Determination of force acting on the rice transplanter finger

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Abstract: In order to measure the forces acting on a fixed fork type transplanting finger during separation of rice seedlings, a laboratory model transplanter was developed.It was equipped with transducers to measure the forces and to measure the speed of rotation of the crank that give motion to the finger. The nursery seed rate was varied from 0.35 to 1.15 kg/m^2. Planting velocity varied from 0.29 to 0.55 m/s. Average tangential force on the finger had minimum and maximum magnitudes of 3.68 N and 4.70 N, respectively for 15 mm mat and 3.10 N and 5.32 N, respectively for 20 mm mat. However, one millisecond peak value of the resultant forces had a maximum value of 28.3 N and 29.7 N for 15 mm and 20 mm mats respectively.These values can be used for calculating the magnitude of deflection during the design of the transplanting finger.

Keywords: Rice transplanter, fixed fork type finger, seedling mat, planting velocity, seedling separation force

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1 Introduction

Rice contributed 39.28% of total food grain production of India in the year 2010-2011 (Anon, 2012). Among staple foods of the country, rice ranks first, feeding nearly onebillion of the population. On global level, rice is the major crop in India, China and adjoining countries of South-East Asia and Pacific regions. This region accounts for about 90% of world rice production (De Datta, 1981). United Nations Development Programme had put efforts in popularizing mechanical transplanters (Anon, 1979; Anon, 1983). A national level test code was formulated in the Philippines (Anon, 2010).Many models of self-propelled rice transplanters and few models of manually operated rice transplanters are available in India (Dixit, et al, 2007; Manjunatha, et al, 2009; Garg, et al, 1997; Singh and Vatsa, 2006). Many designs are being tried and recommended for adaptation (Farooq, et al, 2001). Among the rice growing countries of the world, Japan has mechanized transplanting of rice almost fully, about 98% (Anon., 1992).

In a power operated rice transplanter, the planting arm is powered so that the finger should pass through the slot of the seedling gate during picking of the seedlings. During the return motion, the finger returns to its initial position by executing an elliptical path so that it would not hit the seedling mat. A four bar linkage mechanism is used for moving the planting finger. Most transplanters used planar four bar linkage mechanisms with the planting finger forming a coupler point (Singh et al., 1981; Agrawal et al., 1986; Basu et al., 1987; Kohli and Agrawal, 1993; Thomas, 2002). In the Chinese self-propelled rice transplanter named 'Yanji Shakti' the planting finger executes motion in a loop while travelling through picking and planting points. The planting faults in a mechanical rice transplanter can be reduced to a large extend by improving the transplanting mechanism and design of the finger.

The forces acting on a transplanting mechanism are force required to separate the seedlings from the mat and force required to plant. In addition to the forcesabove there will be inertial forces and moments due to variation of the velocity of different links constituting the planting

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mechanism. The above forces and moments can be overcome by the torque applied on the crank and by the reactions at the crank pin.Application of force brings in a deformation of the links and this deformation, if excessive, can alter the path of travel of the planting finger (Kohli and Agrawal, 1993). Deformation on the links can be calculated from the magnitude of force and link dimensions (Vinogradov, 2000). If deformation is excessive the finger may hit part of the tray while attempting to pass through the slots, giving rise to mechanical faults.

For designing an efficient transplanting mechanism and improving the quality of transplanting operation knowledge of force distribution on transplanting mechanism is required. An investigation was undertaken with the following objectives:

i. To design and develop a laboratory model rice transplanter for studying the force requirement in separation of rice seedlings from seedling mat.

ii. To study the effects of age of seedlings, seed rate and velocity of finger at the point of picking on force requirement during picking of seedlings from the mat.

2Materials and methods

A laboratory model rice transplanter was developed in order to measure the forces acting on the planting finger. Details of the transplanter and details of experiment carried out for measurement of the force are explained.

2.1 Development of laboratory model rice transplanter

A laboratory model rice transplanter was developed. It had a single row and was used to measure the force experienced by the planting finger (Kumar, 2013). The planting finger was equipped with transducers which measured the forces acting on the finger in the plane of motion of the finger. Magnitude of force acting perpendicular to the plane was neglected and was not measured. The planting unit was driven by a variable speed electric motor through apower transmission system. A clutch facilitated automatic disengagement of the drive after the cutting stroke of the finger was completed.

The laboratory model ricetransplanter had a two dimensional four bar linkage mechanism. It consisted of the following major parts:

a) Transplanting unit;

b) Seedling tray and tray movement mechanism;

c) Power transmission system;

d) Variable speed motor and speed control unit; and

e) Main frame.

2.1.1 Transplanting unit

Components of the transplanting unit werecrank, coupler link, follower link assembly, and frame.Side view of the transplanting unit is shown in Figure1. The link dimensions were

OA = length of crank = 56.25 mm

AB = length of coupler = 280.6 mm

BC = length of follower = 85 mm

OC = length of fixed link = 300 mm

The fixed link OC made an angle of 10° with the vertical. Angle BCE was 149°.With this arrangement the finger point E passes through the tray slot nearly at the middle of the oscillation.Crank was the driving member of the mechanism. It was constructed from a metallic disk of diameter 150 mm and was driven by an electric motor through a power transmission system consisting of speed reduction gears and a clutch. Functional length of crank was 56.25 mm. The coupler link was connected to the crank through a pin.

