INCLINED VIBRATING PLATE TOMATO SORTER

A Thesis

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by

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LIST OF SYMBOLS

A = half amplitude of the vibrating plate, cm
A₁ = area under the force vs. time impulse curve, N-s
B = damping coefficient, N-s/cm
d = diameter of the tomato, cm
e = coefficient of restitution
F = friction force on the vibrating plate, N
Fₖ = kinetic friction force on the sliding tomato, N
Fₛ = static friction force on the tomato, N
F(t) = force between the tomato and the transducer during contact
Fₛ(t) = contact force between plate and tomato as a function of time
g = gravitational acceleration, 9.807 m/s²
h₀ = drop height of the tomato
h₁ = rebound height of the tomato
I = angular moment of inertia of the tomato about an axis through its centroid, Kg-cm²
K = spring coefficient, N/cm
m = mass of the tomato, Kg
m₂ = mass of the active element in the force transducer
mᵥ output = average mᵥ output
P₁ = weight of the tomato plus additional weight, grams
P = normal force between the plate and the tomato, N
P_c = B (ṡ - ẏ) + K (s - y)
\( P_L \) = limitor making the normal force greater than
or equal to zero
\( r \) = radius of the tomato, cm
\( S \) = displacement of the tomato’s surface measured
perpendicular to the plate, cm
\( \dot{S} \) = velocity of the tomato’s surface perpendicular
to the plate, cm/sec
\( S_{en} \) = sensitivity in grams/mv
\( t_1 = t_{ab} \) = time for the tomato to go from a to b
\( t_2 = t_{bc} \) = time for the tomato to go from b to c
\( t_{total} \) = total time tomato is in the air between
integrating modes, S
\( V_0 \) = absolute velocity of the tomato immediately
before impact, cm/sec
\( V_1 \) = absolute velocity of the tomato immediately
after impact, cm/sec
\( V_2 \) = velocity of the plate on the transducer
\( W_G \) = weight of green tomato, grams
\( W_R \) = weight of red tomato, grams
\( X \) = displacement of the tomato’s center of gravity
measured parallel to the plate, cm
\( \dot{X} \) = velocity of the tomato’s center of gravity
parallel to the plate, cm/s
\( \ddot{X} \) = acceleration of the tomato's center of gravity parallel to the plate, \( \text{cm/s}^2 \)

\( Y \) = displacement of the tomato's center of gravity measured perpendicular to the plate, \( \text{cm} \)

\( \dot{Y} \) = velocity of the tomato's center of gravity perpendicular to the plate, \( \text{cm/s} \)

\( \ddot{Y} \) = acceleration of the tomato's center of gravity perpendicular to the plate, \( \text{cm/s}^2 \)

\( Y_{\text{max}} \) = maximum bounce height of the tomato, \( \text{cm} \)

\( Y_0 \) = initial displacement of the tomato's center of gravity perpendicular to the plate, \( \text{cm} \)

\( \dot{Y}_0 \) = initial velocity of the tomato's center of gravity perpendicular to the plate, \( \text{cm/s} \)

\( Z_x \) = displacement of the plate measured parallel to the plate, \( \text{cm} \)

\( \dot{Z}_x \) = velocity of the plate measured parallel to the plate, \( \text{cm/s} \)

\( \ddot{Z}_x \) = acceleration of the plate measured parallel to the plate, \( \text{cm/s}^2 \)

\( Z_y \) = displacement of the plate measured perpendicular to the plate, \( \text{cm} \)

\( \beta \) = plate angle of tilt, degrees

\( \xi = s - y \)

\( \varepsilon \) = distance normal force is offset from the tomato axis to represent rolling resistance, \( \text{cm} \)
\( \zeta = \text{damping ratio} \)
\( \theta = \text{angular displacement of the tomato, rad} \)
\( \dot{\theta} = \text{angular velocity of the tomato, rad/s} \)
\( \ddot{\theta} = \text{angular acceleration of the tomato, rad/s}^2 \)
\( \theta_1 = \text{angle of tilt of the plate on the electro-
dynamic shaker and the vibratory plate sorter from the - x axis} \)
\( \theta_2 = \text{angle of tilt of the electro-dynamic shaker} \)
\( \theta_3 = \text{angle of tilt of the plate on the vibratory plate sorter from the Z - axis.} \)
\( \mu = \mu_k = \text{kinetic friction coefficient} \)
\( \rho_G = \text{density of green tomato, grams/cm}^3 \)
\( \rho_R = \text{density of red tomato, grams/cm}^3 \)
\( \psi = \text{angle due to the radius of the area of contact} \)
\( \omega = \text{frequency of the vibrating plate, rad/sec} \)
\( \omega_n = \text{undamped natural frequency of the tomato on the plate, rad/sec} \)
1.0 INTRODUCTION

Automatic sorting of mechanically harvested tomatoes is needed because present day once-over tomato harvesters yield a mixture of ripe and green fruit. When the tomato crop is harvested, 30 percent or more of the tomatoes are often green (Stephenson, 1974). In California, in 1977, virtually all processing tomatoes were harvested by machine. In the Midwest (Ohio, Indiana, and Michigan) approximately 20 percent were machine harvested, but the trend is toward mechanical harvesting to reduce harvest costs.

Presently in the Midwest, 6 to 20 workers ride on a harvester to remove green and rotten tomatoes as well as dirt, stones, and other extraneous material. The additional frame needed to support these workers adds to the bulkiness, weight, and initial cost of the harvester, and it reduces the machine's maneuverability. The workers add to the labor costs and often limit the harvester's capacity. Thus, a more economical method of automatic sorting is needed to replace manual sorting procedures.

Electronic color sorting for tomatoes has been developed in the past decade. It has many advantages and a few limitations. First, it is quite expensive ($25,000 to $50,000 per machine). Second, only a small surface area of a tomato is sampled causing rejection of some partially-ripe (showing
both red and green color) tomatoes. Third, reflected light used for sorting does not measure the internal quality of the fruit, thereby causing some green tomatoes to be rejected which are internally ripe. Fourth, since dirt clods are rejected, some dirty tomatoes are also rejected.

Specific gravity sorters have also been used but their separation of red and green tomatoes is not accurate. Since this method of sorting is best done at the processing plant, it also introduces the problem of what to do with the rejected tomatoes.

Holmes (1977) developed a vibratory tomato sorter based upon fruit resiliency which bouncing green tomatoes out of a trough and allows the red tomatoes to pass by the vibrator. This system has limited capacity because the tomatoes pass single-file through a sorting channel and it may require several channels per harvester.

This study was undertaken to investigate the potential of a vibratory conveyor for separating ripe and green tomatoes. If successful, a vibratory conveyor would have the advantages of being simple, inexpensive, easy to feed, and should separate tomatoes at a high rate.

During the summer of 1976, preliminary tests with a vibratory inclined plate indicated that this sorting principle had promise. Many design parameters had to be investigated including vibration frequency and amplitude, angle of tilt
of the plate and type of forcing function (the phase relationships between the normal and parallel motions of the conveyor surface). Before this information could be evaluated, the pertinent properties of tomatoes had to be determined. They were: mass, size, coefficient of kinetic friction, stiffness, and the energy absorption quantities.
2.0 OBJECTIVES

The general objective of this research was to explore a vibrating inclined plate for sorting tomatoes. Specific objectives were:

1. To develop a mathematical model of the motion of a tomato on a vibrating inclined plate.

2. To measure the physical properties of a tomato which affect sorting, including:
   A. Mass
   B. Size
   C. Spring Coefficient
   D. Damping Coefficient
   E. Coefficient of Kinetic Friction

3. To program the mathematical model on a computer to determine the effect of angle of tilt and frequency and amplitude of vibration on sorting.

4. To build a prototype vibrating inclined plate sorter and evaluate its performance.

5. To compare theoretical and experimental sorting results.
3.0 REVIEW OF LITERATURE

3.1 Previous Vibratory Sorting Methods

Hamann and Carol (1971) used a variable stroke and frequency electrodynamic shaker for sorting grapes. The grapes were placed in a trough inclined 30 degrees from horizontal and vibrated with constant current applied to the vibrator. Constant current caused the vibration amplitude to vary inversely with frequency (0.0229 cm at 200 Hz to 0.0635 cm at 100 Hz). It separated grapes based upon the frequency at which they bounced from the trough. By both visual inspection and certain chemical indices, they showed that these grapes were sorted according to ripeness. The sorting concept received a patent (Hamann, 1972).

Stephenson, et al. (1973) studied the possibility of sorting by studying the response of tomatoes to vibration. He used a low power speaker (slightly more than one watt) to excite a diaphragm, which in turn, acoustically excited the tomato. He tested tomatoes of various maturity and found that the response of green tomatoes averaged roughly six times larger than that of ripe tomatoes.

Hamann, et al. (1973) tested vibration for sorting blueberries according to ripeness. Vibration frequencies and amplitudes for these tests ranged from 0.037 cm at 160 Hz to 0.018 cm at 230 Hz. The riper berries tend to be softer
and more viscous and have a lower resonant frequency. However, the success of vibration sorting of berries according to ripeness was limited because they found a poor correlation between ripeness and firmness. There was a strong correlation between the vibration sorting and percent of blueberry decay; therefore, this device was proposed as a mechanism to remove decayed soft blueberries to improve shelf life.

Vibratory sorting of blueberries was also studied by Bower (1973). Limited accuracy in sorting with respect to firmness or quality was found. He found that multiple passes over the sorter gave more accurate sorting than a single pass over the sorter.

Hamann, et al. (1975) tried to determine what property or properties affected sorting. The authors showed that the quasi-static firmness values (measured by the method of Hamann, et al. 1973) accounted for 70 percent of the variation in sorting. They also showed that the dynamic storage modulus (method of Hamann, 1969) had no effect on the sorting frequency for some rubber-like spheres. Due to this, they concluded that stiffness was not the primary property affecting sorting. Eighty to ninety percent of the variation in sorting frequency was attributed to differences in the coefficient of restitution. They found a correlation between the dynamic loss tangent (ratio of loss modulus to storage modulus) and sorting frequency. From the loss tangent, they were able to predict the coefficient of restitution. Thus, they concluded that loss tangent and
the coefficient of restitution were the two most important properties affecting sorting.

Hamann and Diehl (1977) went further into this study of the dynamic complex modulus. The authors tested apples, pears, rubber balls, turnips, potatoes, and polymers and proposed the following equation:

$$|E| = 1.51 \frac{F}{Dd_c}$$

where

$|E|$ = absolute value of complex modulus  
$F$ = peak to peak force  
$D$ = peak to peak displacement  
$d_c$ = mean contact diameter

During the summer of 1976, Hamann tested several Heinz 1350 tomatoes and found an average $|E|$ for green tomatoes of $6.76 \times 10^6$ N/m² and $3.09 \times 10^6$ N/m² for red tomatoes.

Bayer (1976) investigated sorting tomatoes by conveying the tomatoes single-file along a sorter channel consisting of a vibrating plate perpendicular to an inclined shelf. The firm green tomatoes were bounced out of the 4 cm wide channel while the softer, ripe tomatoes were retained. He was successful in sorting Heinz 1439 with a frequency around 65 to 70 Hz.

Holmes (1977) continued the investigation of the vibratory sorting concept by conveying tomatoes single-file along both
sides of a vibrating cylinder. The firm green tomatoes were rejected from the conveyor and the soft ripe tomatoes pass by the vibrator. He also proved that the concept would successfully sort other products such as onions and clods, potatoes and clods, and ripe and unripe peaches.

3.2 Vibratory Conveyor Systems

The experimental vibratory tomato sorter utilizes the principles of an inclined vibratory conveyor. Because no research was found on using a vibratory conveyor as a sorter, the review was limited to work done in the area of a material conveying.

Vibratory conveyors have the advantages of being versatile, simple in concept, self-cleaning, economical, low in maintenance, and have a projected long life (Kreis, 1977). All vibrating conveyors work on the same principle and have similar components (trough, legs, base, and a drive unit). The trough vibrates and causes the material to be conveyed along it. The base provides the reaction mass (several times heavier than the trough) for the trough and supports the drive unit. The legs stabilize and support the trough. The drive unit produces the force to vibrate the trough.

