Shattered Rice Grain Loss Attributable to the Combine Harvester Reel: Model Formulation and Fitting to Field Data

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ABSTRACT

A major issue in the design and use of the combine harvester is minimization of crop losses that occur while using the machines. A shattered grain loss model based on the linear statistical model is formulated, with header loss as the response variable. The independent variables, which are functions of reel parameters and crop properties, are identified on the basis of theoretical mechanical considerations complemented by laboratory experiments. Stochastic aspects of the model are discussed. Subsequently, the model is fitted to header loss data that were acquired through field measurement while harvesting a Japonica rice variety in Kyushu, Japan, using a combine harvester that was equipped with a tined reel. The results show a good fit of the data to the model but farther and more extensive research is recommended.

Keywords: Shattered grain loss, rice, combine harvester, combine harvester reel, linear statistical model, Kenya

1. INTRODUCTION

Ultimately, the goal of any crop harvesting system is to retrieve from the field as much of the mature crop as possible. Consequently, the design and operation of any component of a harvesting system should consider possible crop losses attributable to its use and how these may be minimized.

In certain instances of harvesting with the combine harvester, header loss can be the largest component of total crop loss (Rutherford, 1973; Quick, 1973). Header loss has been categorized into shattered loss, stubble loss, lodged loss, and stalk loss (Lamp et al., 1961; Quick et al., 1974). Stubble loss does not appear to be directly attributable to the reel. Improved kinematic design of the tined reel may reduce lodged loss (Oduori et al., 1992). Furthermore, shattered loss and stalk loss are thought to be so different as to warrant independent consideration of each of them. This paper is concerned with shattered loss. The work being reported here originated from a broader study on the principles of the design and use of a combine harvester reel (Oduori, 1994). In Kyushu, Japan, where the research was done, rice is the most important grain crop.

Hitherto, studies addressing shattered loss have been primarily empirical, (Lamp et. al., 1961; Quick, 1973; Quick,1974; Quick and Wesley, 1974). In this paper, a linear statistical model with header loss as the response variable is proposed. The nature of relevant mechanical phenomena is considered. The independent variables are theoretically conceived but empirically identified. If this model is validated, it could be useful in future combine harvester research, design and use. The modeling approach developed here may be readily applied to crops other than rice and could also find use in other areas of agricultural machinery engineering, and engineering in general.

2. MODEL FORMULATION

2.1 The Linear Model

Consider a response variable, denoted η, thought to be dependent on the functionally independent variables z_1, z_2, …, z_m, which are known as factors. We say that η obeys a linear model if,

$$\eta = f(z_1, z_2, \cdots, z_m) = \sum_{j=1}^{k} \beta_j x_j (z_1, z_2, \cdots, z_m) \tag{1}$$

where the x_j are functions of the factors only, and are known as the independent variables. The quantities denoted β_1, β_2, …, β_k are known as parameters (Guttman, 1982). Initially, the parameters are usually unknown. Quite often actual functional relationships correspond to the linear model, at least to a degree that is acceptable for practical purposes. Therefore, the linear model was adopted in an attempt to model shattered grain loss attributable to the combine harvester reel.

2.2 A Linear Model of Shattered Loss Attributable to the Reel

Figure 1 illustrates a tined reel with relevant parameters and a coordinate reference frame. Figure 2 illustrates the trajectory of a tine on such a reel, over one cycle of its motion. The mechanical influences that cause grain shattering are complex and multifarious but can broadly be categorized as impulsive or non-impulsive.

With impulsive influences, finite changes in momenta occur during infinitesimal time intervals and accelerations are undefined (Rosenberg, 1977). The effects of impact should therefore be correlated with velocity, but not with acceleration. On the other hand, non-impulsive action occurs over finite time intervals and, in general, the effects may be correlated with both velocity and acceleration. Consequently, shattered grain loss attributable to the reel is possibly correlated with both the velocity and acceleration of a reel slat or tine bar. The factors to be included in the model should therefore have a bearing on both velocity and acceleration of a reel slat or tine bar and are tentatively considered to be the following (see figs. 1 and 2).

- Reel radius, denoted *R*.
- Reel advance velocity, denoted *V*.
- Reel rotational velocity, denoted ω. By definition, $R_0 = V/\omega$.

- A dimensionless factor denoted *A*, relating height of the crop to height of the reel axis above the ground. By definition, $A = (Y_r - Y_c)/R_0$ (see figs. 1 and 2).

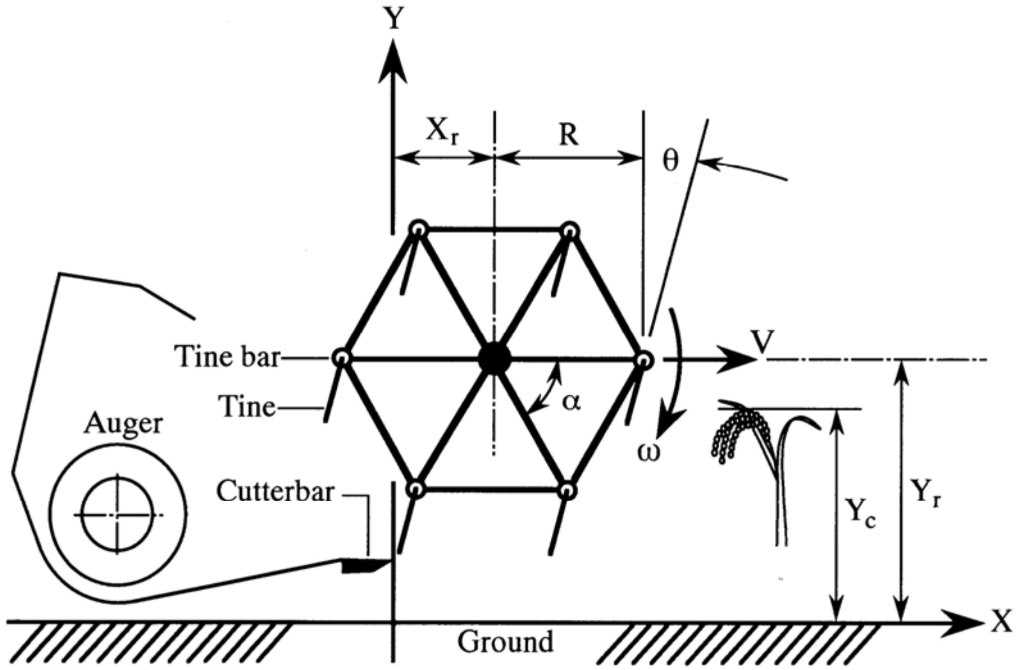

Figure 1. The tined combine harvester reel with the coordinate reference frame and the parameters relevant to the analysis of its motion

