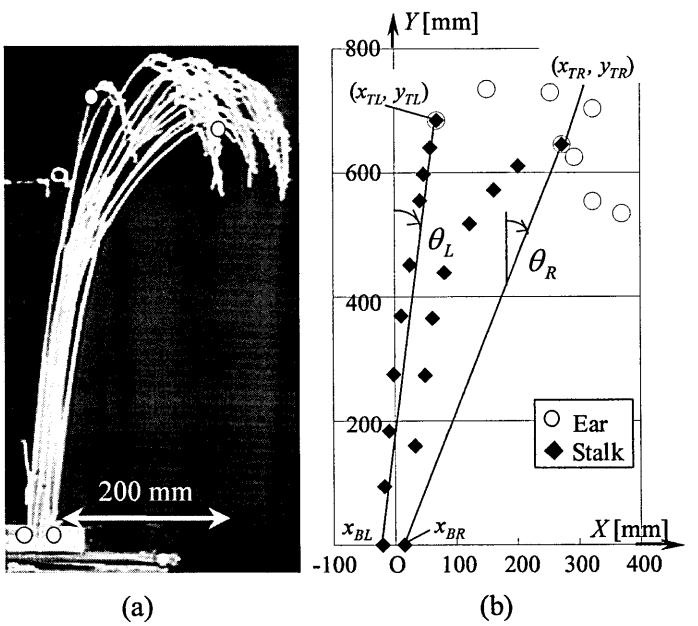

Fig. 4. Initial shape of a bunch of rice stalk (No. 2)

were calculated by the following equation (1). These two lodging angles were defined as assessment parameters of the initial shape.

$$\theta_L=\tan^{-1}\left(\frac{x_{TL}-x_{BL}}{y_{TL}}\right),\ \theta_R=\tan^{-1}\left(\frac{x_{TR}-x_{BR}}{y_{TR}}\right) \tag{1}$$

where, x_{BL} is the x coordinate at the left side base in mm; x_{BR} is the x coordinate at the right side base in mm; x_{TL}, y_{TL} are the x, y coordinates at the left side tip in mm; x_{TR}, y_{TR} are the x, y coordinates at the right side tip in mm; θ_L is the left lodging angle in rad; and θ_R is right lodging angle in rad. The lodging angles θ_L, θ_R were then taken to be positive in the clockwise direction from the Y axis. Next, lodging angles of individual rice stalks composing a bunch was calculated based on the assessment parameters of the initial shape. The variation rate β of the lodging angle on X direction was determined by the following equation (2).

$$\beta=\frac{\theta_R-\theta_L}{x_{BR}-x_{BL}} \tag{2}$$

where, β is the variation rate of the lodging angle in rad/mm.

The basal coordinates of a bunch of rice stalks, which was arranged experimentally, were assumed to be known information, and then the lodging angle θ_i of an arbitrary rice stalk (subscript i indicates the rice stalk's number) was calculated by the following equation (3).

$$\theta_i=\theta_L+\beta(x_i-x_{BL}) \tag{3}$$

where, x_i is the basal x coordinate of the i^{th} rice stalk in mm; θ_i is the lodging angle of the i^{th} rice stalk in rad.

Finally, based on the lodging angle calculated by Eq.(3), the initial shape of individual rice stalks composing the bunch was simulated utilizing the equation of curvature describing the initial bending as follows.

$$\frac{d\theta}{ds}=\frac{W(E_0-x_d)}{D_j}+\frac{F_S''}{\left(1+F_S'^2\right)^{3/2}} \tag{4}$$

where, $F_S=A\left(\frac{y_S}{L_{ap}}\right)^n$, $F_S'=\frac{dF_S}{dy_S}$, $F_S''=\frac{d^2F_S}{dy_S}$, $E_0=x_0+(E_l\sin\theta_0)/2$

and: A is the amplitude of intrinsic shape in mm; D_j is the flexural rigidity of the j^{th} internode in N·mm^2; E_l is the length of an ear in mm; E_0 is the x coordinate of center of an ear in the initial position in mm; F_S is the intrinsic shape function of a rice stalk; F_S' and F_S'' are the first and second derivation of the intrinsic shape function F_S; L_{ap} is the appearance height of intrinsic shape in mm; n is the exponent of integer equals or more than 3; s is the length of arc along the stalk in mm; W is the weight of an ear in N; x_0 and x_d are the x coordinates at the tip in the initial position and of the reference stalk in mm; y_S is the height of the intrinsic shape in mm; θ is the deflection angle of the reference stalk in rad; θ_0 is the deflection angle at the tip in the initial position in rad. Here, x_d, y_S and F_S are function of s. The Eq.(4) is a differential equation regarding the deflection angle. To calculate the deflection angle, the Runge–Kutta Method was applied. Also, the deflection

and height (x, y coordinates) of the initial shape were calculated by integrating increments in x, y directions calculated from deflection angle. For the value of exponent n in the intrinsic shape function, the integer from 3 to 6 was determined in the case of a single rice stalk, based on the x, y coordinates at the tip of the rice stalk (Hirai *et al.* 2003b). On the other hand, the lodging angle used in this analysis doesn't involve the information to assess each value of exponent. Thus, the exponent value 3, which was most frequent in the case of single rice stalk, was used for the analysis of a bunch of rice stalks. Details of the simulation are shown in previous paper (Hirai *et al.*, 2003a; Hirai *et al.* 2003b).