Much theoretical work has been done on vibratory conveyors by Gutman (1963 and 1968), Morcos and Massoud (1969), Mansour (1972), Berry (1958 and 1959), Booth and McCallin
(1963 - 1964), Taniguchi, et al. (1963), Gaberson (1972), Schertz and Hazan (1963), Redford and Boothroyd (1967 - 1968), Kreis (1977) and others. Gaberson (1972) and Mansour (1972) explained the most important modes in which a particle could move on the vibrating conveyor. They were: riding on the conveyor, slip forward relative to the conveyor, slip backwards relative to the conveyor, or be in free flight. These same writers also recognized and analyzed many properties which affect conveying. Gutman (1963 and 1968) studied shaking conveyors and concluded that the forward motion of the particle is produced by the frictional force which is greater than the inertia force, hence, the material moves forward with the conveyor. On the return stroke, the inertia force needed to move the material backward with the conveyor should be larger than the frictional force, hence, the material does not return as far back as the conveyor.

Booth and McCallin (1963 - 1964) studied the effect of frequency of vibration, the angle between the plane and the conveying surface and the plane of vibration, angle of tilt of conveying surface, and the material being conveyed on the performance of a vibratory conveyor. DeCock (1962 - 1963) found the particle velocity on a vibratory feeder was more dependent on the magnitude of the acceleration than on the amplitude of vibration or frequency of vibration. The mass of the particle and geometry of the particle had very little effect on conveying. Also, small changes in angle of inclination (for a given forcing vibration angle) and coefficient of
friction did not change the maximum average velocity. Kreis (1977) determined that horizontal amplitude was more critical than vertical amplitude in determining average velocity of horizontal conveying.

3.3 Physiology of Tomato Fruit

Tomatoes used for food belong to the genus and species *Lycopersicon esculentum* (Bailey, 1949). After flowering, tomato fruit formation involves fruit development, ripening, and senescence (Khudairi, 1972). Soon after the fruit attains its maximum size, it is mature, green in color due to its chlorophyll content, and quite hard (Goss, 1973). Visible changes in ripening occur about the same time as the increase in the rate of respiration known as the climacteric rise (Goss, 1973). Shortly after the climacteric is reached, the tomato becomes ripe. Senescence (old age) follows ripening and is accompanied by an increase in the viscosity of cell cytoplasm (Goss, 1973).

The conversion of protopectin and calcium pectate in the middle lamellae and the primary cell walls of the pericarp to soluble pectins cause a tomato to soften as it ripens (Gruelach, 1973). The middle lamellae act as a cementing agent between cell walls, so this conversion dissolves the middle lamellae which allows the cells to separate and slide over one another.

These internal changes effect the spring constant (energy
storage element) and the internal damping (energy dissipation element). Changes on the surface of the tomato also take place during ripening affecting the surface coefficient of friction.

The outer surface of the fruit is covered by a cuticle. The cuticle is 4 - 10µm thick (Wilson, et al. 1975) and environmental conditions as well as other unknowns control its development (Kretchman, 1977). The cutinized layer can be broken up into two main regions: the cutinized layer just above the epidermal cells and the waxy layer outside of the cutinized layer (Esau, 1965 and Wilson, et al. 1975).

During ripening the cuticle becomes homogeneous, and there is less distinction between the cuticular layer and the waxy layer than during fruit development (Wilson, et al. 1975).

The lipids which form the cuticle can be classified into two classes: cutin and waxes (Hulme, 1970). Cutin forms the major part of the plant cuticle. Cutin is difficult to analyze because of its insolubility in most organic solvents (Hulme, 1970). Bukovac, et al. (1971) found that this cutin had pegs that extend through the epidermal cells. They also investigated the surface of tomatoes with the scanning electron microscope and showed the general appearance of the mature cuticle. From these electron micrographs he showed the existence of fruit waxes.

These waxes are of two types, epicuticular and cuticular.
The epicuticular wax is found on the surface of a tomato, whereas the cuticular wax is contained within the cuticle (Kretchman, 1977). Morse (1970) studied the distribution of these waxes.

The cuticular wax passes through the cuticle forming the epicuticular wax. An interesting note here is that the cutin apparently has no pores which can be interpreted as the pathways for the wax to move to the surface (Esau, 1965). Weathering and other unknowns cause the wax to break down. It then appears as a soft-sheet-like covering (Bukovac, et al. 1970). In reality, this covering is made of small plate-like structures (Bukovac, et al. 1970).

3.4 Physical Properties of Tomatoes

Three major tomato properties seem to affect sorting in this research. They are: the spring constant, the internal damping, and the coefficient of kinetic friction.

The tomato fruit is a viscoelastic biological material, and its mechanical properties are not well defined. The stress in the tomato is dependent on time as well as on strain and strain rate (Bayer, 1976). The mechanical properties also vary between tomatoes and on location on the tomato surface. Environment and other unknowns also affect these properties.

Ways to determine the static or quasi-static firmness

The internal damping and stiffness can be determined with dynamic tests. When viscoelastic materials are tested dynamically, a frequency-dependent complex modulus of elasticity is often used to describe the material properties. This complex modulus is composed of a real part and an imaginary part. The real part is called the storage modulus and deals with the energy storage. The imaginary part is called the loss modulus and deals with the energy loss (Mohsenin, 1970). Dynamically, viscoelastic materials can be tested four ways: the sinusoidally-varying stress-strain method, the resonant method, the pulsed wave propagation method, and the electrical-mechanical impedance method (Mohsenin, 1970).

Stephenson, et al. (1973) used sonic waves in the pulsed wave propagation method. He found the first resonant peak for ripe tomatoes between 200 and 400 Hz and between 300 and 960 Hz for green tomatoes.

Singh (1972) used a dynamic response method to characterize the tomato mechanically. Green field-grown tomatoes
showed resonant frequencies between 250 to 300 Hz and ripe field-grown tomatoes had resonant frequencies between 150 to 200 Hz.

Fluck and Ahmed (1973) ran impact tests on various fruits, including tomatoes. They found that as relative velocity of impact increased, the peak force and impulse increased and the duration of impact decreased. As the masses involved in the impact increased, both peak force and duration of impact increased.

Bayer (1976) used the drop test to determine the properties of Heinz 1439. Knowing the drop height and determining the time of contact and rebound height from high speed movies, he was able to calculate the spring and damping coefficients. The natural frequency was determined to be approximately 27.5 Hz for red tomatoes and 49.5 Hz for green tomatoes, considerably lower than previous work done with tomatoes.

The two usual methods to evaluate the coefficient of friction ($\mu$) are the tilting of an inclined plane or the moving of a specific surface against the material. Very little work has been done on the coefficient of friction of tomatoes. Mohsenin (1970) reported the only information that could be found. The tomato was placed on its calyx end on an inclined plate and the platform raised until the tomato began to roll. From this data the kinetic coefficient of friction was calculated. For the static coefficient of
friction the angle was decreased until the tomato rolled
down the plate at a uniform velocity. He reported, for ripe
tomatoes on sheet aluminum, the static coefficient of friction
was between .33 to .52 and the kinetic coefficient of friction
was .28 to .40. These values are probably a measurement of
the rolling resistance of tomatoes more than the coefficient
of kinetic friction.
4.0 MODELING A TOMATO ON AN INCLINED VIBRATORY PLATE

Early in this study the hypothesis was formed that an inclined vibratory conveyor could be used as a tomato sorter. Figure 1 shows the schematic of an inclined vibrating plate with horizontal (B) and perpendicular (A) driving components.

![Diagram of inclined conveyor with angle of tilt labeled](image)

Figure 1
Driving components of inclined conveyor.

When the operating frequency of the conveyor is higher than the natural frequency of red tomatoes, the ripe tomatoes do not bounce allowing the horizontal component (B) to move the tomato up the plate. When the operating frequency of the plate is slightly less than the natural frequency of green tomatoes, the vertical component (A) causes the green tomato to bounce. Gravity then causes the green tomatoes to bounce down the plate.

A computerized model showing the movement of a tomato on an inclined vibrating flat plate was developed to test
this hypothesis. From analysis, the parameters needed for the model were identified. The results of the experimental sorter were compared to the results of the computer program. The computer model was also used to predict what would happen under conditions that were not tested experimentally.

4.1 Derivation of Equations of Motion on the Tomato

Figure 2 shows a freebody diagram of a tomato when in contact with a vibrating plate.

![Freebody diagram](image)

**Figure 2**
Freebody of a tomato in contact with a vibrating plate.

From Figure 2 and using Newton's Second Law of Motion, one
can write:

\[ mX = F - mg \sin \beta \] (1)
\[ mY = P - mg \cos \beta \] (2)
\[ I\theta = rF + \epsilon P \] (3)

where

- \( m \) = mass of the tomato, Kg
- \( X \) = displacement of the tomato's center of gravity measured parallel to the plate, cm
- \( F \) = frictional force on the vibrating plate, N
- \( g \) = gravitational acceleration = 9.807 m/s\(^2\)
- \( I \) = angular moment of inertia of the tomato about an axis through its centroid, Kg cm\(^2\)
- \( \beta \) = the plate angle of tilt, degrees
- \( Y \) = displacement of the tomato's center of gravity measured perpendicular to the plate, cm
- \( P \) = normal force between the plate and the tomato, N
- \( \theta \) = angular displacement of the tomato, rad
- \( r \) = radius of the tomato, cm
- \( \epsilon \) = distance normal force is offset from tomato axis to represent rolling resistance, cm

Since the tomato is not cemented to the plate, it can go into free flight like a projectile. Figure 3 shows a freebody diagram of a tomato when it is not in contact with a vibrating plate.
Figure 3
Freebody of the tomato in free flight.

From Figure 3 there are two conditions which need to be satisfied if the tomato is to be in contact with the vibrating plate:

1. $P$ cannot be negative
2. $S$ cannot be less than $Z_y$

where

$S =$ displacement of the tomato's surface measured perpendicular to the plate, cm and
$Z_y =$ the displacement of the plate measured perpendicular to the plate.

The normal force is

$$P = \begin{cases} P_L & \text{for } Z_y \geq S \\ 0 & \text{for } Z_y < S \end{cases} \quad (4)$$

and
\[ p_L = \begin{cases} p_c & \text{for } p_c \geq 0 \\ 0 & \text{for } p_c < 0 \end{cases} \]  (5)

where

\[ p_c = B (\dot{S} - \dot{Y}) + K (S - Y). \]  (6)

Figure 4 shows the tomato modeled as a Kelvin model when in contact with the plate.

![Diagram](image)

**Figure 4**

Representation of the tomato in terms of mechanical elements.

Where

\[ K = \text{spring coefficient, N/cm,} \]
\[ B = \text{dashpot coefficient, N - sec/cm,} \]

and \[ Zx = \text{the displacement of the plate measured parallel to the plate, cm.} \]

The value of rolling resistance is determined by the value of \( P \) and \( \varepsilon \). Since \( P \) depends on the weight of the tomato and
the acceleration force in the Y direction, its value is known. The value of $\epsilon$ is more complex and was determined as follows.

Since the tomato is modeled as a sphere, the acceleration force causes a circular area of contact with the plate. When the tomato rolls, the normal reaction $P$ is assumed to act through a point on the perimeter of this area of contact (Figure 5). When the tomato does not roll, $P$ is located within this area of contact and is determined by the dynamics, orientation, and internal structure of the tomato.

![Figure 5](image)

Offset normal force representation for the rolling resistance of a deformed tomato.