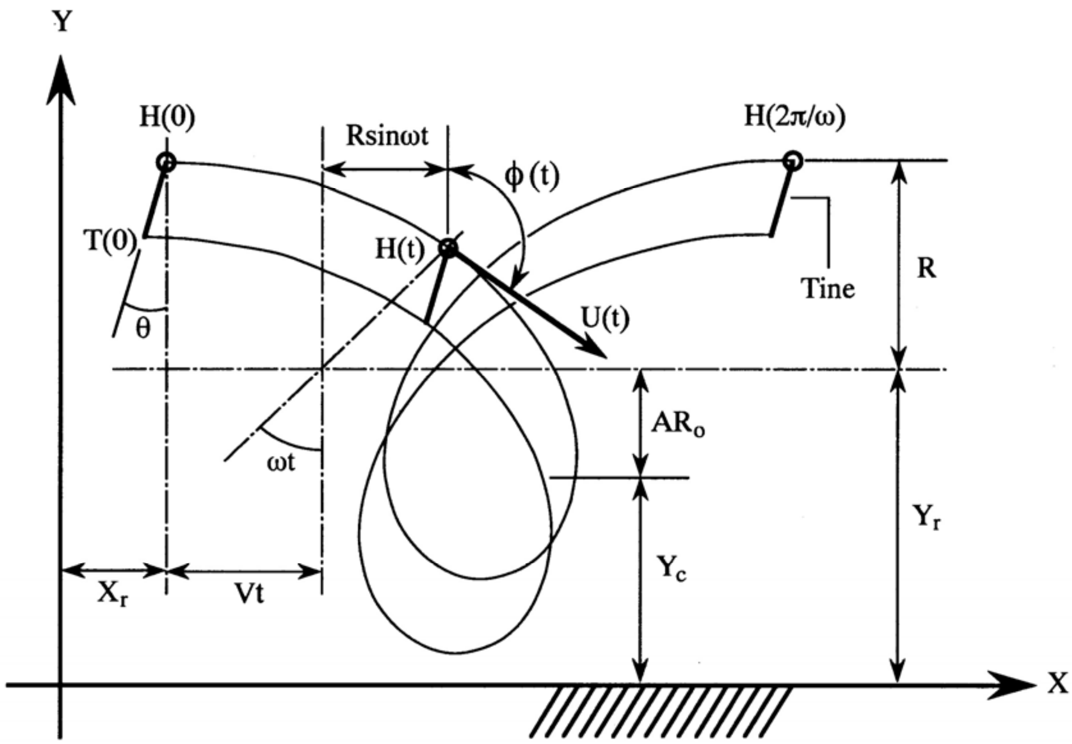

Figure 2. Trajectories of a hinge and a tip of a reel tine. *H* denotes hinge, *T* denotes tip and *t* denotes time

Though the linear model requires the factors to be functionally independent, *A* is evidently not independent of the combination of *V* and ω (which can be represented by R_0). However, since it is possible to alter *A* without altering R_0, these two factors may be considered to be independent. Furthermore, the number of reel slats or tine bars determines the frequency of interaction between the reel and the crop, and should therefore be a relevant factor in the model. However, it is convenient not to consider this factor until a later stage in the modeling process. The general form of the proposed model is therefore

$$\lambda_s = f(A, R, V, \omega) = \sum_{j=1}^{k} \beta_j x_j (A, R, V, \omega) \tag{2}$$

where λ_s is the response variable and in this case it is the shattered grain loss attributable to the combine harvester reel.

2.3 The Independent Variables

It has been inferred that shattered loss attributable to the reel is correlated with both velocity and acceleration, so the independent variables should be functions of the factors *A*, *R*, *V* and ω that represent the magnitudes and directions of both velocity and acceleration of a reel slat or tine bar. The following are considered.

$$\left.\begin{aligned} x_1(A,R,V,\omega) &= f_1(U) \\ x_2(A,R,V,\omega) &= f_2(\phi) \\ x_3(A,R,V,\omega) &= f_3(a) \\ x_4(A,R,V,\omega) &= f_4(\psi) \end{aligned}\right\} \tag{3}$$

and, so far, the model may be re-written as;

$$\lambda_s = \beta_1 f_1(U) + \beta_2 f_2(\phi) + \beta_3 f_3(a) + \beta_4 f_4(\psi) \tag{4}$$

where U is the magnitude of tine bar velocity, ϕ is the direction of tine bar velocity, a is the magnitude of tine bar acceleration and ψ is the direction of tine bar acceleration.

The functions denoted f_j (j = 1, 2, 3, 4) would depend on relevant crop properties as well as aspects of reel-crop interaction.

2.4 Experiments

In order to determine actual forms of the independent functions in equation (4), some laboratory experiments were performed as detailed below.

2.4.1 Tensile Force Required to Detach a Single Grain from the Ear

The object was to obtain an approximate value of the tensile force required to detach a single grain from the ear. This value could be used in the design of equipment for subsequent experiments. Since high accuracy was not required, a spring balance was used for force measurement. Furthermore, it was desired to determine the statistical distribution of this force. Two hundred distinct measurements were taken in order to obtain a large enough sample of force data. The grain ears used were obtained from a Japonica rice variety that was ready for harvesting.

In each test, a single grain on a grain ear was clasped in a clip that was hung onto the hook of a spring balance whose upper end was suspended on a rigid support. The stalk of the grain ear was then slowly pulled downward until the grain was detached from the ear. The balance had an indicator for the maximum force attained before detachment. This procedure is perhaps easier to perform with rice, whose grains are more loosely packed and flexibly attached to the ears, than with other crops such as wheat. The results are plotted in figure 3 which may be used to estimate the percentage of grains requiring a given tensile force for detachment.

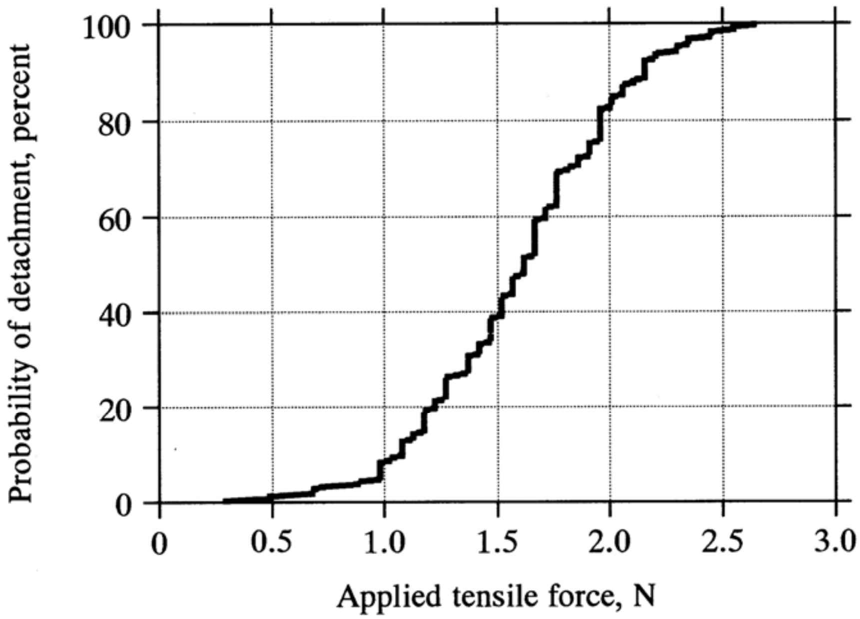

Figure 3. Probability of detachment of a grain from the ear (Koshihikari variety of Japonica rice)

2.4.2 Magnitude of Impact Velocity and Grain Shattering

Since the reel is rigid and power-driven, and the crop much more compliant, reel-crop impact can be simulated by impact between moving grain ears and a stationary rigid object. Figure 4, below, illustrates such a gravity-driven pendulum apparatus that was used in this study. To attain high impact velocities, a four-bar linkage was used to multiply and transmit the motion of a driving pendulum to a driven impacting arm. The transmission ratio could be altered by changing the lengths of some of the links. The speed of the driving pendulum could be altered by varying the angle of its initial displacement from the equilibrium position. Grain ears were attached to the lower end of the driven impacting arm by use of adhesive tape.