Simulated results of the initial shape of rice stalk's bunch

The assessment parameters of No. 1 (negative shape) shown in Fig. 3 were −17.0 degrees (left lodging angle) and −6.9 degrees (right lodging angle); on the other hand, those of No. 2 (positive shape) shown in Fig. 4 were 7.5 degrees and 21.8 degrees, respectively. The simulated results of the initial shape of rice stalks are shown in Figures 5 and 6. The simulated results were projected on the x–y plane for the sake of comparing them with actual images. In the present study, the simulated results were compared with actual images in terms of just the outline of the bunch. The distribution of individual stalks composing the bunch involved a certain amount of error, and further the ear's shape had some error due to assumption of its rigid body. However, it was judged that the features of the bunch of rice stalks were simulated sufficiently. From comparison results, it was shown that the effect of the initial shape of the bunch could be considered for analysis of reaction forces.

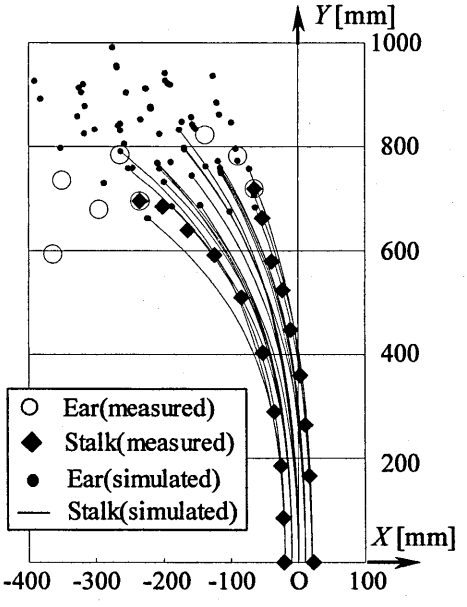

Fig. 5. Simulated result of the initial shape of rice stalks (No. 1)

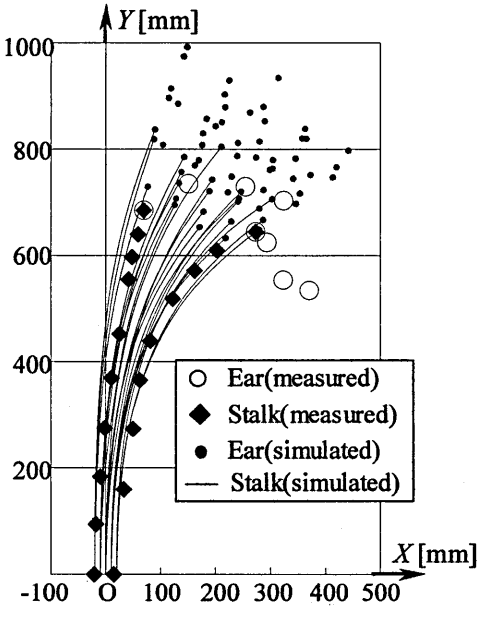

Fig. 6. Simulated result of the initial shape of rice stalks (No. 2)

ANALYSIS OF REACTION FORCES OF A BUNCH OF RICE STALKS

The equation of curvature describing bending of a rice stalk undergoing forced displacement

The resultant force acting on a rice stalk undergoing forced displacement is composed of normal force P_n and tangential force P_t (Fig. 7). The tangential force P_t gives the elongation on the surface of stalk 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 were considered. The bending moment M acting on the stalk is obtained as follows.

$$\begin{aligned} &(\mathrm{I})\ 0 \leq y_d \leq y_p \\ &\quad M=P_n \cos\theta_p (y_p - y_d) + P_n \sin\theta_p (x_p - x_d) + W(E - x_d) \\ &(\mathrm{II})\ y_p \leq y_d \leq y_t \\ &\quad M=W(E - x_d) \end{aligned} \tag{5}$$

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

and: E is the the x coordinate of the center of the ear in mm; M is the bending moment acting on a rice stalk in N·mm; P_n is the normal force acting on a rice stalk in N; y_d is the y coordinates of the reference stalk, mm; x_p, y_p are the x, y coordinates at loading point in