From Figure 5,

$$\tan \left(\frac{\psi}{2}\right) = \frac{d}{\epsilon}$$

and

$$\sin \psi = \frac{\epsilon}{r}$$
where
\[ \delta = s - y \]  
\[ \psi = \text{angle due to radius of the area of contact.} \]  

For small angles
\[ \tan \frac{\psi}{2} = \frac{\psi}{2} \]
and
\[ \sin \psi = \psi \]
so,
\[ \frac{\psi}{2} = \frac{\psi}{\varepsilon} \]  
and
\[ \psi = \varepsilon/r. \]

Solving 7, 8, and 9 for \( \varepsilon \) gives
\[ \varepsilon = \sqrt{2r (s - y)}. \]

The direction of rotation determines which side of the tomato the normal force is located. If the tomato is rolling to the right, the force is located on the right. If the tomato is rolling to the left, the force is on the left. The following equations give the correct sign depending on rotation.

\[ \varepsilon = \begin{cases} 
- \sqrt{2r (s - y)} & \text{for } r > 0 \\
+ \sqrt{2r (s - y)} & \text{for } r < 0 
\end{cases} \]

The friction force, \( F \), between the tomato and the vibrating
plate depends on whether the tomato is sliding, rolling, or in free flight. When the tomato is in the air, $F = 0$. When the tomato is sliding, $\ddot{x} \neq \dot{x} + r\dot{\theta}$ and

$$F_k = \begin{cases} \mu_k^F \text{ for } \ddot{x} > \dot{x} + r\dot{\theta} \\ -\mu_k^F \text{ for } \ddot{x} < \dot{x} + r\dot{\theta} \end{cases}$$

(11)

where

$F_k = \text{kinetic friction force on tomato when sliding, N}$

$\mu_k^F = \text{kinetic friction coefficient.}$

When the tomato is rolling, $\dot{x} + r\dot{\theta} = \dot{Z}_x$ and $\ddot{Z}_x = \ddot{x} + r\ddot{\theta}$. The frictional force, $F$, then equals the static friction force, $F_s$. The equation for $F_s$ was not explicitly derived and incorporated into the model. Going back through the logic already presented, one gets the same five equations which describe a pure rolling motion of a tomato. Therefore, the time-average of the friction force computed by the computer program (± $\mu_k^F$) converges to the correct value of the frictional force. In other words, the digital program which can only calculate the frictional force as ± $\mu_k^F$, predicts a sequence of very small sliding motions in alternating directions relative to the flat plate. Its time-average is equal to the lateral displacement of the flat plate.

Equations 1 through 11, which describe the motion of a tomato on a vibrating plate, were programmed on analog and digital computers (see Figure 8 and Appendix A-1). These
programs calculated the path of the tomato by integration.

For the digital program shown in Appendix A-3, integration was used to calculate the tomato's path when below the half amplitude of the vibrating plate (A). Above A, the path of the tomato was calculated algebraically.

Figure 6 shows a freebody sketch of a tomato in free flight.

![Diagram of tomato path](image)

**Figure 6**

Path of tomato in free flight.

The following equations predict where the tomato is located as a function of time, velocity, and direction after leaving the plate:

\[
\begin{align*}
\ddot{Y} &= -g \cos \beta \\
\dot{Y} &= -g \cos \beta t + Y_0 \\
Y &= -g \cos \beta t^2/2 + \dot{Y}_0 t + Y_0.
\end{align*}
\]

(12)

(13)

When the tomato is at the top of its bounce (point b,
Figure 6) $\dot{Y} = 0$. Solving equations 12 and 13, the time for the particle to go from point a (leaving plate) to point b is given by

$$t_{ab} = t_1 = \frac{Y_0}{g \cos \beta}$$

$$Y_{max} = Y_0 + \frac{\dot{Y}_0^2}{2g \cos \beta} \quad (14)$$

where

$Y_{max} =$ maximum bounce height, cm.

The following equations calculate the tomato's movement from point b to point c (Figure 6). Point c is the end point of free flight because below the half amplitude of the vibrating plate (A) there is the possibility of the plate hitting the tomato. Below point c, the integration mode is resummed.

Thus, at point c,

$$Y = S = A$$

or from equations 13 and 14

$$A = -g \cos \frac{t_2^2}{2} + Y_{max}$$

which gives the time for the tomato to drop from point b to point c.
\[ t_{bc} = t_2 = \sqrt{\frac{2(\gamma_{max} - A)}{g \cos \beta}} \]  \hspace{1cm} (15)

and from equations 12 and 15

\[ \dot{\gamma} = -\sqrt{2g \cos \beta (\gamma_{max} - A)} \]

and

\[ t_{total} = t_1 + t_2 \]

where

\[ t_{total} = \text{total time tomato is in the air} \]
\[ \text{between integrating modes.} \]

The \( x \) displacement and the \( x \) velocity are given by the following:

\[ \ddot{x} = -g \sin \beta \]
\[ \dot{x} = -g \sin \beta \ t_{total} + \dot{x}_0 \]
\[ x = -g \sin \beta \ \frac{t_{total}^2}{2} + \dot{x}_0 \ t_{total} + x_0 \]

These equations are used to calculate the initial conditions when returning to integration. From here until the tomato again leaves the plate, integration continues.

4.2 Derivation of Equations of Motion on the Plate

To simulate the circular motion of the plate it was
necessary to break the motion of the plate into X and Y components (Figure 7).

\[ \begin{aligned}
Z_y &= \text{the plate's displacement measured perpendicular to the plate, cm} \\
Z_x &= \text{the plate's displacement measured parallel to the plate, cm.}
\end{aligned} \]

If \( Z_y = A \sin \omega t \) and \( Z_x = -A \cos \omega t \), a circular motion is obtained where

\[ A = \text{half amplitude of the vibrating plate, cm}. \]

4.3 Analog Computer

McClure (1977) derived the equations of motion for a tomato bouncing on an inclined vibrating flat plate during
Winter Quarter of 1977 in the following steps: cam follower, particle bouncing on a flat horizontal plate, particle sliding on a flat horizontal conveyor (no rolling), particle sliding and rolling on a flat horizontal conveyor (point contact), particle sliding and rolling on a flat horizontal surface with rolling resistance included, and particle bouncing, rolling, or sliding on an inclined vibrating surface.

As these chapters were developed, analog and digital computer programs were written and tested. Figure 8 shows the final computer circuit for a particle bouncing, rolling, or sliding on an inclined vibrating surface. It was amplitude scaled for \( A = 0.0254 \) cm.

The variables used in this program were:

\[
\begin{align*}
g & = \text{gravitational acceleration} = 9.807 \text{ m/sec}^2 \\
A & = \text{half amplitude of the vibrating plate, cm} \\
\omega_n & = \text{undamped natural frequency of the particle on the plate, rad/sec} \\
\beta & = \text{the plate's angle of tilt, rad} \\
\dot{Y} & = \text{the vertical velocity of the tomatoes center of gravity, cm/sec} \\
Y & = \text{displacement of the tomato's center of gravity measured perpendicular to the plate, cm} \\
\zeta & = \text{damping ratio} \\
P & = \text{normal force between the plate and the tomato, N} \\
S & = \text{displacement of the tomato's surface measured}\n\end{align*}
\]
perpendicular to the plate, cm

\( P_L \) = limitor that makes the normal force equal to zero or greater

\( Z_y \) = the vertical displacement of the plate, cm

\( \omega \) = frequency of the vibrating plate, rad/sec

\( \dot{Z}_x \) = the horizontal velocity of the plate, cm/sec

\( r \) = radius of the tomato, cm

\( \dot{\theta} \) = the angular velocity of the tomato, rad/sec

\( F \) = frictional force on the vibrating plate, N

\( \mu \) = coefficient of kinetic friction

\( m \) = mass of the tomato, Kg

\( \varepsilon \) = distance the normal force is offset due to rolling resistance, cm

4.4 Digital Computer

To study the motion of a tomato on an inclined vibratory surface the equations of motion were programmed on an IBM System 370 using CSMP III (Continuous System Modeling Program III). Appendix A-1 shows the digital program that was developed. To get acceptable accuracy the integration interval had to be very small making the running cost prohibitively expensive. In order to cut computing cost an alternative program was developed (Appendix A-2). It was developed with a changing integration step, 3\( \mu \)s, when the tomato was in contact with the plate and 0.6 ms when the
tomato was in the air. This program reduced the cost but made multiple runs impossible. A third digital program (Appendix A-3) was developed which further reduced computing costs and increased accuracy by calculating the tomato's path as a projectile when in free flight.

The tomato motion predicted from this computer program was compared with the results obtained experimentally from the tomato sorter. The variables which were used in the program are shown in Appendix A-4. The logic and subroutine used in implementing this program will now be described.

Integration was used whenever the tomato was below the half amplitude of the vibrating plate \( (A) \). Above \( A \), the path of the tomato was calculated algebraically as a projectile in free flight. Integration resumed again when the tomato was at point \( C \) (Figure 6). The criterion which determined when contact was lost was when \( P \leq 0 \). The criterion which determined when contact occurred was \( S = Z \), indicating an interference between the plate and tomato.

There are three cases in which the tomato could rebound from the plate. Figure 9 illustrates these three cases. If a bounce occurred such that the maximum bounce height \( (Y_{\text{max}}) \) was above \( A \) (Figure 9-a), then the tomato's path would be calculated algebraically as a projectile. If a bounce occurred such that the maximum bounce height was less than \( A \) (Figure 9-b and 9-c), integration calculated the tomato's path.
Figure 9

Paths of motion for a particle bouncing on a vibrating plate.
5.0 EXPERIMENTAL PROCEDURES

5.1 Coefficient of Kinetic Friction Tests

5.1.1 General

From Equations 1, 3, and 11 (Section 4.1), it is obvious the kinetic coefficient of friction is an important parameter affecting sorting. The value of \( \mu \) (coefficient of kinetic friction) directly influences the magnitude of the frictional force. Since sorting depends on the red tomato moving up the vibrating plate, and this movement depends on the frictional force, the coefficient of kinetic friction is needed.

Figure 10 shows the apparatus used to measure the coefficient of kinetic friction. From this figure, notice that the tomato was held securely by a laboratory clamp preventing it from rotating. An aluminum plate was moved under the tomato at a constant velocity. The coefficient of kinetic friction was then evaluated by dividing the measured frictional force into the known normal force.

Figure 10

Coefficient of kinetic friction test apparatus.
5.1.2 Equipment Used

1. Proving ring (10.16 cm in diameter, .1588 cm thick, and 1.27 cm wide) with four strain gages
2. Deltron, series RP power supply
3. Digitec, HT series, 2210 multimeter voltmeter
4. Bay power amplifier
5. Gould, Brush 220 Recorder
6. Filter containing a variable resistor, R, ranging from 0 to 1 meg Ω and a 1 mf capacitor
7. Friction table hydraulically driven at a constant linear velocity

Figure 11 shows how the equipment was connected.

![Diagram](image)

Figure 11

Wiring diagram for coefficient of friction tests.

The resistances shown in the wheatstone bridge were strain gages mounted on a standard proving ring (Cook, 1963).
5.1.3 Procedure

Before tests were run, the electronic equipment was allowed to warm up at least one hour. Care was taken to make sure the power supply maintained a constant voltage of 10 ± .01 volts.

The proving ring was calibrated in the vertical position with masses of known weight. A change in output was measured by the recorder, then a plot of force (grams) verses output (millivolts) was constructed. The slope of this line (grams/mv) represented the sensitivity of this proving ring. This calibration test was conducted before and checked after the experiments were run.

The tomatoes used in these tests were picked the same day the tests were run. The only exception to this was for the tests when the tomatoes were wiped with acetone. These tomatoes were picked the day before the tests were run. All tomatoes used were wiped with a damp cloth to remove the dirt, then dried with a clean cloth. Once dry, the tomatoes were only handled with clean cotton gloves.

Figure 12 shows a close up of the device that held the tomato and the proving ring used in the experiments. The weights (steel washers) in the upper portion of Figure 12 serve as counter weight to balance the laboratory clamp and bar. This allowed only the weight of the tomato to be used in determining μ.

Figure 12 also shows the string used to connect the proving ring to the clamp. String was used to eliminate the
possibility of torque being transmitted from the clamp to the proving ring. Care was taken when positioning the clamp on the tomato so the pull was always horizontal.

![Figure 12](image)

**Figure 12**

Laboratory clamp used to hold the tomato.