Originally, a driving pendulum had been included, consisting of a slender rigid rod with a weight fastened to its lower end. However, during trial operation, undesirable vibration of the apparatus was traced to the flexural compliance of the pendulum rod. It was also realized that the weights of the three moving links together with the bearings at the two moving revolute joints would be sufficient to provide the required driving pendulum effect. Therefore the driving pendulum was discarded.

Two Indica varieties and one Japonica variety of rice were investigated. For each of the Indica varieties, tests were performed at seven different impact velocities with three grain ears being tested at each velocity. For the Japonica variety, which was more difficult to shatter, tests were performed at six impact velocities. For each variety, the grains on the ears had been counted prior to commencement of the tests and the grains still attached to the ears after impact were also counted in order to determine the percentage of the original count that had been shattered.

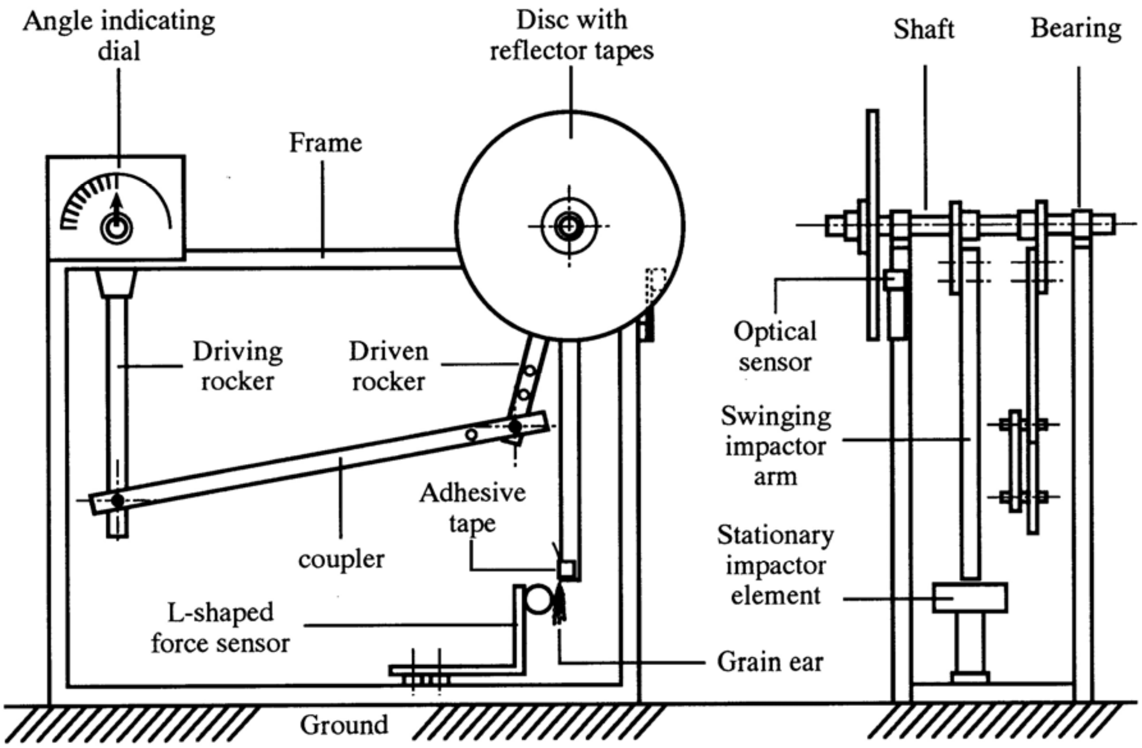

Figure 4. Impact shattering apparatus

The results, averaged over the replications, are illustrated in figures 5, 6, and 7. The low shattering propensity of Japonica rice varieties is evident in figure 7.

On the basis of these results, it was concluded that the term in the shattered loss model corresponding to the magnitude of impact velocity should be approximately proportional to the square of that magnitude. Thus, in equation 4,

$$f_1(U) = U^2 \tag{5}$$

which is consistent with the fact that there should be no shattering when U is zero. This sort of relationship might arise from an approximation of the lower part of the probability curve of figure 3.

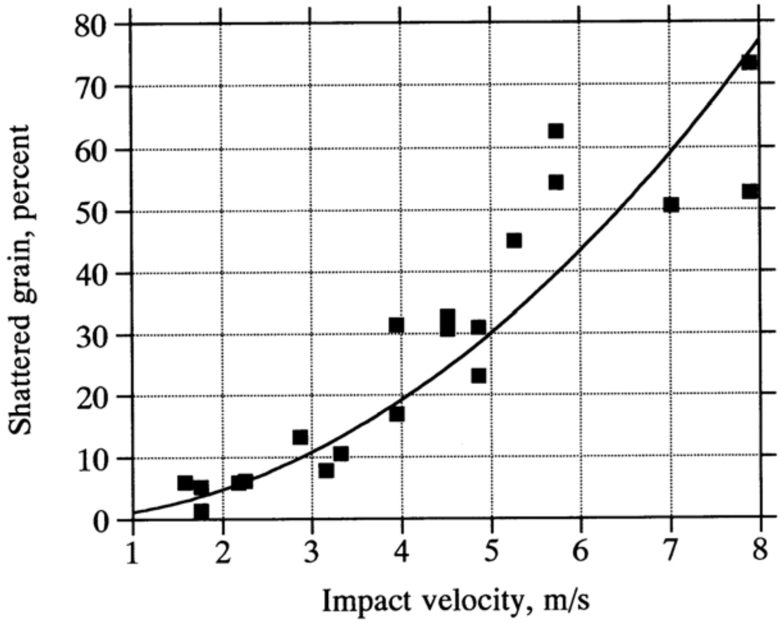

Figure 5. Impact shatter characteristics (IR36 variety of Indica rice). Fitted equation: $y = 1.205x^2$. Sample size: $n = 20$. Coefficient of determination: $r^2 = 0.802$