The follower link assembly consisted of follower BDGC, a ring, a bush and finger HE (Figure1).The ring was placed between the link BDG and the bush. Motion was transmitted from the crank to the coupler and then to the link BDG of the follower. Link BDG was connected to the bush. The bush could rotate about its axis. The motion was transmitted from the link BDG to the bush. The ring was rigidly attached to the bush and hence it moved with the bush and with the link BDG as one body. The transplanting finger and the finger body was attached rigidly with the ring at K. This arrangement facilitated measurement of forces by mounting strain gauges on the ring and on the finger body. The finger body HE made an angle ψ of 30.5° with the radial line CE. The finger when it passed through the tray at the point Lmadean angle of 25° with the horizontal. This angle represented approximately the angle of transplanting finger at the time of picking in the transplanters available in the market.

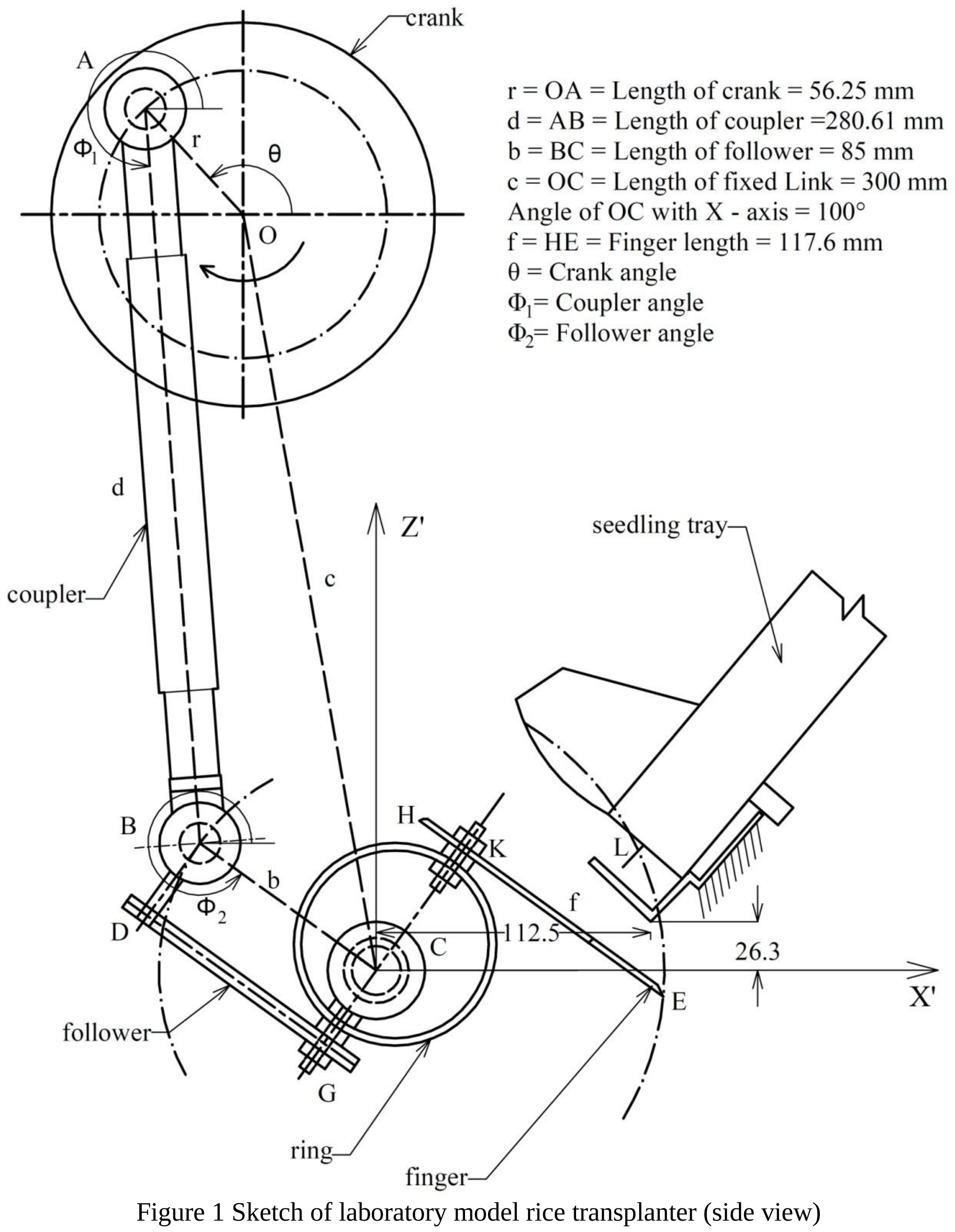


Figure 1 Sketch of laboratory model rice transplanter (side view)

The transplanterwas equipped with transducers which measure the forces acting on the finger. The finger body was equipped with strain gauges to measure the forces acting in a direction perpendicular to HE. The ring was equipped with strain gauges to measure the forces acting in the direction parallel to HE. Knowing these two components, theforces acting on the vertical plane could be calculated. Forces acting perpendicular to this plane were neglected. Details of mounting of strain gauges are shown in Figure2. The finger body acted as a cantilever. Strain gauges were mounted at a distance of 15.3 mm from the bracket.