This string was 2.54 cm above the plate; therefore, the proving ring measured a force that was actually greater than F. To take this into account, the force measured on the proving ring was multiplied by 0.92 (a factor determined by summing moments about the pivot point at the top of the clamp).

The two pivot points shown in Figure 12 had shielded ball bearings to reduce friction in the linkage. These bearings minimized rotational torque resistance in the linkages.

In the upper right hand corner of Figure 12 is a bolt
on the pivot bar used to attach the weights so the normal 
force could be varied. The additional weight that was 
applied to a tomato was determined by placing the end of 
the holding clamp on a top loaded balance. Either 104.3 or 
267.1 grams of additional weight was applied. 

The velocity at which the plate moved underneath the 
tomato was calculated by measuring the time for the plate 
to move 76.20 cm. The velocity was then calculated by 
dividing the 76.20 cm by the time. Except for Section 
7.1.9 (Effect of Sliding Velocity Between the Tomato and 
Plate), the velocity was maintained at 5.79 cm/sec. 

After every four or five runs, the plate was wiped 
with acetone to keep it clean so wax did not build up on the 
plate. At first the plate was wiped after every test but 
it was found that several tests could be run between cleaning 
without affecting the test results. 

All tomatoes picked for these tests came from the Ohio 
State University horticulture farm except for those picked 
on 9/14/77 and 9/28/77. They came from the Ohio Agricultural 
Research and Development Center's Northwestern Branch 
located near Custar, Ohio. 

5.1.4 Interpretation of the Data 

A typical output from the recorder appears in Figures 
13 and 14.
Figure 13
mv verses time for a green tomato sliding on an aluminum surface.

Figure 14
mv verses time for a red tomato sliding on an aluminum surface.

On these graphs, a line was drawn which represents the average force. The following equation was used to calculate $\mu$:

$$F = (mv_{\text{output}}) \times (S_e) \times (0.92)$$

where

$F = \text{friction force in grams}$
$$S_{en} = \text{sensitivity in grams/mv}$$

$$m_{output} = \text{average mv output},$$

then

$$\mu = F/F_1$$  \hspace{1cm} (16)

where

$$F_1 = \text{weight of the tomato (grams) plus any additional weight added.}$$

5.1.5 Checking the Experiment

The equipment was checked by replacing the tomato by a piece of square cold rolled steel to determine if the coefficient of kinetic friction was .47 (aluminum on mild steel) as listed by Bolz and Tuve (1970). When these tests were run, the coefficient of kinetic friction ranged between .37 to .56 with an average of .46. It should be noted that the output trace was more irregular than the trace shown in Figure 13 indicating a stick-slip phenomena.

5.2 Impulse Tests

5.2.1 General

For the computer model, a tomato was represented by a Kelvin model. For this model, the spring coefficient (K) and the damping coefficient (B) needed to be evaluated. One possible way to determine these parameters was by dropping
tomatoes on a force transducer and calculating the coefficient of restitution. With the drop height, time of contact, and coefficient of restitution, K and B could be found by using the computer model developed by Bayer (1976).

There was an added advantage to this procedure in that a permanent impulse trace could be obtained. Figure 15 shows the apparatus used to obtain this trace.

![Image of impulse test apparatus](image)

**Figure 15**
Impulse test apparatus.

5.2.2 **Equipment Used**

1. Wilcoxon Force Gage, model L-10
2. Tektronix 5403 Oscilloscope with polaroid camera
3. Kistler Dual Mode Amplifier, Model 504E

Figure 16 shows how the equipment was connected.
5.2.3 Procedure

Before tests were run, the equipment was allowed to warm up at least one half hour. The force transducer was bolted in the center of a 88.0 cm long section of C6X8.2 American Standard Channel Iron. This channel iron was clamped to the top of a 1.83 m long, 76.2 cm wide, and 3.81 cm thick maple table.

The calibration of the force transducer (from manufacturer) was checked two ways. The first calibration check was made by placing weights on the transducer. Since the force transducer only measured dynamic force and no static forces, the charge amplifier was adjusted to the long time constant so the discharge time would be long. The weights were lifted off as quickly as possible and the output on the oscilloscope observed. Finally, the output (mv) was divided by the weight removed to obtain the sensitivity (mv/N).

The second check was made by mounting the force transducer
on the electrodynamic shaker. The weight of the active element inside the transducer was known (other weights were added to the transducer for different checks) and the maximum acceleration of the shaker was held constant. Knowing \( F = ma \), converting the weight to mass and multiplying by the acceleration, the force was obtained. Finally, this force was divided into half of the peak to peak output on the scope to get sensitivity.

The impulse tests were conducted by holding the tomatoes 15.24 cm above the force transducer and dropping them on the plate (see Figure 17). The impact of the tomato on the force transducer caused a mv impulse curve to be generated which was recorded by the oscilloscope.

The oscilloscope was adjusted for a single sweep and triggered the instant the tomato hit the plate. A polaroid camera was used to obtain a picture of the impulse in terms of millivolts versus time (sec).

5.2.4 Interpretation of the Data

A typical output from the oscilloscope is shown in Figure 17.
Figure 17

Typical impulse curve of a tomato.

Since the manufacturer's specification for the stiffness of the force transducer was greater than $5 \times 10^6$ lb/in, the first assumption was that the movement of the 9.8 gram plate on top of the force transducer was negligible. Thus, from the definition of the coefficient of restitution:

$$e = \frac{V_1}{V_0} \quad (17)$$

where

$V_1$ = absolute velocity of the tomato just after impact, cm/sec,

$V_0$ = absolute velocity of the tomato just before impact, cm/sec,
and \( e = \text{coefficient of restitution of the tomato.} \)

Relating the velocities in terms of drop and rebound heights, one gets:

\[
V_1 = \sqrt{2gh_1} \quad (18)
\]

and

\[
V_0 = \sqrt{2gh_0} \quad (19)
\]

where

\( h_1 = \text{rebound height of the tomato}, \)

\( h_0 = \text{drop height of the tomato}, \)

and \( g = \text{acceleration due to gravity}. \)

Summing momentum results in

\[
\int F_s \, dt = m(V_1 + V_0) \quad (20)
\]

where

\( m = \text{mass of the tomato} \)

and \( F_s(t) = \text{contact force between plate and tomato as a function of time}. \)

Combining equations 16 and 17 and calculating the area under the impulse curve with a planimeter, the coefficient of restitution can be evaluated by the following equation:

\[
e = \frac{A_1}{mV_0} - 1 \quad (21)
\]
where

\[ A_1 = \text{area under the force vs. time impulse curve (N-sec)} \]

Using this equation and analyzing the impulse data, coefficients of restitution were found which were consistently larger than those for simple drop tests (ratio of \( \sqrt{h_1}/\sqrt{h_0} \)). One reason for this could be due to the velocity of the plate \( V_2 \) not being zero. From the definition of the coefficient of restitution, one can write

\[ e = \frac{V_1 - V_2}{V_0} \]

Notice, if \( V_2 \) were not zero, then the coefficient of restitution would be smaller. Thus, \( V_2 \) needed to be evaluated.

The following illustration shows the momentum balance.

Initial Momentum + Momentum change = Final Momentum due to impact

Then,
where

\[ m_2 = \text{mass of active element in force transducer} \]
\[ = 48.8 \text{ grams} \]

\[ F(t) = \text{force between tomato and transducer during contact}. \]

The equations of motion were written by summing momentum, taking to the right as positive. This results in

\[ - \int F dt = -m V_1 - m V_0 \quad (22) \]

\[ \int F dt - \int F_s dt = m_2 V_2 \quad (23) \]

Adding equations 22 and 23 gives:

\[ \int F_s dt = m \ (V_1 + V_0) - m_2 V_2 \]

Dropping a tomato on the transducer resulted in a response that was a combination of a tomato and transducer \( F_s(t) \). To get the response of a tomato alone \( F(t) \), the response of the transducer alone needed to be determined.

When a steel ball was dropped on the transducer, the transducer did not respond fast enough mechanically to give the true impulse response of the steel ball. Therefore, the impulse curve obtained had to be the response of the transducer.

Fourier transformation was then used to normalize the \( F_s(t) \) curve to get \( F(t) \). It was carried out in the following steps:
1. The fourier transform of \( F_s(t) \) (response of tomato and transducer) was found.

2. The fourier transform of the response of the transducer was found.

3. The transform of the response of the transducer was divided into the transform of \( F_s(t) \).

4. The inverse of the result in step three was found. It was \( F(t) \), the response of the tomato.

The two curves, \( F_s(t) \) and \( F(t) \), were compared and found to be almost identical. From this analysis it was proven that \( V_2 \) was so small during impact that it could be assumed to be zero. Thus, for this study equation 21 is valid.

5.3 Determination of Fruit Size

5.3.1 General

In the computer program the approximate size of a tomato was needed. The apparatus shown in Figure 18 was used to measure the size of a tomato.

![Figure 18](image)

Tomato sizer.
5.3.2 Procedure

A tomato was placed in the corner and a wood block was brought in contact with it. The diameter of the tomato was then read off the grid (marked in centimeters).

Each tomato was measured at three orientations (two equatorial and one axial diameters).

5.4 Preparation of Tomato Surfaces for the Scanning Electron Microscope

5.4.1 General

From the coefficient of kinetic friction tests, the average coefficient of kinetic friction, $\mu$, for a green tomato was 1.71 on a dry aluminum plate. A coefficient of kinetic friction above one suggested the hypothesis that an adhesive effect existed between the green tomato and the aluminum plate. The Cambridge S4-10 scanning electron microscope was used to observe red and green tomato surfaces to look for evidence to explain the high coefficient of kinetic friction for green tomatoes.

5.4.2 Procedure

The tomatoes were picked the day before the test specimens were prepared for examination. One set of fruit came from the Ohio State University Horticulture farm and the second set was from the Ohio Agricultural Research and
Development Center's Northwestern Branch near Custar, Ohio. From the first set, the test specimens were cut at random from the side of the tomatoes. For the second set, care was taken to cut the test specimens from the shaded or exposed side of the tomato with respect to sunlight as the tomato grew in the field. If the shaded side samples had dirt on them, they were wiped with a damp towel prior to cutting the test specimen. The samples were cut by a razor blade to approximately 0.5 cm square and 0.25 to 1.0 mm in thickness.

The samples were prepared as outlined in the fixation procedure shown in Appendix B-1. In the critical point drying procedure, carbon dioxide was used as the transitional fluid.

Finally, the samples were mounted and gold coated by the vacuum evaporation procedure. The samples were then observed through the scanning electron microscope and polaroid pictures taken of the observations.

5.5 Electro-dynamic Shaker

During the Summer of 1976, a flat aluminum plate (Figure 19) was mounted on an Unholtz-Dickie electro-dynamic shaker (Control Console Model SP-2CD, Oscillator Model OSC-1, Power Amplifier Model TA30). Tests were run to see if a vibrating flat plate could separate tomatoes based upon firmness.
Various angles of tilt of the plate ($\theta_1$) were tested, the angle of tilt of the shaker ($\theta_2$) was maintained at $70^\circ$. The frequency ranged from 20 to 120 Hz and the amplitude ranged from 0.127 to 0.381 cm. Several tomato varieties were tested.

![Diagram of electro-dynamic shaker](image)

**Figure 19**

Flat plate on electro-dynamic shaker.

5.6 **Prototype Tomato Sorter**

5.6.1 **General**

The tests done on the electro-dynamic shaker proved so successful that a prototype tomato sorter was built to further investigate the possibility of sorting tomatoes using an inclined vibrating plate (Figure 20). This experimental sorter was used to verify the assumptions and test the parameters used in the theoretical model.
Figure 20

Experimental inclined vibrating plate tomato sorter.

5.6.2 **Equipment Used**

1. Experimental inclined flat plate tomato sorter
2. Tachlite (Strobe light)
3. Level
4. Meter stick

5.6.3 **Procedure**

The aluminum flat plate (61 cm long by 48 cm wide) was
driven by a 2 Hp variable speed motor shown in Figure 20. Figure 21 is a schematic of how the flat plate was driven by three eccentric shafts.