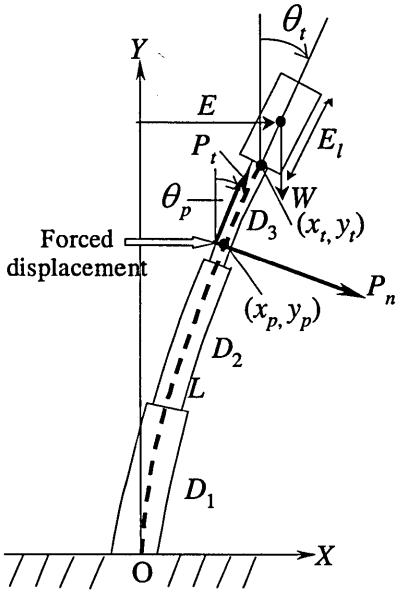

Fig. 7. Mechanical model of a rice stalk undergoing forced displacement

mm; x_t, y_t are the x, y coordinates at the tip of a rice stalk in mm; θ_p is the deflection angle at loading point in rad; θ_t is the deflection angle at the tip of a rice stalk in rad.
Further, when the effect of intrinsic shape F_S is considered, the equation of curvature describing bending of a rice stalk is derived as follows:

$$\frac{d\theta}{ds} = \frac{M}{D_j} + \frac{Fs''}{(1+Fs')^{3/2}} \tag{6}$$

Also, the reaction force of a rice stalk is composed of normal reaction force P_r, balanced by normal force P_n, and frictional force f, which is the resistance force against tangential force P_t. Thus, reaction forces F_x, F_y in horizontal and vertical directions are obtained as follows:

$$\begin{cases} F_x = P_r \cos\theta_p - f \sin\theta_p \\ F_y = P_r \sin\theta_p + f \cos\theta_p \end{cases} \tag{7}$$

Utilizing Equations (5), (6) and (7), the reaction force of a bunch of rice stalks was analyzed. Now, the coefficient of friction 0.14, which was determined from experimental results of a single wheat stalk, was used in this analysis. Details of the simulation are shown in previous paper (Hirai *et al.* 2003b).

Comparison between calculated and experimental values of the reaction force

Comparisons of reaction forces between numerical analysis and measurement are

shown in Figures 8 (No. 1) and 9 (No. 2). The simulated results in both case of initial shape agreed fairy well with measured values. Also, because kinetic friction is assumed constant in this analysis, discontinuous change of the vertical reaction force was shown around the origin involving a change of frictional direction. The disagreement with the real data at the beginning of the simulation was caused by error in determining the contact point between the sensor and a rice stalk due to error of the simulated initial shape. Difference of force increment in the horizontal force was due to difference of distribution of the initial shape between analysis and measurement. Thus, the analytical results regarding the horizontal and vertical reaction forces expressed a slight degree of error in

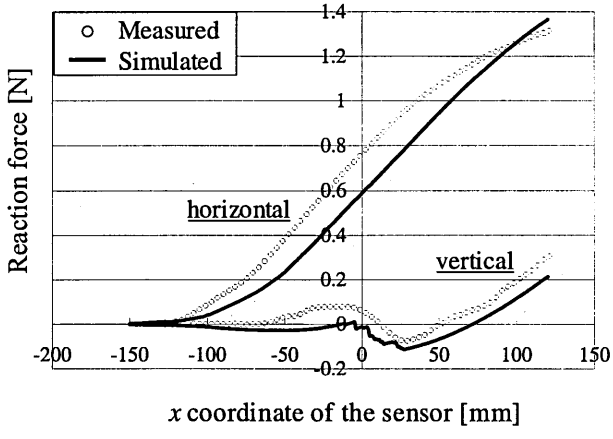

Fig. 8. Comparison between numerical analysis and measurement results of reaction forces (No. 1)

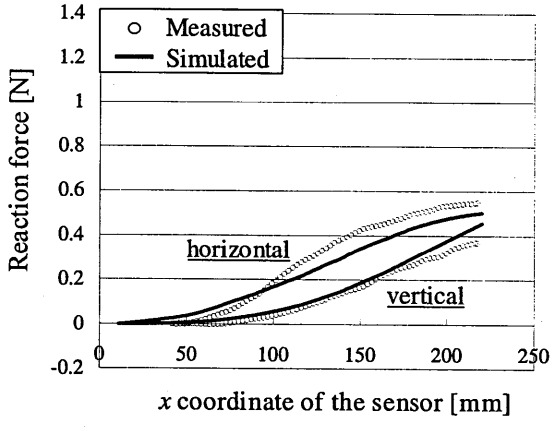

Fig. 9. Comparison between numerical analysis and measurement results of reaction forces (No. 2)

comparison with measurements, but the results showed a generally high predictive accuracy. From above the results of this comparison, it was demonstrated that the reaction forces involving the effects of the initial shape were predicted specifically in the case of a bunch of rice stalks as well.

CONCLUSIONS

In the present study, previous analytical methods for the reaction force, taking into account the initial shape, were applied to a bunch of rice stalks, and the accuracy was assessed by experiment. The following conclusions were drawn from this study

1) The initial shape of a bunch of rice stalks was simulated based on the assessment parameters of shape. It was confirmed by comparison with actual images that the features of the bunch were simulated sufficiently. From this result, it was shown that the effect of the initial shape of the bunch could be considered for analysis of reaction forces.
2) The reaction forces of a bunch of rice stalks were analyzed according to their simulated initial shape. Reaction forces in both the horizontal and vertical directions were accurately predicted without depending on the initial shape. Thus, it was demonstrated that the reaction forces involving the effects of the initial shape were predicted specifically in the case of a bunch of rice stalks.

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