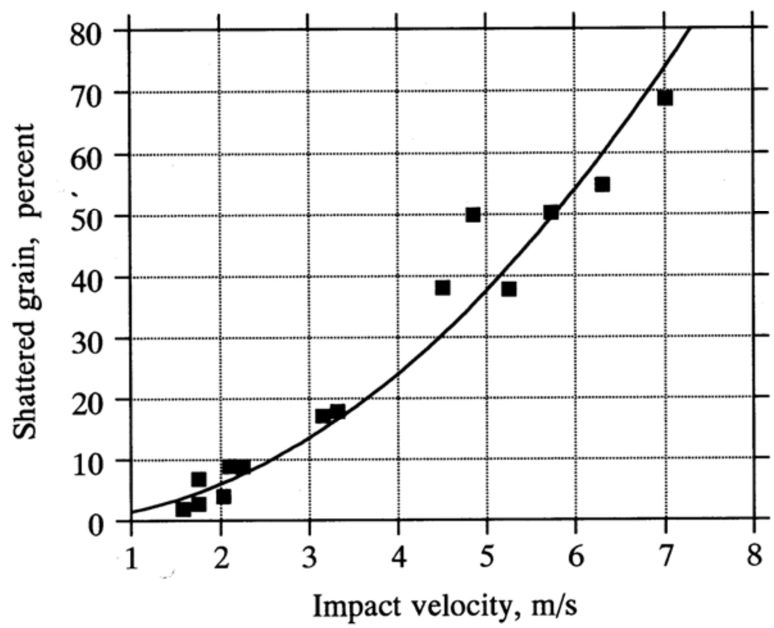

Figure 6. Impact shatter characteristics (ASD8 variety of Indica rice). Fitted equation: $y = 1.502x^2$. Sample size: $n = 19$. Coefficient of determination: $r^2 = 0.946$

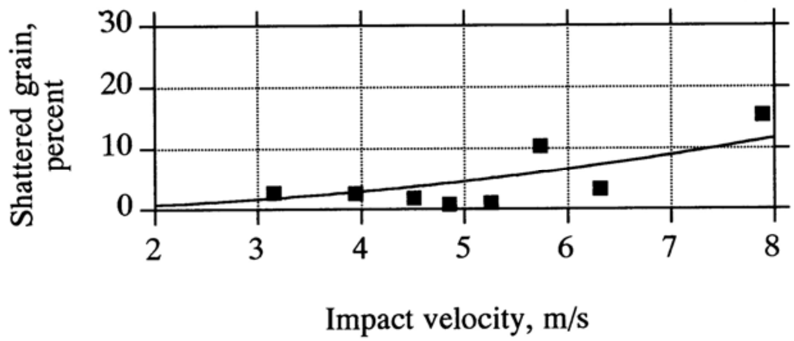

Figure 7. Impact shatter characteristics (Nihonbare variety of Japonica rice). Fitted equation: $y = 0.182x^2$. Sample size: $n = 17$. Coefficient of determination: $r^2 = 0.564$

2.4.3 Magnitude of Acceleration and Grain Shattering

An attempt was made to determine the relationship between magnitude of acceleration and grain shattering, through centrifugation. A Japonica rice variety was used, other varieties not being available at the time. Tests revealed that acceleration greater than 30 000 m/s^2 was required in order to cause appreciable shattering. Furthermore, vibration of the homemade apparatus was substantial and it was impossible to determine what quantity of shattered grain was attributable to centrifugal force alone. However, accelerations of grain ears, arising due to reel-crop interaction, are likely to be much lower than what was observed to cause grain shattering, through centrifugation. Therefore, at least for the Japonica rice variety that was investigated in these tests, acceleration should not be a significant factor in the shattered grain loss model. On this basis, the terms corresponding to the magnitude and direction of acceleration were dropped from equation 4.

Quick (1974) centrifuged Amsoy and Corsoy soybean varieties and found relationships that resembled figures 5 and 6 for Corsoy and one that had the form of the probability curve of figure 3, for Amsoy. This could mean that, even with crops as different as these soybean varieties are from Japonica rice, a major factor determining the percentage of shattered grain, whether by impact or centrifugation, is the statistical distribution of the force required to detach any single grain from the ear (force required to release seeds from the pod, in the case of legumes).

2.4.4 Direction of Impact Velocity and Grain Shattering

Initially, it had been mistakenly assumed that the direction of impact velocity would not be a significant factor. However, a scrutiny of the scatter diagrams of field header loss data plotted against the tangent of the angle ϕ_c (see Appendices 1 and 2) and calculation of the coefficient of correlation between header loss and the tangent of angle ϕ_c indicated that the direction of impact velocity was a significant factor that should be retained in equation 4. Therefore, on the basis of these observations, the following empirical relationship was tentatively included in the model (see discussion).

$$f_2(\phi) = \tan(\phi) \tag{6}$$

2.5 Stochastic Aspects of the Model

Several aspects of the shattering of grain by the reel, among them being those listed below; give the model a stochastic nature.

- The geometry of reel-crop interaction should vary randomly.
- The velocity of reel-crop impact should vary, though in the model only some particular representative value is used.
- The inertial properties of the crop should be expected to vary from one instance of reel-crop interaction to another.

There are possibly many other aspects of random variability to the model that may not be easily identifiable. Fortunately, it is sufficient only to recognize the existence and role of such aspects. In the model, these will be represented by a random error term, generally denoted ε, as detailed below.

2.5.1 Representative Magnitude and Direction of Impact Velocity

The magnitude of impact velocity may be represented as follows (see Appendix 3):

$$U_i = V\sqrt{1 + 2\left(\frac{Y_i - Y_r}{R_0}\right) + \left(\frac{R}{R_0}\right)^2} \tag{7}$$

and by using Y_c instead of Y_i, equation 7 can be re-written as follows (see Appendix 2):

$$U_i = V\sqrt{1 - 2A + \left(R/R_0\right)^2} + \varepsilon_u = U_c + \varepsilon_u \tag{8}$$

The error term denoted ε_u represents the fact that Y_i differs randomly from Y_c. By a similar argument, it can be shown that (see Appendices 2 and 3);

$$\tan(\phi_i) = \frac{A-1}{\sqrt{\left(R/R_0\right)^2 - A^2}} + \varepsilon_\phi = \tan(\phi_c) + \varepsilon_\phi \tag{9}$$