![Figure 21](image)

**Figure 21**

Drive unit on flat plate.

This arrangement was used to achieve the types of motion that were needed. For circular motion, the offset for all three shafts was in the same direction (Figure 22). For straight line motion, shaft #1 was 90° out of phase from shafts #2 and #3 (Figure 22).

![Figure 22](image)

**Figure 22**

Types of motion for the prototype sorter.
The speed of the aluminum plate was measured by a strobe light. Physical limitations of the apparatus limited the peak speed to 80 Hz.

From Figure 20, it can be seen that an aluminum honeycomb material was glued between two aluminum plates to stiffen the flat plate. The static amplitude (peak to peak) was 0.277 cm. Dynamically, deflections increased with frequency. The dynamic deflections were determined by using the accelerometer from the electro-dynamic shaker and reading the peak to peak displacement from the servo-programmer. Appendix D-1 shows the results.

For each sorting test the following sequency of events took place:

1. The aluminum plate was cleaned with acetone.
2. The angle of tilt of the plate was adjusted.
3. The motor was turned on and adjusted to the desired speed.
4. The tomatoes were placed on the flat plate by hand.
5. Observations were made.
6. The speed was reduced and the motor turned off.

The angle of tilt of the plate was adjusted by the turn buckles shown in Figure 20. A level and a meter stick were used to determine the actual angle.

The flat plate was tested for two different cases. For the first case the plate was clean and dry (procedure described
above). For the second case the plate was wetted with water. The only difference from the above procedure for this case was that the tomatoes were in water before they were put on the plate. The plate was also re-wetted between runs.
6.0 EXPERIMENTAL TOMATO SORTER RESULTS

6.1 Electro-dynamic Shaker Results

Appendix C (parts 1-7) shows the results that were obtained for three different varieties of tomatoes (Heinz 1350, Ohio 7624, and Ohio 7669). From these tables, the following general observations were made:

1. Tomatoes moved up the plate when the frequency of the plate was above the natural frequency of the tomatoes and the angle of tilt of the plate ($\theta_1$, Figure 19) was not greater than 90°. When the angle was greater than approximately 90°, the gravity force overcame the frictional force and pulled the tomato down the plate. The maximum angle of tilt is related to frequency. The higher the frequency, the greater the angle of tilt.

2. The green and red tomatoes bounced down the plate when the frequency of the plate was below the natural frequency of the tomatoes.

3. The velocity at which the red tomato moved up the plate increased by either increasing the frequency, the amplitude, or by decreasing the angle ($\theta_1$) of the plate.

4. Ohio 7624 (small oval tomatoes) did not sort well; whereas, Ohio 7669 and Heinz 1350 (round tomatoes)
were separated into red and green fractions. The shape of the tomato appeared to be the limiting factor in sorting.

5. For Heinz 1350 tomatoes, sorting was successful for tilt angles of $\theta_1 = 3^\circ$ and $\theta_2 = 70^\circ$, amplitudes greater than 0.127 cm, and frequencies between 60 to 120 Hz.

6. For Ohio 7669 tomatoes, sorting was successful for tilt angles of $\theta_1$ between $3^\circ$ and $8^\circ$ and $\theta_2 = 70^\circ$, amplitudes from .2032 cm to .2794 cm, and for frequencies between 70 to 90 Hz.

These observations led to the conclusion that tomatoes can be separated using an inclined vibrating flat plate where red tomatoes move up the plate and green tomatoes bounce down.

6.2 Prototype Sorter Results

6.2.1 Vibrating Plate Tomato Sorter

Various angles (0° to 7°) and frequencies (10 to 78.3 Hz) were tested. The forcing functions tested were circular and straight line motion. The results appear in Figures 23 and 24 and Appendix D (parts 2-5).

From these tests, general observations were:

1. Using circular motion, plate dry
   a. As frequencies increased, the bounce heights
Arrow to left of dot = green tomato
Arrow to right of dot = red tomato

Ohio 7669

Amp. is a function of frequency (Appendix D-1)

\[\text{\uparrow} = \text{Up the plate}\]
\[\text{\downarrow} = \text{Down the plate}\]
\[\rightarrow = \text{Does not move}\]

Figure 23
Movement of Ohio 7669 tomatoes on the prototype sorter with a circular forcing function.
Figure 24

Movement of Ohio 7669 tomatoes on the prototype sorter with a straight line.

Arrow to left of dot = green tomato
Arrow to right of dot = red tomato

Amp. is a function of frequency (Appendix D-1)

↑ = Up the plate
↓ = Down the plate
← = Does not move

Tilt of Plate (Degrees)

Frequency (Hz)
of green tomatoes increased.

b. The red tomato stopped bouncing when the frequency of the plate was above the natural frequency of the red tomato.

c. When sliding, the red tomato rotated in a direction opposite to the circular motion of the plate (Figure 25).

\[\text{Diagram:} \]

- Direction of red tomato rotation
- Direction of movement
- Tomato
- Angle of tilt
- Circular motion of plate

Figure 25

Motion of a red tomato on a vibrating plate with circular motion.

d. Of the parameters tested, sorting was best at a frequency of 72 Hz and an angle of tilt of 4°.

e. The area circled in Figure 23 shows where tomatoes moved either up or down the plate. Tomatoes (red and green) below this area moved up the plate. Above this area they moved down the plate.
2. Circular motion, surface wet
   a. Green tomatoes bounced as described above for the surface dry.
   b. Water had a tendency to bead on the vibrating plate. In areas where the water did not bead, the red tomatoes moved similar to those in Figure 23. When the red tomato hit areas where a water bead was located, the red tomato moved down the plate for angles of tilt $> 1^\circ$.
3. Straight-line motion, plate dry
   a. The red tomato moved up the plate and did not rotate.
   b. The green tomatoes bounced similar to that described above for the surface dry.
   c. For straight-line motion, sorting was best at a tilt angle of $4^\circ$ and a frequency of 72 Hz. The red tomatoes moved up the plate, whereas the green tomatoes bounced up or down the plate. In comparing the case of circular motion to straight-line motion at the same settings, circular motion gave more accurate sorting.

   In another test the plate was tilted in two directions ($\theta_1$ and $\theta_3$) as shown in Figure 26. For this test, $\theta_3$ was $3.2^\circ$ and $\theta_1$ was $1^\circ$. The vibrational frequency was 75 Hz and a circular forcing function was applied.
The results were as follows:

1. The red tomato rotated opposite the plate (Figure 25) and moved in the direction as shown in Figure 26.
2. The green tomatoes bounced with a vertical motion of three to four inches and had a tendency to move as shown in Figure 26.

6.2.2 Vibrating Plate Tomato Sorter with Restraining Bar

From the previous section, when there was water on the plate, sorting did not take place due to the change in the frictional force. Therefore, it was concluded that drastic reductions in the coefficient of friction would eliminate sorting. Another way to utilize the flat plate as a sorter
is to use a set of restraining bars across the plate as illustrated in Figure 27. This should make it possible to sort tomatoes even if the coefficient of kinetic friction is significantly less due to a wet plate. It should also widen the range of angles in which sorting should occur.

The influence of a restraining bar was tested by mounting one bar on the plate as shown in Figure 28. It was made out of cardboard (1.27 cm high and 1.27 cm wide) and was glued to the aluminum plate.
Figure 28

Flat plate sorter with cardboard bar.

One test was conducted with this arrangement where $\theta_1 = 90^\circ$, $\theta_3 = 1^\circ$, and the frequency was 70 Hz. The results were as follows:

1. The red tomato vibrated back and forth against the cardboard bar and gradually moved along in the Z direction.
2. The green tomato bounced against the bar a few times before bouncing over the bar and down the plate (-x direction).
7.0 RESULTS AND DISCUSSIONS

7.1 Coefficient of Kinetic Friction

Tests evaluating the coefficient of kinetic friction were conducted and the results were unexpected. The data in Figure 29 indicates that the average coefficient of kinetic friction was consistently above one for green tomatoes. When the three tests (8-12, 8-23, and 9-6) were averaged together, the coefficient of kinetic friction for green tomatoes was as follows:

<table>
<thead>
<tr>
<th></th>
<th>Average</th>
<th>Variance</th>
<th># of Runs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Side</td>
<td>1.79</td>
<td>0.2088</td>
<td>57</td>
</tr>
<tr>
<td>2. Blossom End</td>
<td>1.59</td>
<td>0.3355</td>
<td>42</td>
</tr>
<tr>
<td>3. Stem End</td>
<td>1.71</td>
<td>0.2452</td>
<td>42</td>
</tr>
<tr>
<td>4. Average of 1, 2 &amp; 3</td>
<td>1.71</td>
<td>0.2605</td>
<td>141</td>
</tr>
</tbody>
</table>

Also, the coefficient of kinetic friction for the red tomatoes was:

<table>
<thead>
<tr>
<th></th>
<th>Average</th>
<th>Variance</th>
<th># of Runs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Side</td>
<td>.74</td>
<td>0.0190</td>
<td>53</td>
</tr>
<tr>
<td>2. Blossom End</td>
<td>.71</td>
<td>0.0567</td>
<td>36</td>
</tr>
<tr>
<td>3. Stem End</td>
<td>.87</td>
<td>0.0359</td>
<td>36</td>
</tr>
<tr>
<td>4. Average of 1, 2 &amp; 3</td>
<td>.77</td>
<td>0.0383</td>
<td>125</td>
</tr>
</tbody>
</table>
Figure 29
Effect of harvest date on the coefficient of kinetic friction for Ohio 7669 tomatoes.
From these results it was apparent that the coefficient of kinetic friction for green tomatoes was approximately two to two and one-half times greater than for red tomatoes.

7.1.1 Effect of Harvest Date

Data in Figure 29 shows the affect of harvest date on the kinetic coefficient of friction. No correlation between the coefficient of kinetic friction and the harvest date was found. Figure 29 does indicate that the average coefficient of kinetic friction for the stem end was consistently higher than for the blossom or side. The green tomatoes showed no such correlation.

The variance and range of the coefficient of kinetic friction for green tomatoes increased when picked later in the season, as shown in Appendix E-1. The data for red tomatoes does not show this increase in the variance and range.

7.1.2 Effect of Tomato Mass

Ohio 7669 was used for these tests and only the sides of the tomatoes were tested. The data (Figure 30) suggests that there is no correlation between size and the coefficient of kinetic friction for green tomatoes. For the red tomatoes, the coefficient of kinetic friction decreased slightly as the weight increased. It was originally hypothesized that the smaller green tomatoes
Variety: Ohio 7669

= Red, Harvested and Tested: 8-12-77
= Green, Harvested and Tested: 9-6-77
= Green, Harvested and Tested: 8-12-77

Velocity: 5.79 cm/sec
Aluminum plate, clean and dry

Effect of tomato weight on coefficient of kinetic friction.
would have a higher coefficient of kinetic friction than larger ones. The same should also hold true for red tomatoes.

These results suggest that the coefficient of kinetic friction changes as the tomato color changes during the ripening process. This suggests the need for tests using partially-ripe tomatoes (tomatoes showing both red and green color).

7.1.3 Partially-Ripe Tomato Tests

Appendix E-2 shows the value of the coefficient of kinetic friction for partially ripe Campbell 28 tomatoes. From this table, it is apparent the coefficient of kinetic friction for the green stem end was always higher than for the red blossom end, except for tomato #11. For tests run on the red and green spots on the sides of these tomatoes, there was no correlation.

Data in Appendix E-3 shows values of the coefficient of kinetic friction for the red and green spots for Chico III tomatoes. Generally, the coefficient of kinetic friction for green spots was higher than for red spots.

Appendices E-2 and E-3 indicate that the coefficient of kinetic friction changes during ripening. Changes in color were not a good indicator of changes in the coefficient of kinetic friction. The coefficient of kinetic friction values (Appendices E-2 and E-3) for the red spots were generally higher than the values for the coefficient of kinetic friction.
in Appendix E-5. The coefficient of kinetic friction for green spots was approximately the same. This leads to the speculation that a chemical and/or physical change takes place as the tomato ripens which results in a reduction in the surface friction coefficient.