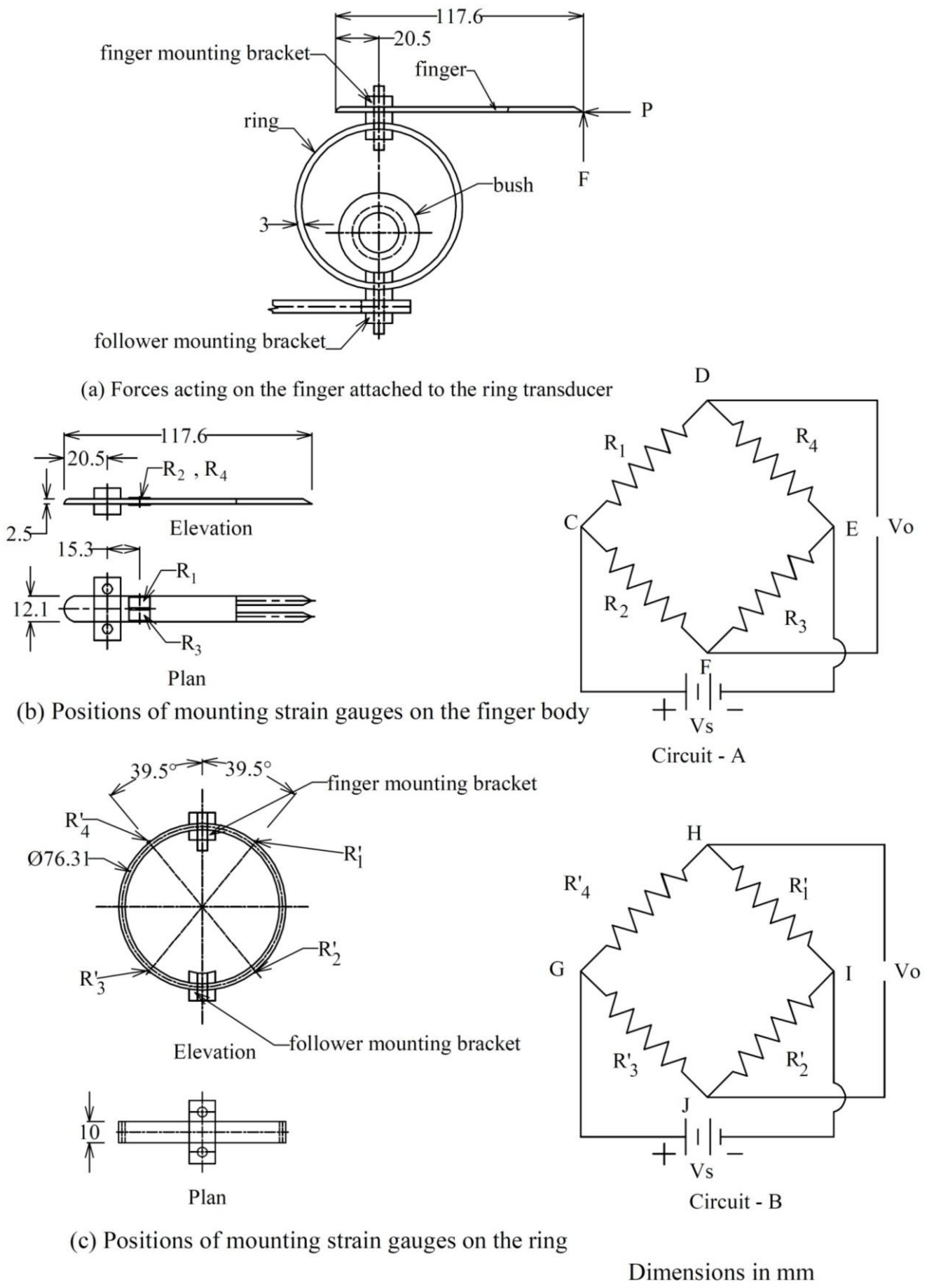


Figure2Position of mounting of strain gauges and details of Wheatstone bridge circuits used in the measurement of forces acting on the transplanting finger

Output of the strain gauge circuit was amplified using a DC amplifier and the amplifier output was sampled in Channel 2 of an oscilloscope. The bridge circuit was calibrated in static condition.

$$y = 4.751\,x - 0.728, \qquad [R^2 = 0.993] \quad (1)$$

where, x is magnitude of signal voltage sampled in the oscilloscope, volts; y is bending load applied at the tip of finger, N.

On the ring the strain gauges were mounted at an angle of 39.5°. The output of the Wheatstone bridge circuit was amplified and sampled in Channel 1 of the oscilloscope. It was calibrated in static condition by applying axial load at the tip of the finger.

$$y = 2.495\,x + 0.056, \qquad [R^2 = 0.994] \quad (2)$$

where, x is magnitude of signal voltage sampled in the oscilloscope, volts; y is axial load applied at the tip of finger, N.

2.1.2 Seedling tray and tray movement mechanism

Seedling tray could accommodate a mat of 220 mm in width and 400 mminlength. Tray was placed with one end on the seedling gate and the other end mounted on a pair of rollers supported on a horizontal beam. The tray was moved sideways by a screw and nut arrangement. The amount of rotation of the handle of the screw required to make 20 mm movement of the tray was noted down and this value was used for indexing the tray during the experiments.