By using equations 4, 5, 6, 8 and 9, and representing all random phenomena by a single term, denoted ε, the model may be written as;

$$\lambda_s = \beta_1 U_c^{\,2} + \beta_2 \tan(\phi_c) + \varepsilon \tag{10}$$

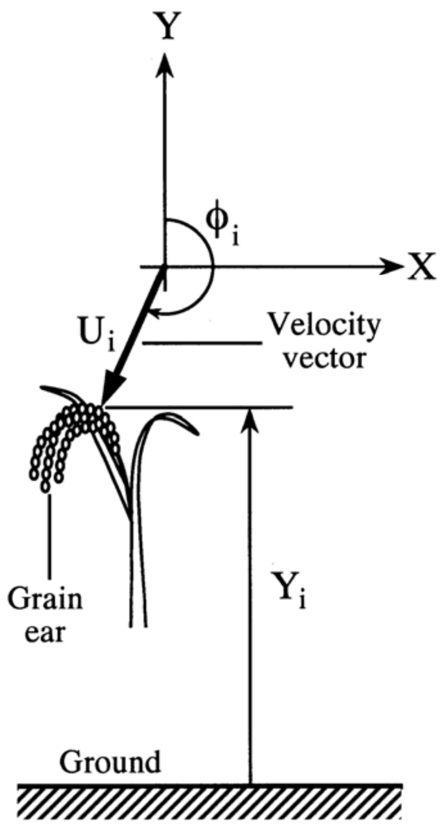

Figure 8. Vector diagram of impact velocity. The subscript "i" denotes impact

2.6 Adaptation of the Model for Field Testing

Two aspects of field testing necessitate modification of the model as follows:

- The model so far has been based on a single impact though grain losses in the field result from numerous impacts. The number of impacts per unit distance of reel advance is inversely proportional to R_0 (Appendix 4). Since shattered loss should increase linearly with this number, the independent variables should be divided by R_0.
- As it is difficult to isolate individual header loss components by measurement, the model should allow for such isolation through calculation. A constant term, denoted β_0, is therefore included in the model to represent the components of header loss that are not attributable to the reel.

The model, having been adapted for field testing, becomes;

$$\lambda_h = \beta_0 + \beta_1 \frac{U_c^{\,2}}{R_0} + \beta_2 \frac{\tan\phi_c}{R_0} + \varepsilon \qquad (11)$$

Where,

$$U_c = V\sqrt{1-2A+\left(R/R_0\right)^2} \text{ and } \tan\phi_c = \frac{A-1}{\sqrt{\left(R/R_0\right)^2 - A^2}}$$

Since the expected value of a completely random variable is zero, the expected value (Frank, 1974) of header loss should be the following.

$$E(\lambda_h) = \beta_0 + \beta_1 \frac{U_c^{\ 2}}{R_0} + \beta_2 \frac{\tan\phi_c}{R_0} \tag{12}$$

The problem of fitting the model to field data then amounts to finding acceptable estimates B_0, B_1, and B_2 of β_0, β_1, and β_2, respectively. This can be achieved through least-squares multiple regression (Younger, 1979; Edwards, 1985), given field header loss data.

3. ACQUISITION OF FIELD HEADER LOSS DATA

3.1 Equipment and Methods

Essentially, the method of measurement of header loss was the one in which rear-end losses are prevented from falling onto the ground in the wake of the harvester. Header loss can then be sampled by counting the grain in areas of definite size on the ground in the wake of the harvester. In this case, rear-end losses were collected on a canvas sheet carried by two people who followed the harvester. Header loss, which is the response variable in our model, was sampled in randomly selected areas defined by a square frame of stiff steel wire measuring 500 mm by 500 mm. All measurements were completed on a single day with fine weather.

The measurements were done on a rice field at Kurume, Kyushu, Japan. A combine harvester equipped with a conventional reel-type header and a rotary thresher was used. The test crop was a ready-for-harvest Nishihomare variety of Japonica rice.

3.2 Procedure

The harvester advance velocity, V, the reel rotational velocity, ω, and the height of the axis of rotation of the reel above the ground, Y_r, were the controlled variables. The harvester advance velocity was selected by the operator using a speed selection lever but also measured during operation by recording the time required for the harvester to advance through a given distance. The reel rotational velocity was pre-selected with the aid of a hand-held tachometer but also measured during operation using an optical tachometer with reflector tape stuck on the reel. The height of the axis of rotation of the reel was preset using a tape measure. The experimental levels of the controlled variables are given in Table 1. These values were selected to cover, as much as possible, the range of possible settings on the harvester, including those that are typical. The effective height of the crop, Y_c, and crop yield, C_y, had been determined prior to field measurement of header losses and were 0.82 m and 0.556 kg/m^2, respectively. The radius of the tined reel (the distance from the reel axis to the axis of the hinged tinebar) was measured and found to be 0.5 m.

For each combination of settings of the controlled variables, three samples of header loss grain counts were taken. The mass of a single grain of rice was determined by weighing a sample of one thousand grains and calculating the mean value, which was found to be 0.0228 g. Given these data, header loss in each sample can be expressed as a percentage of crop yield by use of the following formula (see Appendix 5);

$$L_h = 0.0164 n_g \tag{13}$$

In order to transform the controlled variables into data suitable for analysis according to the proposed header loss model of equation 2, further calculations were necessary as follows;

$$\omega = 0.105 N \text{ rad/s} \tag{14}$$

$$R_0 = V/\omega \text{ (m)} \tag{15}$$

$$A = (Y_r - 0.82)/R_0 \text{ (dimensionless)} \tag{16}$$

$$x_u = \frac{U_c{}^2}{R_0} = \omega V\left[1 - 2A + (R/R_0)^2\right] \text{ (m/s}^2\text{)} \tag{17}$$

$$x_\phi = \frac{\tan(\phi_c)}{R_0} = \frac{A - 1}{\sqrt{R^2 - (AR_0)^2}} \text{ (m}^{-1}\text{)} \tag{18}$$

and by using equations 12, 17 and 18, the regression model could then be re-written as follows;

$$E(\lambda_h) = \beta_0 + \beta_1 x_u + \beta_2 x_\phi \tag{19}$$

Table 1. Experimental levels of the controlled variables

Height of the reel axis Y_r, m	Harvester advance velocity V, m/s		Reel rotational velocity N, rev/min	
	Preset	Measured	Preset	Measured
1.14	0.2	0.24	10.13	10.77
1.07	0.2	0.25	12.66	12.90
1.09	0.5	0.82	20.25	20.66
1.23	1.1	1.36	20.25	20.73
1.16	0.8	0.82	25.31	25.77
1.27	1.1	1.06	25.31	25.67
1.21	1.1	0.99	28.86	29.43
1.30	0.8	0.75	17.21	17.43
1.23	0.8	0.79	20.25	20.78

Note that, the measured value of *V* that is entered in the third column of the third row of the data in Table 1, above, is far different from the corresponding preset value. This is possibly due to and error in recording of either the preset or the measured value, during the tests.

Given field header loss data, estimates of the model parameters can be determined as the least-squares regression coefficients in following equation;

$$L_h = B_0 + B_1 x_u + B_2 x_\phi \tag{20}$$

the underlying hypothesis being that if the regression coefficients so determined are used in equation 19, the estimated loss, $E(\lambda_h)$, should reasonably agree with measured loss, L_h.