7.1.4 Effect of Normal Force

During sorting the inclined plate vibrates causing the normal force that a tomato experiences to vary from zero to a maximum value determined by the previous bounce height, plate amplitude, frequency, and position when contact occurs. Therefore, a study was conducted to see if increasing the normal force had any effect on the coefficient of friction. Figure 31 and Appendix E-4 show the results of these tests for Ohio 7669.

Figure 31 indicates there was not much change in the coefficient of kinetic friction as the normal force was increased. In general, the coefficient of kinetic friction for the red tomato increased slightly with increased normal weight while the range and variance did not change much (Appendix E-4). The green tomatoes showed a decrease in range and variance as the normal force was increased, but virtually no change in the coefficient of kinetic friction.

This observation can be explained in terms of the amount of deformation a tomato experiences. Red tomatoes
Figure 31
Effect of normal force on the coefficient of kinetic friction.

- ○ = Side of tomato touching plate
- △ = Blossom end of tomato touching plate
- □ = Stem end of tomato touching plate

Velocity:
5.79 cm/sec

Conditions:
- Aluminum plate
- Clean and dry

Variety:
Ohio 7669

Date tested:
9-6-77
are softer than green tomatoes; therefore, the red tomatoes deform more with increasing normal force which results in a larger area of contact. According to $\mu = F/P$, the area of contact between two particles does not affect the coefficient of friction. In reality, it is known that a larger area of contact will cause the coefficient of friction to increase (Mohsenin, 1970). This reasoning could explain why increasing the normal force causes $\mu$ to increase slightly for red tomatoes and not for green tomatoes.

7.1.5 Effect of Tomato Variety

All of the tests discussed so far were with Ohio 7669 tomatoes. Other varieties were also tested to see if the observed changes in the coefficient of kinetic friction with ripening was a variety effect or if it appeared in other varieties as well.

Appendix E-5 shows the results for Ohio 7669, Chico III, and Campbell 28 tomatoes. For Ohio 7669 and Chico III, the ratio of $\mu_{\text{green}}/\mu_{\text{red}}$ was from two to three. For Campbell 28, it was from 1.6 to 1.8. Thus, for these three varieties the ratio of $\mu_{\text{green}}/\mu_{\text{red}}$ was quite large indicating the effect from ripening was common to all three. The coefficient of kinetic friction for the green tomatoes for Campbell 28 was also above one, while some tests on green Chico III gave values less than one.
7.1.6 Effect of Wiping Surface of Tomato with Ether

The coefficient of friction data suggested there was something on the surfaces of green tomatoes that caused the coefficient of kinetic friction to be larger than one. One possibility could be an adhesive effect due to the wax on the surface of tomatoes.

To test this hypothesis, one test was run to find the coefficient of kinetic friction for a tomato. A second test was conducted with the same tomato surface touching the plate but with the surface cleaned with ether.

Results of these tests (Appendix E-6) show that the coefficient of kinetic friction increased when the tomatoes (red and green) were wiped with ether. The ratio of the average increase was as follows:

<table>
<thead>
<tr>
<th>Red Tomatoes</th>
<th>Green Tomatoes</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu_{\text{ether}} = \frac{.92}{.62} = 1.48$</td>
<td>$\mu_{\text{ether}} = \frac{2.65}{1.77} = 1.50$</td>
</tr>
</tbody>
</table>

7.1.7 Effect of Wiping Surface of Tomato with Acetone

For this test, acetone was used in place of ether because acetone is a polar solvent and ether is a non-polar solvent and, thus, acetone and ether dissolve different types of organic compounds. The same spot on the surface of the tomato was tested before and after cleaning with
acetone.

After the acetone was applied, the tomatoes had a higher coefficient of kinetic friction (Appendix E-7). The ratio of the increase is as follows:

<table>
<thead>
<tr>
<th></th>
<th>Red Tomatoes</th>
<th>Green Tomatoes</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mu_{\text{acetone}} )</td>
<td>1.11</td>
<td>3.22</td>
</tr>
<tr>
<td>( \mu )</td>
<td>0.79</td>
<td>2.53</td>
</tr>
</tbody>
</table>

\[
\frac{1.11}{0.79} = 1.41 \quad \frac{3.22}{2.53} = 1.27
\]

The ratio of the increase for the red tomato was approximately the same as the increase when ether was applied. But, the increase in \( \mu \) for the green tomato was not as much with acetone as it is with ether.

The waxes on the surface of tomatoes are soluble in ether or acetone (Kretchman, 1977). Wiping the surface of a tomato with ether or acetone caused the coefficient of kinetic friction to increase; therefore, wax on the surface lowered the coefficient of friction. This led to the conclusion that wax on the surface was not the reason for the high coefficient of kinetic friction measured for green tomatoes.

7.1.8 Effect of the Plate Surface

In all the previous tests the plate was always kept clean with acetone. If the vibrating flat plate sorter was in actual operation, the plate would be expected to get soiled
with dirt, tomato juice, water, etc. Therefore, a test was conducted to determine the effect of dirt, water, and tomato juice on the coefficient of kinetic friction.

Data in Appendix E-8 shows that when the plate was dirty and had tomato juice on it, the coefficient of kinetic friction was the same for red and green tomatoes. The coefficient of kinetic friction for the red tomato was lower when the plate was wetted with water than when the plate was dirty and had tomato juice on it. Interestingly, the reverse was true for green tomatoes. This research did not provide a satisfactory explanation for this phenomena.

7.1.9 Effect of Sliding Velocity Between Tomato and Plate

Two tests were conducted with velocities of the aluminum plate at 6.25 cm/sec and 20.12 cm/sec. The results (Appendices E-9 and E-10) show that increasing velocity decreased the coefficient of kinetic friction. The accuracy of the data are questionable because at the higher velocity, the tomatoes bounced around considerably during the test.

7.2 Impulse Tests

Equation 16, from the experimental procedure section 5.2, was used to calculate the coefficient of restitution. Table 1 shows the values obtained.
Table 1

Impulse test results for Ohio 7669.

<table>
<thead>
<tr>
<th></th>
<th>Average e</th>
<th>Highest e</th>
<th>Lowest e</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red Tomatoes</td>
<td>.69</td>
<td>.84</td>
<td>.44</td>
</tr>
<tr>
<td>Green Tomatoes</td>
<td>.90</td>
<td>1.18</td>
<td>.67</td>
</tr>
</tbody>
</table>

As expected, the coefficient of restitution was higher for green than red tomatoes. However, these coefficient of restitution values are unrealistically high. Observations of drop tests indicated the coefficient of restitution should be in the range of .2 to .4.

Other objects were dropped on the force transducer besides green and red tomatoes. There were onions, clods, puddy, plastic balls, and steel balls. Figure 32 shows the general results of these tests. The harder the object, the larger the peak force and the shorter the time of contact. Also, the larger the coefficient of restitution, the larger the area under the force-time curve.

Since reasonable coefficients of restitution were not found, the spring constant and the damping coefficient of a tomato was not determined. For the computer model, therefore, the spring constant (K) was determined by finding the natural frequency of red and green tomatoes (Ohio 7669). In previous work done by Stephenson (1973) and Singh (1972), the natural frequency for tomatoes was determined by
Weight = 50 grams
Dropped from
15.24 cm

Figure 32
Impulse curves of various items.
positioning the fruit between two surfaces. One surface was fixed and the other one vibrating. Bayer (1976), on the other hand, dropped tomatoes on a surface and determined the natural frequency by assuming a Kelvin model.

The tomato model used by Stephenson (1973) and Singh (1972) would in effect be a lumped mass between two springs. One spring would be rigidly attached and the other spring forced. The natural frequency of this system is $\sqrt{2k/m}$. Bayer's (1976) natural frequency is $\sqrt{k/m}$. The difference between the two models is $\sqrt{2}$ which is probably one of the reasons Singh (1972) and Stephenson (1973) reported higher natural frequencies for tomatoes than did Bayer (1976). Since the tomato in this study was modelled as a Kelvin Model (Figure 4) and only one surface of the tomato contacted the aluminum plate, Bayer's data was used to determine K and B.

After vibrating Ohio 7669 tomatoes on an electro-dynamic shaker, it was determined that the natural frequencies of red and green tomatoes were 55 Hz and 155 Hz, respectively. Applying $k = \omega_n^2 m$, the stiffness was determined to be 72.23 N/cm for red and 368.00 N/cm for green tomatoes. Bayer (1976) recorded values of stiffness and damping for Heinz 1439. After interpolating his data, damping coefficients of 0.30 N-sec/cm for red tomatoes and 0.35 N-sec/cm for green tomatoes were determined.
7.3 **Size of the Fruit**

Three varieties of tomatoes (Ohio 7669, Campbell 28, and Chico III) were dimensioned and weighed. The data for these tests are shown in Appendix F-1. The following conclusions can be made from this data:

1. A red tomato has a larger radius and weight than a green tomato.

2. Ohio 7669 is a round tomato with an average experimental diameter of 4.9 cm for red tomatoes and 4.4 cm for green. The average weight for red tomatoes is 60.5 grams and 38.8 grams for green. Theoretical calculations using the densities \( \rho \) of the red and green tomatoes results in smaller average diameters as compared to their experimental diameter. The following calculations show why:

Red Tomato

\[
\rho_R = 1.107 \text{ g/cm}^3 \\
W_R = 60.5 \text{ g} \\
\text{Vol} = \frac{60.5}{1.107} = 54.65 \text{ cm}^3 \\
\frac{4}{3} \pi r^3 = 54.65 \text{ cm} \\
r = 2.354 \text{ cm} \\
d = 4.7 \text{ cm}
\]
Green Tomato

\[ \rho_G = 1.053 \text{ g/cm}^3 \]

\[ W_G = 38.8 \text{ g} \]

\[ V_{ol} = \frac{38.8}{1.053} = 36.85 \text{ cm}^3 \]

\[ \frac{4}{3} \pi r^3 = 36.85 \text{ cm} \]

\[ r = 2.064 \text{ cm} \]

\[ d = 4.1 \text{ cm} \]

These theoretical diameters were used for Section 7.5 (Computer Verification).

The difference between the experimental and theoretical diameter was because the tomato was assumed to be a sphere. Experimentally, this was not true.

3. The axial diameter of Campbell 28 tomatoes are smaller than their equatorial diameter.

4. Chico III tomatoes have axial diameters larger than their equatorial diameters.

7.4 Scanning Electron Microscope

From all of the electron micrograph pictures, there were two observations that were true in nearly all cases. First, the cells of red tomatoes were larger than the cells of green tomatoes (Compare Figures 33 & 34, 36 & 37, and 38 & 39). The increase in size was due to ripening (Khudairi, 1972).
Second, the center of each red tomato cell was depressed when compared to the cell walls (Figures 33, 37, and 38). The green tomatoes generally did not show this characteristic (Figures 37, 35a, 35b, and 39). Figure 36 is an exception to this. From now on the depressed center characteristic will be described as an indentation.

There were believed to be two reasons why red tomatoes showed the indented characteristic. The first reason could be due to the fixation procedure. The second reason could be that this characteristic is an inherent property of red tomatoes.

All of the samples (red and green) from the horticulture farm of The Ohio State University showed the presence of surface wax in strings. (Figure 35a) and a very thin layer of wax. Samples from the Northwest Branch of the Ohio Agricultural Research and Development Center showed a thicker film layer (Figures 33, 34, 35b, 36 and 37) and a very few strings of wax (Figure 35b). Figures 38 and 39 are exceptions. Figure 34 also shows that this film layer can be wiped off.

These strings of wax break down with time (Kretchman, 1977) to form some of the plate-like structures shown in Figures 36 and 37. Another portion of this plate-like structure could be soil debris.

The following is a description of the samples together with specific observations made from the tomato skins of these samples using the scanning electron microscope.
Figure 33
Wax film on surface of red tomato (200X).
(Surface exposed to direct sunlight)

Figure 34
Wax film removed by wiping surface of green tomato with wet paper towel (200X).
(Surface exposed to direct sunlight)
Figure 35a

Strings of wax on green tomato (640X).