2.1.3 Power transmission system

Power transmission system consisted of a main speed reduction unit, clutch and associated gears. This is shown in Figure3. A speed reduction of 4.5:1 was obtained at the main speed reduction unit. Output shaft of the main speed reduction unit provided power to the gear A. Gear A meshed with another gear integral with the collar A. Collar A and the integral gear rotated freely on its shaft and could mesh with collar B. Collar B in turn rotates integral with its shaft and was used to receive power from collar A and pass the power on to the gear B through a gear and the shaft of the collar. Collar B could slide axially along its shaft. The two collars were meshed by actuating a fork. They initially meshed and started rotating together. Meanwhile a cylindrical cam mounted on the collar B moved over a roller mounted on the frame.As soon as one rotation was completed the collars got separated automatically because of the roller. Thus, soon after engagement motion was transmitted for one rotation only. The gear B and its meshing gear had a velocity ratio of 2:1. Therefore, the crank rotated only half a rotation in one cycle of the clutch operation.The crank shaft was configured in order to start the motion from an extreme position of the follower link and end the motion at the other extreme.

2.1.4 Variable speed motor and speed control unit

A DC motor of 1.12 kW capacity and speed control unit was used to operate the transplanter. A rectifier in the control unit converted the line supply AC power into DC power and a variacchanged the motor input voltage. The motor was operated from 320 rev/min to 610rev/min by varying the controller knob.

A revolution counter was used for measuring the angular speed of the output shaft of the main speed reduction unit. This was made out of a proximity sensor and an electronic counter.

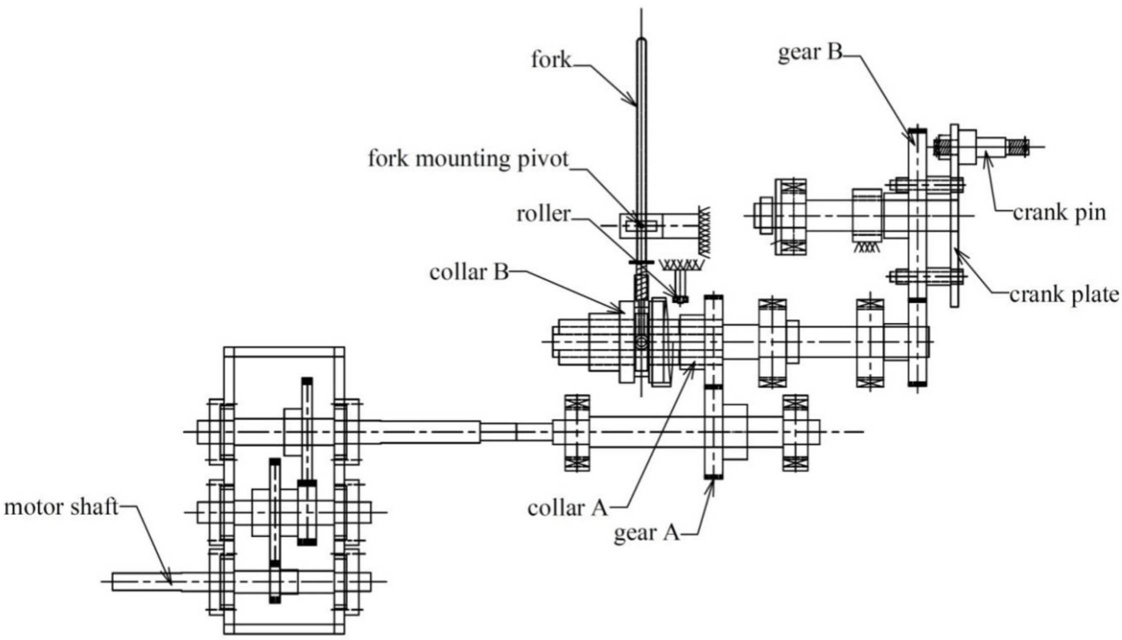


Figure3 Power transmission system of laboratory model rice transplanter

2.1.5 Main frame

Main frame was used to support the transplanting unit, seedling tray, power transmission system, variable speed motor,andmotor speed controller.

A pictorial view of the laboratory model rice transplanter is given in Figure 4. A photograph of the transplanter is given in Figure5.

2.2 Determination of force required for separation of seedlings by finger of rice transplanter

An experiment was carried out in order to determine the force required to separate seedlings from seedling mat using laboratory modelricetransplanter at different values of planting speed, age of growth of seedlings and nursery bed seed rate. The independent variables are listed in Table 1.

Table 1 List of independent variables

S.No.	Name of variables	Symbol	Range	Number of levels
i.	Planting velocity, m/s	v	0.29-0.55	5 levels (0.29, 0.34, 0.42, 0.50, 0.55)
ii.	Age of seedlings, days	d	10 – 20	5 levels (10, 12, 15, 18, 20)
iii.	Seed rate, kg/m^2	s	0.35–1.15	5 levels (0.35, 0.51, 075, 0.99, 1.15)

1. Speed control unit 2. DC motor 3. Main speed reduction unit 4. Counter 5. Clutch system 6. Seedling tray 7. Screw handle 8. Oscilloscope 9. Electrical battery 10. Planting unit 11. Movable platform 12. Main frame 13. Platform actuating lever

Figure4 Pictorial view of the laboratory model rice transplanter

Figure5 Photograph of the laboratory model transplanter

Trials were replicated 100 times. Two values of mat thickness, namely 15 mm and 20 mm, were considered. The dependent variable was force acting on the seedling finger.

Experiment was designed using response surface methodology of central composite design with the above independent parameters. Stat-Ease Design-Expert Software 7.0.0 distributed by M/s John Wily and Sons was used in preparing layout of the experiment and analysis of data.