4. RESULTS AND DISCUSSION

For the independent variable corresponding to the direction of impact velocity, a tentative variable was adopted as stated in equation 6. Some theoretical difficulties arise from the fact that, considering a single cycle of reel motion;

$$\tan(m\pi) = 0; m = 0,1,2 \text{ and } \tan(n\pi/2) = \infty; n = 1,3$$

However, the value of ϕ_c in the model (equation 11) cannot be zero or 2π radians since such values imply that a reel slat or tine bar strikes the crop with a velocity directed away from the crop. Furthermore, a value of ϕ_c equal to $3\pi/2$ radians occurs at the lowest point of the trajectory of a reel slat or tine bar, which is not the likely point at which the reel slat or tine bar strikes the crop. On the other hand, it is not only possible, but also likely that a reel slat or tine bar may strike the crop when the value of ϕ_c is equal to π radians. In such a case, any grain shattering may be solely attributed to the magnitude of impact velocity as implied by equation 10. For any direction of impact velocity, so long as that direction remains unchanged, any variation in grain shattering would be due to variation in magnitude of impact velocity. In other words, the datum for the effect of direction of impact velocity on grain shattering may be arbitrarily selected.

A more rigorous empirical identification of the actual relationship between grain shattering and the direction of impact velocity is desirable. Furthermore, the effect of acceleration on grain shattering is evidently insignificant only in the case of the Japonica rice variety for which centrifugation was attempted. The same may not be true for other varieties of rice or for crops other than rice. To adopt the model for field testing, it was necessary to allow for the number of impacts between the reel slats or tine bars and the crop in a unit distance of header advance. As a result, the independent variables were divided by R_0. Though the number of slats or tine bars on the reel also affects this spatial frequency of reel-crop impacts, on most combine harvester models, this number appears to have been standardized to six and may be assumed to be included in the parameters denoted β_1 and β_2. However, if the appropriate number of slats or tine bars on the reel should be in question, then that number, represented by the angle denoted α in figure 1, should be considered as a factor whose effect is to be studied (see Appendix 4).

The header loss data in the form suitable for regression analysis are given in Table 2. To reduce the effects of chance variation, and thus highlight the effects of the regressor variables, for each combination of regressor variable values, header loss count was averaged over the three replications and then used to determine percentage loss according to equation 13. To do this is justified because the response variable of the model in equation 19 is the expected value of header loss, denoted $E(\lambda_h)$, and is therefore the average value of header loss for each combination of regressor variables.

Table 2. Regressor variables and header loss data

x_u	x_ϕ	Header loss grain count			Header loss % of crop yield
		Sample 1	Sample 2	Sample 3	
0.95	1.29	45	15	90	0.820
1.94	0.87	39	19	55	0.618
2.35	-0.67	26	29	25	0.437
0.97	-1.21	08	11	39	0.317
3.20	0.35	10	17	38	0.355
0.94	0.68	07	89	39	0.738
3.08	0.71	46	05	38	0.487
0.20	1.27	41	72	14	0.694
1.10	0.44	58	31	37	0.689

Results of statistical analyses of the data are presented in Tables 3, 4, and 5. In Table 3, each number in the main body of the table is the simple coefficient of correlation between the variable at the top of the column and that at the left end of the row, calculated using the data in Table 2. The moderate correlation between L_h and x_u along with the fairly strong correlation between L_h and x_ϕ imply that a multiple regression analysis could be fruitful. However, the apparent correlation between x_u and x_ϕ, a situation known as multicollinearity (see Appendix 6), is undesirable because it leads to loss of reliability in the determination of regression coefficients. In other words, multicollinearity may cause the values of regression coefficients determined using different data samples drawn from a single population to vary considerably. Each set of regression coefficients would then be reliable only for the regressor variable levels of the sample data. However, the mean values of regression coefficients so determined would still converge on the correct values as the data samples used become numerous. In this case, since the correlation between x_u and x_ϕ is weak, multicollinearity may not be a significant problem. Still it would be more satisfactory to use several samples obtained at different combinations of the levels of the regressor variables. In controlled experiments, the levels of the regressor variables may be selected so as to eliminate the coefficient of correlation between them.

A multiple regression analysis was performed and the resultant analysis of variance is presented in Table 4. The value of the Fisher F-statistic in this table, when compared with the critical value at the relevant degrees of freedom, indicates with more than 99% confidence that the linear model proposed in this study may be used to predict header loss, at least for the levels of the regressor variables at which the sample loss data were acquired.

Table 3. Correlation coefficients. Sample size: $n = 9$

Variables	Correlation coefficients		
	x_u	x_ϕ	Measured loss (L_h)
x_u	1	-0.178	-0.596
x_ϕ	-0.178	1	0.777

Table 4. Analysis of variance

Sources of variation	Degrees of freedom	Sum of squares	Mean squares	Fisher F-Statistic
Regression	2	0.211	0.105	13.611
Residual	6	0.046	0.008	
Total	8	0.257		

Table 5. Regression coefficients

Regressor variable	Regression coefficient	Standard error	Standard coefficient	Partial F-Statistic
None (Intercept)	0.643	0.054		
x_u	-0.08	0.03	-0.472	7.173
x_ϕ	0.147	0.038	0.693	15.431

The regression coefficients with other relevant information are given in Table 5. An examination of the contribution of the reel to header loss should involve comparison of the intercept to the linear combination of the coefficients and the regressor variables. The standard coefficients of Table 5 may be regarded as the relative weights of the regressor variables in the regression equation. The partial F-statistics indicate the significance of each regressor variable taken alone. Too low a value of the partial F-statistic would indicate redundancy of the corresponding regressor variable. In this case the values of the partial F-statistics indicate significance at more than 95% and 99% confidence levels for x_u and x_ϕ, respectively. Hence neither of the regressor variables may be considered redundant. The regression equation (sample size: $n = 9$) may be written as follows;

$$L_h = 0.643 - 0.08x_u + 0.147x_\phi \tag{21}$$

Equation 21 was used to determine the values plotted on the X-axis of figure 9. The goodness of fit of the model to field header loss data is evident visually in the figure and in the high value of the coefficient of determination, denoted r^2. The levels of x_u and x_ϕ used to plot figure 1 are the same levels used in the acquisition of field header loss data as well as in the regression analysis.