Figure 35b

Film of wax on green tomato (200X). (Surface exposed to direct sunlight)
Figure 36
Wax or debris on surface of a green tomato (470X).
(Surface exposed to shade)

Figure 37
Wax or debris on surface of a red tomato (500X).
(Surface exposed to direct sunlight)
Figure 38

Red tomato surface free from wax or debris (500X).
(Surface exposed to shade)

Figure 39

Green tomato surface free from wax or debris (510X).
(Surface exposed to direct sunlight)
1. Samples were cut at random from tomatoes grown at The Ohio State University Horticulture farm.
   a. The red tomatoes exhibited more indented cell centers than the green tomatoes.
   b. The waxy film appeared to be very thin on both the red and green tomatoes (Figure 35a).
   c. There were more long strands of wax on both the red and green tomatoes than the red and green samples from the Ohio Agricultural Research and Development Center's Northwestern Branch (Compare Figures 35a and 35b).

2. Samples were cut from the side of the fruit exposed to direct sunlight from tomatoes grown at the Ohio Agricultural Research and Development Center's Northwestern Branch.
   a. The red samples tended to show more wax clumps or debris than the green samples.
   b. The red samples showed that the center of the cells were indented compared to the green samples (Compare Figures 33 and 34).
   c. A few strings of wax were on the green samples; whereas, none were on the red samples (Figure 35b).

3. Samples were cut from the side of the fruit facing away (shaded) from the sun. These tomatoes were grown at the Northwestern Branch.
   a. The cells in both the red and green shaded samples
seemed to be equally indented (Figures 36 and 38).

b. The green shaded tomatoes seemed to have more clumps of wax or debris on them (Figures 36 and 38).

4. Samples were cut from the side of red fruit shaded from and exposed to direct sunlight. The tomatoes were grown at the Northwestern Branch.
   a. In both samples the cells were equally indented (Figures 37 and 38).
   b. The wax film on both samples seemed to be about the same thickness.

5. Samples were cut from the side of green fruit exposed to and shaded from direct sunlight. These tomatoes were grown at the Northwestern Branch.
   a. In the green shaded samples, the cells were indented farther than the cells in the green light samples (Figures 34 and 36).
   b. More wax or debris appeared on the green shaded samples than the green light samples.

It was noted that the shaded side of the tomato had more debris on it than on the side exposed to direct sunlight. One explanation could be that the shaded side of a tomato was more exposed to soil. The side exposed to direct sunlight would be washed off by the rain.

The effect of wax on the surface of the tomato seemed to have very little effect on the coefficient of friction because
no correlation was found between tomato color and quantity of wax on the surface. It should be noted that the cuticular waxes have chain lengths ranging from C_{20} to C_{35} (Hulme, 1970). These chain lengths are too short to be an adhesive (Lynn, 1977). Adhesives typically have chain lengths in the range of polymers (C_{1500}). The effect of wiping the surface of the tomato with ether or acetone indicated that the wax on the surface of the tomato does not cause the high coefficient of kinetic friction (See Appendices E-6 and E-7).

The indented cell characteristic of the red tomatoes was the only visual phenomenon based on the scanning electron microscope samples which appeared to have a possibility of effecting the coefficient of friction. According to equation 16, the area of contact is assumed to have no effect on the coefficient of kinetic friction. In reality this is known to be untrue. Area of contact does effect the coefficient of kinetic friction, because smaller areas of contact result in lower coefficients of kinetic friction.

Since the red tomato was softer, it flattened more when in contact with a flat plate than a green tomato. Also, since the cells of a red tomato were indented, the area of contact would be less. It was not clear how these two effect the coefficient of kinetic friction.

Another phenomenon which could have affected the coefficient of kinetic friction was the oil on the surface of a tomato. Green tomatoes have more oil than red
tomatoes (Kretchman, 1977); therefore, an adhesive effect could exist due to these oils. Further research needs to be conducted to see if this oil affects the coefficient of kinetic friction.

7.5 Computer Verification

The computer program used in this study is found in Appendix A-3. For this computer program, average values for the stiffness, damping coefficient, mass, radius, and coefficient of kinetic friction for a tomato were determined experimentally. The following list shows the average values and the section in which they were determined.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Red</th>
<th>Green</th>
<th>Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>K (stiffness)</td>
<td>72.23 N/cm</td>
<td>368.00 N/cm</td>
<td>7.2</td>
</tr>
<tr>
<td>B (damping co-</td>
<td>0.30 N-sec/cm</td>
<td>0.35 N-sec/cm</td>
<td>7.2</td>
</tr>
<tr>
<td>efficient)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M (mass)</td>
<td>60.5 grams</td>
<td>38.8 grams</td>
<td>7.3</td>
</tr>
<tr>
<td>R (radius)</td>
<td>2.345 cm</td>
<td>2.064 cm</td>
<td>7.3</td>
</tr>
<tr>
<td>μ (coef. of</td>
<td>.77</td>
<td>1.71</td>
<td>7.1</td>
</tr>
<tr>
<td>kinetic</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>friction</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Experimentally, separation of the red and green tomatoes was best at 72 Hz. At 72 Hz the displacement of the vibrating plate was .36 cm (Appendix D-1), so .36 cm was used as the displacement of the plate in the computer model. With this amplitude, theoretical bounce heights from the computer
program agreed closely with experimental bounce heights observed.

Even though average values of the system parameters were determined, a range was used to determine the effect of each parameter on sorting. Stiffness was varied from 64.719 to 552.99 N/cm for a green tomato and from 48.368 to 100.91 N/cm for a red tomato. The damping coefficient was varied from 0.27 to 0.30 N-sec/cm for a red tomato and from 0.30 to 0.40 N-sec/cm for a green tomato. The coefficient of kinetic friction was varied from .2 to 1.71 for a green tomato and from .2 to .77 for a green tomato. Lower coefficients of kinetic friction were chosen because the coefficient of kinetic friction could be expected to decrease when the plate gets dirty or wet. The half amplitude of the vibrating plate was varied from .127 cm to .2 cm (a little below static deflection and above the dynamic amplitude of the plate). The angle of tilt of the plate was adjusted from 0 to 11 degrees. These angles were used because experimental data was collected from 0 to 7 degrees. Four different frequencies were used (200, 350, 439.82, and 550 rad/sec). A frequency of 200 rad/sec was used because it was below the natural frequencies of red and green tomatoes. A frequency of 350 rad/sec was used to determine the effect of higher frequencies in sorting.

The computer results are reported in terms of average velocity which was calculated by dividing the distance a
tomato moved in ten bounces by the time required to move that distance.

Figures 37, 38, and 39 show that as the angle of the flat plate increased, the velocity up the plate decreased. From Figures 38 and 39, as the frequency increased, the velocity increased.

Figure 37 illustrates the general movement of a red and green tomato on an inclined vibrating flat plate. For the green tomato, points every .5 degrees were used to determine the regression line (statistically found). The variability in the points could be due to the following reasons:

1. By chance the tomato hit all the right spots to cause it to always go up or down. Allowing for more bounces of the tomato should cut down the variability.

2. Each run was biased. All tomatoes were bounced up the plate for the first bounce. Initially, the tomatoes were placed on the plate when it was moving to the right and going up.

Figure 39 shows the effect of frequency of the vibrating plate on the movement of the red tomato. When the frequency was at or below the natural frequency of the red tomato, the red tomato bounced down the plate or up very slowly. Operating above the natural frequency caused the red tomato to go up the plate.

Overall, the computer results compared favorably with
Figure 41.

Theoretical response of green and red tomatoes on flat plate vibrating at 439.82 rad/sec and an amplitude of 0.18 cm.
Figure 42

Movement of a green tomato (Ohio 7669) on an inclined vibrating flat plate - theoretical response.
Movement of a red tomato (Ohio 7669) on an inclined vibratory flat plate - theoretical response.

\[ \omega = 200 \text{ rad/sec} \]
\[ \omega = 350 \text{ rad/sec} \]
\[ \omega = 439.02 \text{ rad/sec} \]
\[ \omega = 550 \text{ rad/sec} \]

\[ A = 0.18 \text{ cm} \]
\[ B = 0.77 \text{ g} \]
\[ W = 60.5 \text{ g} \]
\[ B_R = 0.30 \text{ N cm} \]

Figure 43
the experimental results with one exception. For the computer model the angle of tilt of the plate had to be higher for separation to occur than was observed experimentally. Figure 37 shows the predicted range of angles for sorting to occur between 7 and 12.25 degrees. Experimentally, the best sorting occurred at four degrees. Possible reasons for the differences between the computer and experimental models are:

1. Tomato was assumed to be a sphere.
2. Tomato was assumed to fit the Kelvin model.
3. Coefficient of kinetic friction was too high.
4. Stiffness and damping coefficients used in the model do not correctly describe ripe or green tomatoes.

DeCock (1962-1963) stated that geometry of the particle had very little effect on conveying velocity for a vibrating conveyor. This leads me to believe that assuming the tomato to be a sphere is probably a valid assumption. Assumption number two was not checked in this thesis.

The effects of varying the coefficient of kinetic friction (µ) can be seen in Figure 40. As µ decreased, the velocity also decreased for the red tomato. For the green tomato, velocity did not change until over a 2 to 1 reduction was made in µ. This indicates that small changes in µ did not affect sorting for the green tomato. In order for these effects to explain why theoretical results do not agree with
Figure 44

Theoretical effects of coefficient of kinetic friction of tomatoes (Ohio 7669) on an inclined vibrating flat plate.
experimental results, \( \mu \) for a red tomato would have to be approximately .3 to .4. For the green tomato, \( \mu \) would have to be approximately the same. This could explain why theoretical and experimental results do not agree. This suggests that the actual value of \( \mu \) during sorting was probably considerably less than was found experimentally. A more thorough study of \( \mu \) when impact between the tomato and plate is occurring is needed to further explain this phenomena.

Table 1 shows the results of changing the damping coefficients. Notice that decreasing the damping coefficient increased the bounce height. The effects of varying stiffness gave no indication as to its effect on the bounce heights of red and green tomatoes. Also, no conclusion was obtained as to the effect of stiffness on average velocity.

Table 3 shows the effect of changing the amplitude of the vibrating plate. Increasing the amplitude increased the bounce heights and decreased distance and velocity up the plate for green tomatoes.

The number of computer runs were limited because of expense. It cost approximately $12 for each run giving ten bounces of the tomato.
Table 2  
Varying Damping Coefficient

<table>
<thead>
<tr>
<th></th>
<th>B (N-sec/cm)</th>
<th>Average Bounce Height (cm)</th>
<th>Distance up Plate (cm)</th>
<th>Velocity cm/sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red</td>
<td>0.30</td>
<td>0.49</td>
<td>4.0</td>
<td>7.23</td>
</tr>
<tr>
<td>K = 72.23 N/cm</td>
<td>0.27</td>
<td>2.00</td>
<td>35.8</td>
<td>27.40</td>
</tr>
<tr>
<td>Green</td>
<td>0.40</td>
<td>1.74</td>
<td>11.6</td>
<td>9.67</td>
</tr>
<tr>
<td>K = 368.0 N/cm</td>
<td>0.35</td>
<td>2.49</td>
<td>6.8</td>
<td>5.26</td>
</tr>
<tr>
<td>Green</td>
<td>0.40</td>
<td>0.67</td>
<td>10.4</td>
<td>18.20</td>
</tr>
<tr>
<td>K = 153.18 N/cm</td>
<td>0.30</td>
<td>0.82</td>
<td>13.8</td>
<td>19.35</td>
</tr>
</tbody>
</table>

A = .127 cm  
W_R = 60.5 g  
r_R = 2.354 cm  
Angle = 4°  
W_G = 38.8 g  
r_G = 2.064 cm  
\( \omega = 439.82 \text{ rad/sec} \)

Table 3  
Varying Amplitude of Vibrating Plate

<table>
<thead>
<tr>
<th>Amplitude (cm)</th>
<th>Bounce Height (cm)</th>
<th>Distance up Plate (cm)</th>
<th>Velocity cm/sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>.127</td>
<td>1.74</td>
<td>11.60</td>
<td>9.67</td>
</tr>
<tr>
<td>.138</td>
<td>1.88</td>
<td>7.58</td>
<td>8.00</td>
</tr>
<tr>
<td>.200</td>
<td>3.74</td>
<td>-.45</td>
<td>-.304</td>
</tr>
</tbody>
</table>

Angle = 4°  
\( \omega = 439.82 \text{ rad/sec} \)  
B = 0.40 N-sec/cm  
r = 2.064 cm  
K = 368.0 N/cm  
\( \mu = 1.71 \)  
m = 60.5 g
8.0 SUMMARY AND CONCLUSIONS

From this investigation of an inclined vibrating plate tomato sorter, it was concluded that ripe and green tomatoes could be separated. When operating at a frequency between the resonant frequencies of red and green tomatoes the soft ripe tomatoes moved up the plate and firm green tomatoes bounced down the plate. For Ohio 7669 tomatoes, sorting was successful at a plate angle of tilt of 40°, amplitude of .18 cm, and an operational frequency of approximately 72 Hz.