2.3.1 Procedure

Mat type seedlings were prepared following the guidelines prepared by IRRI (Anon, 2010) and research institutions in India. The height of shoot varied from 66 mm to 85 mm with an average of 74.9 mm at the age of 10 days. The number of leaves varied from onetothree with an average of 2.3. Similarly at the age of 20 days the shoot height varied from 80 mm to 123 mm with an average of 102.1 mm. The number of leaves varied from twotofour with an average of 3.2. Plant population of the seedlings varied from 0.944 to 2.208 number/cm^2 on 15 mm mat and from 0.970 to 2.258 number/cm^2 on 20 mm mat as the seed rate increased from 0.35 to 1.15 kg/m^2. The increase was nearly linear.Seedling mat was wetted by sprinkling water on the mat up to saturation. This was loaded on the seedling tray on the laboratory model rice transplanter and maintained on the tray for onehour before seedling separation. This was to allow removal of free water by drainage.

Position of the tray was adjusted by rotating the handle of the threaded shaft. The clutch was set in disengaged position. The motor was put on and the controller was adjusted to give the set speed of the motor. The clutch was engaged suddenly by actuating the fork. The crank plate rotated driving the finger through the forward stroke. The finger passed through the tray and separated few seedlings.Output of bending and axial force sensing transducers were sampled in the oscilloscope. The sampling rate was 1000 samples per second. The transplanting finger reached at lowermost position and remained there, as the motion of the transplanting finger was stopped due to automatic disengagement of the clutch. Sampling of data in the oscilloscope was stopped and the collected data were saved in the memory. The platform having follower link pivot bush was moved backward and the clutch was engaged once more. The transplanting finger executed return motion and reached the topmost position, where it was ready for the next planting stroke. During this motion the finger did not pass through the tray.

The data stored in the oscilloscope was transferred to a personal computer using flash card memory device. The data was analyzed using a software Tektronix TDS PCS1 Open Choice PC Communication Software purchased from M/s Tektronix Inc., United States. Using Matlab software the data on values of force for each trial was used to calculate the quantities, average tangential force; average radial force; average resultant force; 1 millisecond peak value of tangential force; 1 millisecond peak value of radial force; 1 millisecond peak value of resultant force; average energy requirement during seedling separation/millisecond and total energy requirement during seedling separation. The quantities explained above were transferred to Design-expert software for analysis of variance, and for carrying out three dimensional regression analysis.

2.3.2 Calculation of values of tangential and radial force components acting on the transplanting finger during separation of seedlings

Figure6 shows forces acting on the finger. F_A is the axial force measured by the ring transducer and F_B is the bending force measured by the cantilever load cell of the finger body. Point C represent pivot point of the follower and E represent tip of finger.$\xi$is the angle of radial line CE with the horizontal at a given instant.ψrepresents the angle between radial line and the finger. At any instant of time the tangential force acting at E is given by

$$F_t = F_A\sin(\psi) + F_B\cos(\psi)$$

Radial force at E is given by

$F_r = -F_A\cos(\psi) + F_B \sin(\psi)$

Resultant force is given by

$$F_{Res} = \sqrt{F_t^2 + F_r^2}$$

Figure7 shows a sample plot of force transducer signals versus time recorded by the oscilloscope.

$$\text{Average tangential force} = \frac{\sum_{i=1}^{N}(F_t)_i}{N}$$

where, N is number of observations in the interval A to B;iisindex number for summation in the equation.

$$\text{Average radial force} = \frac{\sum_{i=1}^{N}(F_r)_i}{N}$$

$$\text{Average resultant force} = \frac{\sum_{i=1}^{N}(F_{Res})_i}{N}$$

Maximum value of the tangential force obtained in the interval A to B is 1 millisecond peak tangential force.Similarly maximum values of radial force and resultant force obtained in the interval represent 1 millisecond peak values. A computer program was written incorporating above calculation steps in Matlabsoftware. (4)

Energy expended by the finger during seedling separation can be calculated from the relationship

…(5)

$E = \int \tau.\, d\xi$

where, τ is torque on the follower extension, CE;d$\xi$is incremental angle of movement of finger during time interval dt. …(6)