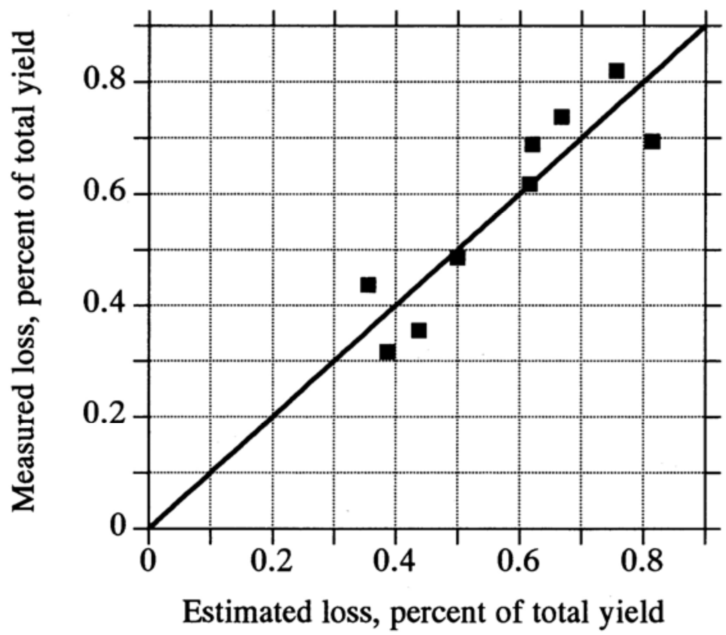

Figure 9. Measured loss versus loss estimated by the model. Fitted line: $y = x$. Sample size: $n = 9$. Coefficient of determination: $r^2 = 0.819$

When using equation 21, some difficulty may arise due to the possibility of occurrence of very high and even infinite values of x_ϕ, which would then yield very high values of header loss. Yet there is logic in this situation too. The definition of x_ϕ in equation 18 reveals that infinite values of this variable correspond to situations where the reel would not engage the crop at all, leading to very high crop losses. However, as mentioned earlier in the paper, the appropriate definition of x_ϕ needs to be more rigorously identified empirically.

Equation 21 implies that header loss should decrease with increasing x_u. However, to draw such a conclusion may be misleading for the following reasons.

1. Only a single rather small sample of loss data was used in the regression analysis. Therefore, while equation 21 may be used with some confidence to predict header loss for the combination of regressor variable levels at which the loss was sampled, the same cannot be said for other combinations of the regressor variable levels.
2. The levels of the regressor variables at which loss was sampled were not varied independently of each other. Indeed, considering that x_u and x_ϕ, are determined by the same factors, namely A, R, V, and ω, in practice it may be difficult to vary the two regressor variables independently of each other. Therefore, rather than the independent effect of any one of the regressor variables, it would seem more appropriate to consider the combined effect of these variables.

The results of the regression analysis at least indicate that the linear combination of the two variables has a significant effect on header loss that deserves further investigation.

Some possible sources of error are apparent in this work. First, in the model building process, it was assumed that all sources of header loss other than the reel are independent of the operational parameters of the reel. This assumption is a possible source of error because it is quite possible and even likely, for example, that the header loss component attributable to the cutterbar, if any, would be correlated with advance velocity which is an operational parameter of the reel. This problem can be resolved through separate measurement of all the header loss components. Secondly, samples of header loss were taken without paying attention to the part in the cross-section of ground area, in the wake of the combine harvester, from which they were taken. Some researchers (Klinner and Biggar, 1972) have observed a pattern of variation of header loss across the width of the header. This situation could also be a source of error. Fortunately, this kind of error is reducible through random sampling and replication, both of which techniques were used in this work.

There are possibly many other sources of error. However, a regression model cannot be without error. The crucial issue is whether the level of error sustained is acceptable. Perhaps the real concern in this work should be whether the results obtained using a single and rather small sample of data are truly representative of the behaviour of the whole population of header loss data. The answer to this question is to be found in further and more extensive experiments. Furthermore, the low shattering propensity of Japonica rice does not make this crop variety the most appropriate candidate for this kind of study.

5. CONCLUSIONS

The following conclusions can be drawn from the endeavour to model shattered grain loss attributable to the combine harvester reel as detailed above.

- A linear statistical model of shattered grain loss attributable to the combine harvester reel is proposed. The factors included are reel radius, denoted R, the rate of header advance per unit radian of reel rotation, denoted R_0, and a dimensionless number, denoted A, which relates the effective height of the crop to height of the reel axis above the ground.

These factors are either directly measurable or can be calculated from directly measurable quantities.

- In general, the independent variables in the model should represent the magnitudes and directions of both velocity and acceleration of a reel slat or tine bar. However, results of centrifugation tests on the ears of a Japonica rice variety indicated that the contribution of reel slat or tine bar acceleration to shattered grain loss would be insignificant, at least in the case of that rice variety. Thus only the independent variables corresponding with the magnitude and direction of velocity were retained in the model.

- Tests on two Indica varieties and one Japonica variety of rice revealed that, with the direction of impact velocity maintained constant, shattered grain loss is approximately directly proportional to the square of the magnitude of impact velocity.

- The magnitude and direction of velocity of impact between the reel and the crop are represented by the values at the point on the relevant trajectory that corresponds with the effective height of the crop. The actual velocity of impact between a reel slat or tine bar and the crop should vary randomly from one instance of impact to another. Such variability, along with other aspects of random variability in the model, are represented by a random error term.

- The spatial frequency of interaction between the reel slats or tine bars and the crop has to be accounted for. Furthermore, a constant term is included in the model to represent the component of header loss that is independent of reel motion because it is difficult, if not impossible, to isolate individual header loss components through measurement.

- A multiple linear regression model was fitted to header loss data acquired in a field of a Japonica rice variety harvested using a combine harvester equipped with a tined reel. The model was found to fit the data well, as indicated by the high coefficient of determination and the Fisher F-statistic.

- Both the regressor variables were found to be significant at the 95 % confidence level, indicating that the theoretically conceived regressor variables had been well selected.

- The sample of data used in the regression analysis was rather small. Furthermore, a weak correlation between the two regressor variables was observed and should lead to a loss in reliability of determination of the regression coefficients, especially when only one data sample is used. As a consequence, more extensive experiments involving several larger data samples would be necessary in order to reliably determine the regression coefficients, for any given crop. If possible, selection of the regressor variable levels so as to eliminate correlation between the variables is recommended.

- Once a model such as the one proposed in this work is fully validated, it could be a useful tool in the design and operation of the combine harvester reel. The reel designer could set the acceptable loss level and then use the model along with other relevant considerations to determine the appropriate values of the variables occurring in the model.

- The linear statistical modeling approach which appears to have been successfully applied in this work could be usefully applied to other areas of agricultural machinery engineering research which exhibit similar phenomena to shattering of grain by the reel. An example could be the important area of threshing of grain. Furthermore, any other problem that exhibits natural variability and involves several causal factors could be amenable to linear statistical modeling.