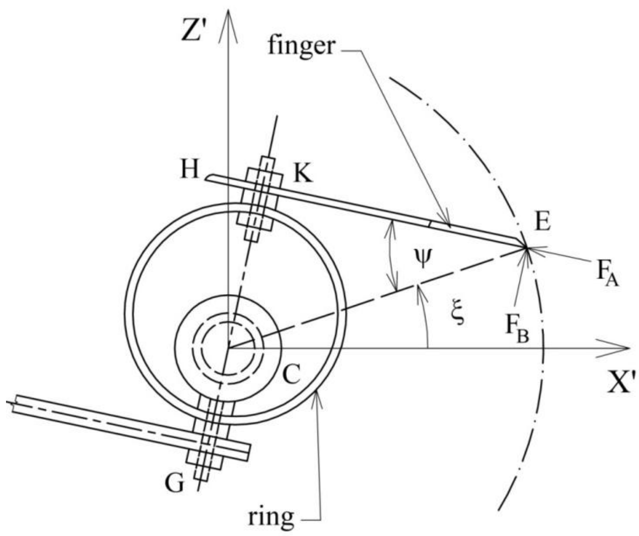
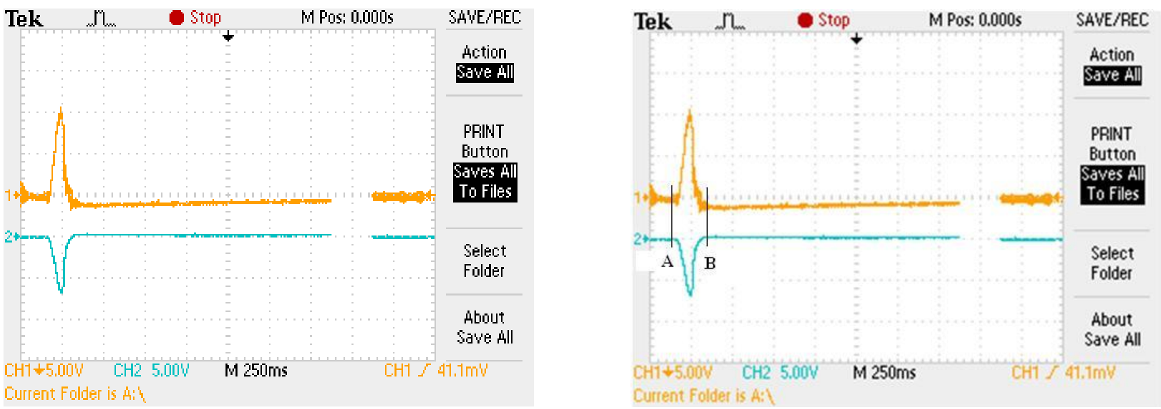


Figure 6 Details of finger body and ring mounted on the bush of the follower assembly



Channel – 1 : Axial force, Channel – 2 : Bending force

(a)Typical recording of axial and bending force signals by the Oscilloscope

Channel – 1 : Axial force, Channel – 2 : Bending force

(b) Signals from the transducers with interval AB corresponding to movement of finger through the seedling mat

Figure 7 ________Recording samples of force signals

$\tau = F_t \times CE$… (10)

where, $F_t$istangential force ;

$d\xi = \omega_2.\, dt$… (11)

$\omega_2 = (d\phi_2/dt)$, it is angular velocity of follower.

Energy expended by the finger can be calculated from Equation9.

$E = \int \tau.\, d\xi = \Sigma F_t.\, CE.\, d\xi = CE.\, d\xi.\, \Sigma F_t$… (12)

Total energy expended by the finger during seedling separation is obtained by summing the values of F_t in the above interval and multiplying by the product (CE × dξ)

$$\left(\begin{matrix}\text{Average energy requirement}\\ \text{during seedling separation/millisecond}\end{matrix}\right) = \frac{CE \times d\xi \times \sum F_t}{N} \ldots \quad (13)$$

3 Results and discussion

3.1 Determination of force required for separation of seedlings by the finger of laboratory model rice transplanter

3.1.1 Force experienced by planting finger with 15 mm thick mat

Magnitude of tangential component of force experienced by planting finger was calculated using Equation3. Average value of tangential force during the seedling separation was calculated. Effect of planting speed, age of seedlings and seed rate on average tangential component of force was analyzed statistically using the analysis of variance. The variables and their interaction terms that had significant influence on the magnitude of force were considered for developing a numerical equation as given below.

Average tangential force = –2.36384 –(0.05812 × d)–(1.27358 × s)(14)

where, d isage of seedlings, days; s isseed rate, kg/m^2.

The magnitude of average tangential force increased with seed rate and was found to be larger for 20 days age of seedlings.

Similarly empirical equations fitted for average radial force, average resultant force, 1 millisecond peak value of tangential force, 1 millisecond peak valueofradial force and 1 millisecond peak valueofresultant force are given below.

Average Radial Force = – 9.07862 – (3.54302 × v)+(0.597456 × d) + (30.1728 × s) –(0.66171 × d × s) –(11.6647 × s^2)(15)

Where, visplanting velocity, m/s

Average resultant force = -5.25111 –(2.27946 × v)+ (0.462179 ×d) + (26.05764 × s) - (0.48065 × d × s)–(10.6461 × s^2)(16)

1 millisecond peak value oftangentialforce = - 2.40361 –(6.20165 × v)–(0.25648 × d) –(3.96193 × s)(17)

1 millisecond peak value ofradialforce = - 14.8965 + (10.01897 × v) + (1.17986 × d)+(52.29727 × s) - (1.23079 × d × s) –(16.6003 × s^2)(18)

1 millisecond peak value of resultant force = - 5.17054 + (11.99153 × v) + (1.190975 × d)+(26.58736 × s) –(1.16025 × d × s)(19)

Tangential component of force contribute to energy consumed in the seedling separation process. The energy consumed in one cycle of operation was calculated using Equation 12 and the average energy requirement was obtained in Equation 13. Effect of planting speed, age of seedlings and seed rate on average energy requirement during seedling separation per millisecond and total energy requirement during seedling separation were analyzed statistically and empirical equations were developed using the significant terms.

Average energy requirement during seedling separation per millisecond= - 0.00014 + (0.0000264 × d) + (0.000488 × s) – (0.000023 × d × s) (20)

Total energy requirement during seedling separation= 0.040696 + (0.001009 × d) + (0.021965 × s) (21)

Minimum and maximum magnitudes of average and peak values of forces experienced by the transplanting finger and energy requirement are given in Table 2.

Table 2 Minimum and maximum magnitudes of average and peak values of force and energy requirementexperienced by the transplanting finger

Parameters	15 mm mat thickness		20 mm mat thickness	
	Minimum magnitude	Maximum magnitude	Minimum magnitude	Maximum magnitude
Average tangential force, N	3.681	4.700	3.105	5.318
Average radial force, N	4.051	7.523	5.847	9.059
Average resultant force, N	6.016	9.379	7.477	10.718
1 millisecond peak value of tangential force, N	9.645	14.016	8.611	13.81
1 millisecond peak value of radial force, N	16.82	25.11	8.876	33.97
1 millisecond peak value of resultant force, N	19.73	28.30	22.99	29.65
Average energy requirement during seedling separation, N mm / millisecond	0.2866	0.4247	0.2591	0.5916
Total energy requirement during seedling separation, Nm	0.06352	0.08110	0.07036	0.12092

The magnitude of average tangential force increased and the average radial force increased as the age of seedling increased from 10 to 20 days. During the same period, the magnitude of resultant of the two forces increased at low seed rates but decreased at high seed rates. One millisecond peak value of the tangential force increased with age of seedlings. However, peak value of both radial force and resultant force increased at low seed rate and decreased at high seed rate. Average energy and total energy requirement during seedling separation increased with age of seedlings.

The average tangential force decreased as the seed rate increased from 0.35 to 1.15 kg/m^2. During the same period, the average radial force and the magnitude of resultant of these two forces increased initially and then decreased with the increase in seed rate. One millisecond peak value of the tangential forceand resultant force increased with seed rate. However, peak value of radial force increased with seed rate initially and thereafter decreased. Average energy and total energy requirement during seedling separation increased with seed rate.

The average tangential force has no influence as planting velocity increased from 0.292 m/s to 0.549 m/s. During the same period, the average radial force and the magnitude of resultant of these two forces decreased with planting speeds. One millisecond peak values of tangential force, radial force and resultant force increased with planting velocity. Average energy and total energy requirement during seedling separation was not influenced by the planting velocity.

The force experienced by the finger depends on the properties of the root mass and of the soil medium. During the process of separation of seedlings a portion of the seed mass which consists of root mass and soil is separated along with the seedlings. The root mass density depends on age of the seedlings and on the seed rate. As a young rice seedling germinate and grows it draws the nutrients needed for its growth from the seed. Gradually it starts absorbing the nutrients from soil. As the age of seedlings increases the root mass increases spending the nutrients stored in the seed. The root mass growth retards after a few days as the availability of food stored in the seed is depleted. The mat provides limited amount of soil space to the roots. In normal soil conditions the roots spread sideways and downwards. The downward spread is limited by the thickness of the mat. The roots become weak when the nutrient availability decreases with the age of the seedlings. This explains the decrease in the resistance to the finger at later stages of growth of the seedlings. Seeds are sown at very close spacing in the mat type nursery. The root mass increases with the growth of the seedlings initially. Later competition between plants starts and growth of the plants in shoot as well as root are negatively affected. This explains the fact that the resistance to the finger increases initially and further increase is stopped after some time with seed rate and with age of the seedlings.

The seedling mat is made of root mass and soil. Initially when the roots are not grown much the properties of the soil plays a dominant role in offering resistance to the finger. At the later stage the root mass plays the dominant role in offering the resistance. In between these periods the root mass with the soil exhibits a property different from the two extremes. During this stage it offers a lower resistance as the few roots along with the soil is not too hard and exhibits softness.

These facts explain the variation of force experienced by the seedling finger.

3.1.2 Force experienced by planting finger with 20 mm thick mat

Magnitude of force requirements and energy requirements during seedling separation for planting with 20 mm thick mat were analyzed and empirical equations were developed.

Average tangential force = $- 30.8534 + (65.29087 \times v) + (1.143041 \times d) + (14.87653 \times s) + (0.36435 \times v \times d) – (0.26303 \times d \times s) – (79.968 \times v^2) - (0.03922 \times d^2) – (7.79468 \times s^2)$ (22)

Average radial force = $18.95803 - (67.8035 \times v) + (0.128452 \times d) + (2.439637 \times s) + (72.04955 \times v^2)$ (23)

Average resultant force = $19.5956 – (63.6534 \times v) + (0.141563 \times d) + (2.503433 \times s) + (66.94585 \times v^2)$ (24)

1 millisecond peak value of tangential force = $-83.4149 + (146.6575 \times v) + (4.15219 \times d) + (41.19711 \times s) – (0.61431 \times d \times s) – (175.676 \times v^2) – (0.1293 \times d^2) – (23.0748 \times s^2)$ (25)

1 millisecond peak value of radial force = $- 3.04163 + (6.250157 \times v) + (1.276798 \times d) + (31.37141 \times s) – (1.59012 \times d \times s)$ (26)

1 millisecond peak value ofresultant force = $3.031437 + (5.760121 \times v) + (1.018185 \times d) + (25.12568 \times s) -(1.15758 \times d \times s)$ (27)

Average energy requirement for seedling separation per millisecond= $0.005657 – (0.01133 \times v) – (0.00027 \times d) – (0.0028 \times s) + (0.0000547 \times d \times s) + (0.013108 \times v^2) + (0.00000797 \times d^2) + (0.001343 \times s^2)$ (28)

Total energy requirement during seedling separation = $0.704637 – (1.49197 \times v) – (0.02614 \times d) – (0.34018 \times s) – (0.0083 \times v \times d) + (0.006031 \times d \times s) + (1.82696 \times v^2) + (0.000896 \times d^2) + (0.178008 \times s^2)$ (29)

Magnitude of forces and energy are given in Table 2.The magnitude of average tangential force first decreased and thereafter increased from 10 to 20 days age of seedlings. During the same period, the average radial force and the magnitude of resultant of the two forces increased with the age of seedlings. One millisecond peak value of the magnitude of tangential force decreased initially and increased thereafter with age of seedlings. Similarly, peak values of both radial and resultant forces increased at low seed rate and decreased at high seed rate. Average energy and total energy requirement during seedling separation decreased and then increased with the age of seedlings.