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NOTATION

a	magnitude of reel slat or tine bar acceleration (m/s^2)
A	factor relating height of the crop to height of the reel axis above the ground (dimensionless)
B_j	estimated values of the model parameters
C_y	crop yield (kg/m^2)
$E(\lambda_h)$	expected value of header loss as predicted by the model, percent of crop yield (%)
f	generic notation for mathematical functions
H	denotes the hinge of a reel tine
i	subscript denoting impact
j	subscript denoting the integers 1,2,3,...
k	number of model parameters (dimensionless)
L_h	measured header loss as a percentage of crop yield (%).
m	number of factors in the model (dimensionless)
n_g	grain count in a header loss sample (dimensionless)
n_i	number of impacts between the tine bars and the crop per metre of reel advance (dimensionless)
N	reel rotational speed (rev/min)
r	simple correlation coefficient
r^2	coefficient of determination in a regression analysis.
R	reel radius (m)
R_0	header advance per radian of reel rotation (V/ω) (m)
t	generic notation for time (s)
t_c	time corresponding to a reel slat or tine bar position that is level with the height of the crop (s)
t_i	time corresponding to impact between a reel slat or tine bar and the crop (s)
T	denotes the tip of a reel tine

U	magnitude of reel slat or tine bar velocity (m/s)
U_c	value of U when the reel slat or tine bar position is level with the height of the crop (m/s)
U_i	magnitude of velocity of impact between a reel slat or tine bar and the crop (m/s)
U_x, U_y	the X and Y components of tine bar velocity (m/s)
V	header advance velocity (m/s)
x_j	generic notation for independent variables
x_u	regressor variable corresponding to U (m/s^2)
x_ϕ	regressor variable corresponding to ϕ (m^{-1})
X, Y	Cartesian coordinates in the plane. Also used to denote coordinate axes (m).
X_r	Distance, in the X-direction, from the tip of the cutterbar to the lateral vertical plane containing the reel axis. This distance is also known as reel stagger (m)
Y_c	effective height of the crop (m)
Y_i	the value of Y at the moment of impact between a reel slat or tine bar and the crop (m)
Y_r	height of the reel axis above the ground (m)
z	generic notation for factor
α	angular spacing between successive tine bars (rad)
β_j	model parameters
ε_u	random error term corresponding to U (m/s)
ε_ϕ	random error term corresponding to ϕ (rad)
ε	overall random error term, percent of crop yield (%)
η	generic notation for response variable
θ	angular orientation of the tines relative to the Y-axis. Also referred to as tine rake angle (rad)
λ_h	total header loss, percent of crop yield (%)
λ_s	shattered grain loss (as a percentage of crop yield)
ϕ	direction of reel slat or tine bar velocity (rad)
ϕ_c	the value of ϕ corresponding to a reel slat or tine bar position that is level with the height of the crop (rad)
ϕ_i	direction of velocity of impact between a reel slat or tine bar and the crop (rad)
ψ	direction of reel slat or tine bar acceleration (rad)
ω	reel rotational velocity (rad/s)

APPENDICES

Appendix 1: Tine Bar Kinematics

With reference to figure 2, at an arbitrary time *t*, the position of the hinge of a tine bar may be represented by the following parametric equations.

$$\left.\begin{aligned} X(t) &= X_r + Vt + R\sin\omega t \\ Y(t) &= Y_r + R\cos\omega t \end{aligned}\right\} \tag{A1}$$

and the corresponding velocity components, obtained by differentiating equation A1 with respect to time, are the following.

$$\left.\begin{aligned} U_x(t) &= V + R\omega\cos\omega t \\ U_y(t) &= -R\omega\sin\omega t \end{aligned}\right\} \tag{A2}$$

Therefore, with the notation $V = \omega R_0$, the magnitude of tine bar velocity is:

$$U(t) = \sqrt{U_x(t)^2 + U_y(t)^2} = V\sqrt{1 + \left(\frac{R}{R_0}\right)^2 + 2\left(\frac{R}{R_0}\right)\cos\omega t} \tag{A3}$$

Further, the direction of tine bar velocity, defined to be the angle measured in the clockwise sense from the positive Y-axis may be represented as follows:

$$\tan\phi(t) = \frac{U_x(t)}{U_y(t)} = -\left[\frac{R_0 + R\cos\omega t}{R\sin\omega t}\right] \tag{A4}$$

Appendix 2: Height of the Reel Axis and Height of the Crop

At the moment, t_c, when a tine bar position is level with the height of the crop, it follows from equations A1 above that,

$$Y_c = Y_r + R\cos\omega t_c \tag{A5}$$

Here we define a dimensionless factor, A, such that,

$$A = \frac{Y_r - Y_c}{R_0} = -\frac{R\cos\omega t_c}{R_0} \tag{A6}$$

This definition of *A* is preferred because it was realized in studies of reel kinematics that the determination of an appropriate value of Y_r should take R_0 into account. Furthermore, Y_r and Y_c are relevant to the grain loss model only inasmuch as they are related to *U* and ϕ. By using equations A3 and A6, it is found that

$$U_c = V\sqrt{1 - 2A + \left(R/R_0\right)^2} \tag{A7}$$

and similarly by using A4 and A6;

$$\tan\phi_c = \frac{A-1}{\sqrt{(R/R_0)^2 - A^2}} \tag{A8}$$

Appendix 3: Velocity of Impact between a Tine Bar and the Crop

At the moment, t_i, when an impact between a tine bar and the crop occurs, it follows from equations A1 above that;

$$Y_i = Y_r + R\cos\omega t_i \tag{A9}$$

or

$$\frac{Y_i - Y_r}{R_0} = \frac{R\cos\omega t_i}{R_0} \tag{A10}$$

and by substituting equation A10 in equation A3 it is found that,

$$U_i = V\sqrt{1 + 2\left(\frac{Y_i - Y_r}{R_0}\right) + \left(\frac{R}{R_0}\right)^2} \tag{A11}$$

Appendix 4: Number of Impacts between Tine Bars and the Crop per Metre of Reel Advance

Consider a time duration denoted by t. In this duration, the distance of reel advance is Vt (m), the angle of reel rotation is ωt (rad) and the number of crop-tine bar impacts is $\omega t/\alpha$. Therefore, for a unit distance (a metre) of reel advance, the number of crop-tine bar impacts is given by:

$$n_i = \frac{\omega t}{\alpha V t} = \frac{1}{\alpha R_0} \tag{A12}$$

Appendix 5: Calculation of Sample Header Loss

$$\text{Sampled area} = 500\ \text{mm} \times 500\ \text{mm} = 0.25\ \text{m}^2$$

$$\therefore \text{Mass of grain in a sample} = 2.28 n_g \times 10^{-5}\ \text{kg}$$

$$\text{Sample loss per unit area} = 9.12 n_g \times 10^{-5}\ \text{kgm}^{-2}$$

$$\text{Crop yield per unit area} = 0.556\ \text{kgm}^{-2}$$

$$\therefore \text{Sample loss per cent of crop yield} = 0.0164 n_g\ \%$$

Appendix 6: A Demonstration of the Effect of Multicollinearity

As a demonstration of the effect of an extreme case of multicollinearity, suppose that the regression equation (equation 20) has been determined using values of x_u and x_ϕ, that are perfectly linearly related as follows;

$$x_\phi = B_3 + B_4 x_u \tag{A13}$$

Then the regression equation can readily be reduced to the following form:

$$L_h = (B_0 + B_2 B_3) + (B_1 + B_2 B_4) x_u \tag{A14}$$

which is the equation of a line. In this case, geometrically speaking, though the regression equation 20 describes a plane, it can be used to predict correct values of L_h only if the values so predicted lie along the line described by equation A14.

In practice this extreme case of multicollinearity is rarely allowed to occur. However, even a weak linear relationship between the regressor variables leads to some loss in reliability of the resulting regression equation.