The average tangential force decreased and then increased as the seed rate increased from 0.35 to 1.15 kg/m^2. During the same period, the average radial force and the magnitude of the average resultant force increased with seed rate. One millisecond peak value of the tangential force decreased initially and thereafter increased with seed rate. However, peak value of both radial and resultant force increased with seed rates. Average energy and total energy requirement during seedling separation decreased and then increased with seed rate.

The average tangential force, average radial force and the magnitude of resultant of the two forces decreased and then increased as planting velocity increased from 0.29 to 0.55 m/s. One millisecond peak value of the tangential force decreased initially and then increased thereafter with planting speed. However, peak value of both radial and resultant force increased with planting velocity. Average energy and total energy requirement during seedling separation decreased and then increased with planting velocity.

Variation of force with mat parameters of 20 mm mat was similar to that of the 15 mm mat. However, some differences can be seen. For example, the average tangential force increased with age of seedlings and with seed rate for the 15 mm mat. It initially decreased and then increased for the 20 mm mat. The difference was mainly due to the presence of more amount of soil for the 20 mm mat. The soil properties played a dominant role initially. Presence of more soil offered more resistance on the finger. When the root mass was developed later the soil -root mass mixture offered lesser resistance. Later the root mass played a dominant role in offering the resistance. Thus the average tangential force decreased initially and then increased. Similar trend is also observed in the average energy requirement and total energy requirement per cycle.

3.1.3 Number of seedlings separated per cycle

Number of seedlings separated by the finger were counted during each run of the experiment. Number of seedlings separated in a cycle depended on seed rate. Number of seedlings separated per cycle is given in Table 3. It can be seen that average number of seedlings per cycle varied from 2.810 to 5.540 as the nursery seed rate increased from 0.35 to 1.15 kg/m^{2}for 20 mm mat. These values were 2.740 to 6.950 respectively for 20 mm mat.

Table 3Number of seedlings separated per cycle from mats of 15 mm and 20 mm thickness at different seed rates

seed rate, kg/m^2	Number of trials	15 mm mat		20 mm mat	
		Average number of seedlings	Std. Dev.	Average number of seedlings	Std. dev.
0.3500	100	2.8100	1.1344	2.7400	1.1066
0.5122	400	3.4675	1.5780	3.6500	1.6121
0.7500	406	4.3276	1.8589	3.9089	1.7650
0.9878	400	4.0700	2.0775	5.1700	2.5490
1.1500	100	5.5400	2.3200	6.9500	3.1055
Mean of total		3.9879		4.3272	
Std. deviation of total		1.9446		2.3020	

4 Conclusions

Magnitude of force acting on seedling finger was influenced by age of seedlings, seed rate and planting speed. The energy required at the crank increased with age of seedlings and seed rate but planting velocity had negligible influence for the 15 mm size mat. The energy required has initially decreased and then increased with the increase in each of the variables, age of seedlings, seed rate and planting speed for the 20 mm size mat.Minimum and maximum magnitudes of average and peak values of force experienced by the finger for the range of variables of the experiment were calculated using empirical relations. Average tangential force on the finger had minimum and maximum magnitude of 3.681 N and 4.700 N, respectively for 15 mm mat and 3.105 N and 5.318 N, respectively for 20 mm mat. Other force values are shown in Table 2.It can be seen that the range of variation in the force and energy requirements are quite small and the magnitude indicated in this experiment can be used with a safety margin to cover usual variations in these variables in field conditions. However, one should ensure proper moistening of the seedling mats.

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Nomenclature

Symbol	Definition
b	length of follower, m
c	length of fixed link, m
cm	centimetre
d	age of seedlings, days length of coupler AB
E	energy expended by the finger during seedling separation
Eq	equation
f	finger length, m
F_A	axial force measured by ring transducer
F_B	bending force measured by the cantilever load cell of the finger
F_t	tangential force acting at E
F_r	radial force at E
F_{Res}	resultant force
Fig	figure
i	index number for summation in the equation
kg	kilogram
kW	kilowatt
m	metre
min	minute
mm	millimetre
N	number of observations in the interval A to B newton force

r	length of crank, m
rev	revolution
R^2	coefficient of regression
s	second seed rate, kg/m^2
t	time
v	planting velocity, m/s
x	load applied at the tip of finger, volts
y	magnitude of signal voltage sampled in the oscilloscope, N

°	degree
τ	torque on the follower extension, CE
θ	crank angle, °
ξ	angle of radial line CE with the horizontal
ϕ_1	coupler angle, °
ϕ_2	follower angle, °
ψ	angle between radial line and the finger
ω_2	angular velocity of follower