Experimentally, the plate's angle of tilt was found to be very critical in determining whether sorting would occur. Theoretical results verified the experimental results except the angle of the plate was found not as critical and had to be steeper for sorting to occur. Increasing this angle theoretically decreased the velocity at which a tomato would move up the plate.

As the vibrational amplitude or frequency increased, the velocity at which a tomato moved up the plate increased. Increasing the amplitude also increases the bounce heights. Operating frequencies below the natural frequency of a tomato caused them to bounce and frequencies above the natural frequency of red tomatoes caused them to move up the plate.

Experimentally, the presence of water on the vibrating inclined plate was found to limit the possibility of sorting
by causing the red tomatoes to slide down the plate at angles of tilt greater than 1°. Theoretically, it was also shown that decreasing the coefficient of kinetic friction decreased the velocity at which a tomato moves up the plate. An inclined vibratory flat plate equipped with a restraining bar showed potential for sorting under conditions where the coefficient of kinetic friction was very low.

In the course of this study many other parameters were investigated: the coefficient of kinetic friction, size, mass, spring coefficient, and damping coefficient.

The coefficient of kinetic friction varied for each variety and the ratio of $\mu_{\text{green}}/\mu_{\text{red}}$ was from 1.6 to 3.0. An average value for Ohio 7669 tomatoes was 1.71 for green and .77 for red. The wax on the surface of these tomatoes did not account for the high coefficient of kinetic friction.

Normal force, tomato mass, or time of harvest were found to have no significant effect on the coefficient of kinetic friction.

The average diameter of Ohio 7669 tomatoes was 4.1 cm for green and 4.7 cm for red. The average weight was 38.8 g for green and 60.5 g for red. No conclusions were drawn as to the effect of mass or size on sorting.

Coefficient of restitution calculated from impulse tests were unrealistically large when compared to those calculated from drop tests. Therefore, no spring or damping coefficients were computed from the impulse tests data. Theoretically, it
was shown that decreasing damping increased the tomato bounce heights.

Scanning electron microscope observations of tomato surfaces did not provide physical evidence explaining the change in the coefficient of kinetic friction as the tomato ripens.
9.0 RECOMMENDATIONS FOR FUTURE STUDY

1. Additional research is needed to explain why the average coefficient of kinetic friction ($\mu$) was consistently greater than one for green tomatoes. The influence on $\mu$ from oils present on the surface of tomatoes should be clarified.

2. Additional research should be carried out to explain why the coefficient of restitution from the impulse tests did not correspond to the coefficient of restitution from the drop tests.

3. A new inclined vibratory flat plate tomato sorter should be developed with capabilities of operating up to 120 Hz. The flat plate should be equipped with restraining bars to test their influence on sorting. Various horizontal and vertical amplitudes should be tested to determine the optimum sorting.

4. The prototype sorter needs to be tested for different varieties of tomatoes to see what effect tomato shape has on sorting.

5. An in-depth study of the dynamic stiffness, damping and resonance frequency properties of tomatoes needs to be undertaken to further clarify these properties and their influences on vibratory sorting.
Appendix A

Computer Programs

A-1  Computer (CSMP) program for a tomato bouncing on a vibrating inclined plate-constant integration increment

A-2  Computer (CSMP) program of a tomato bouncing on a vibrating inclined plate-variable integration increment

A-3  Computer (CSMP) program of a tomato bouncing on a vibrating inclined plate-integration used when tomato surface below amplitude of plate, algebraic solution when in air

A-4  Definition of symbols used in digital programs
Appendix A-1

Computer (CSMP) program for a tomato bouncing on a vibrating inclined plate-constant integration increment.

TITLE TOMATO BOUNCING ON VIBRATING INCLINED PLATE
* CONSTANT INTEGRATION INCREMENT
METHOD RKSFX
* ALL DATA SHOULD GO INTO THE PROGRAM IN EITHER
* KILOGRAMS, NEWTONS, CENTIMETERS, SECONDS, OR
* SOME COMBINATION
PARAM M = .0605, K = 72.23, B = .30, G = 98.66
PARAM A = .18, R = 2.354, MU = .77
PARAM W = 439.82, ANGLE = 9
INIT
NOSORT
BETA=ANGLE*2.*3.1416/360
ICY=-M*G*COS(BETA)/K
S=W*A*COS(W*TIME)
N=B*(SDOT-Y1DOT)+K*(S-Y)

DYNAM
NOSORT
5 IF(SW-1.0)7,7,6
6 IF(N)20,20,10
7 IF(S-Z)10,10,20
* PARTICLE IN CONTACT
10 SDOT=W*A*COS(W*TIME)
Y2DOT=N/M-G*COS(BETA)
N=B*(SDOT-Y1DOT)+K*(S-Y)
SW=2.0
GO TO 30
* PARTICLE FLOATING
20 SDOT=Y1DOT-K/B*(S-Y)
Y2DOT=-G*COS(BETA)
N=0.0
SW=0.0
30 Z=A*SIN(W*TIME)

SORT
* INTEGRATING SECTION
Y1DOT=INTGR(0.0,Y2DOT)
Y=INTGR(ICY,Y1DOT)
S=INTGR(0.0,SDOT)
* SLIDING AND ROLLING
EPSLN=SQR(2*R*(S-Y))
ZX=-A*COS(W*TIME)
ZXDOT=A*W*SIN(W*TIME)
F = \mu N \cdot \Gamma
COMPAR = X \cdot DOTA - XDOT - R \cdot \Theta TAD
\Gamma = FCNSW(COMPAR, -1.0, 0.0, 0.0, 1.0)
X2DOT = F / M - 0.0 \cdot \sin(BETA)
XDOT = INTGRL(0.0, X2DOT)
X = INTGRL(0.0, XDOT)
\Theta T2D = 2.5 \cdot F / (M \cdot R) + 2.5 \cdot \varepsilon S LON \cdot N / (M \cdot R \cdot \times 2) \cdot \kappa PA
\Theta TAD = INTGRL(0.0, \Theta T2D)
\kappa PA = FCNSW(\Theta TAD, 1.0, 0.0, 0.0, -1.0)
TIMER
DELT = .000003, PRDEL = .004, FINTIM = .75
PRINT
S, Z, COMPAR, \Theta TAD, X, XDOT, Y, Y1DOT
END
/*
Computer (CSMP) program for a tomato bouncing on a vibrating inclined plate-variable integration increment.

```
TITLE TOMATO BOUNCING ON VIBRATING INCLINED PLATE
* VARIABLE INTEGRATION INCREMENT
METHOD RKSFX
* ALL DATA SHOULD GO INTO THE PROGRAM IN EITHER
* KILOGRAMS, NEWTONS, CENTIMETERS, SECONDS, OR
* SOME COMBINATION
PARAM M=.0605, K = 72.23, B = .30, G = 98.66
PARAM A = .18, R = 2.354, MU = .77
PARAM W = 439.82, ANGLE = 9
INIT
NOSORT
   SW2=0.0
   VALUE=.1
   BETA=ANGLE*2.*3.1416/360
   ICY=-M*G*COS(BETA)/K
   S=W*A*COS(W*TIME)
   N=B*(SDOT-YDOT)+K*(S-Y)
DYNAM
NOSORT
   5 IF(SW-1.0)7,7,6
   6 IF(N)20,20,10
   7 IF(S-Z)10,10,20
   * PARTICLE IN CONTACT
   10 SDOT=W*A*COS(W*TIME)
      Y2DOT=N/M-G*COS(BETA)
      N=B*(SDOT-YDOT)+K*(S-Y)
      SW=2.0
     GO TO 30
   * PARTICLE FLOATING
   20 SDOT=Y1DOT-K/B*(S-Y)
      Y2DOT=G*COS(BETA)
      N=0.0
      SW=0.0
   30 Z=A*SIN(W*TIME)
SORT
* INTEGRATING SECTION
   Y1DOT=INTGRL(0.0,Y2DOT)
   Y=INTGRL(ICY,Y1DOT)
   S=INTGRL(0.0,SDOT)
   * SLIDING AND ROLLING
   EPSLON=SQR(2*R*(S-Y))
```
ZX=-A*COS(W*TIME)
ZXDOT=A*W*SIN(W*TIME)
F=MU*N*GAMMA
COMPAR=ZXDOT-XDOT-R*THETAD
GAMMA=FCNSW(COMPAR,-1.0,0.0,1.0)
X2DOT=F/M-G*SIN(BETA)
XDOT=INTGRL(0.0,X2DOT)
X=INTGRL(0.0,XDOT)
THET2D=2.5*F/(M*R)+2.5*EPSLON*N/(M*R**2)*KAPPA
THETAD=INTGRL(0.0,THET2D)
KAPPA=FCNSW(THETAD,1.0,0.0,-1.0)

* VARIABLE DELT USED
PROCEDURE SW1,SH2 = DUMMY(VALUE)
SW1=1
IF(S-Z .LT. VALUE) SW1=0
IF (KEEP.EQ.0) GO TO 40
IF (ABS(SW1-SW2) .LT. .5) GO TO 40
SW2=SW1

40 CALL FINISH
41 CONTINUE
ENDPROCEDURE
TERMINAL
TIMER DELT=.000003,PRDEL=.004,FINTIM=.75
PRINT S,Z,COMPAR,THETAD,X,XDOT,Y,Y1DOT
END CONTINUE
TIMER DELT=.0004
END CONTINUE
TIMER DELT=.000003
END CONTINUE
TIMER DELT=.0004
END CONTINUE
TIMER DELT=.000003
END CONTINUE
TIMER DELT=.0004
END CONTINUE
TIMER DELT=.000003
END CONTINUE
TIMER DELT=.0004
END CONTINUE
TIMER DELT=.000003
END CONTINUE
TIMER DELT=.0004
END CONTINUE
TIMER DELT=.000003
END CONTINUE

END
/*
Computer (CSMP) program of a tomato bouncing on a vibrating inclined plate-integration used when tomato surface below amplitude of plate, algebraic solution when in air.

TITLE TOMATO BOUNCING ON A VIBRATING INCLINED SURFACE INTEGRATION AND ALGEBRAIC SOLUTION

METHOD RK5FX

/ COMMON/ZZEXIN/TIMEX,TNEXT,TPRINT,TPLLOT,TLAST
/ REAL*8 TIMES,TNEXT,TPRINT,TPLLOT,TLAST

* ALL DATA SHOULD GO INTO THE PROGRAM IN EITHER KILOGRAMS,
* NEWTONS, CENTIMETERS, SECONDS, OR SOME COMBINATION

PARAM A=.138
PARAM ANGLE=4
PARAM W=439.82
PARAM MU=1.71
PARAM R=2.064
PARAM M=.0388, K=368.0, B=.40, G=980.66
PARAM COUNT=0.0
INIT
NOSORT

BETA=ANGLE*2.*3.1416/360
STEP=1.
ICY=-M*G*COS(BETA)/K
ICYD=0.0
ICS=0.0
ICXD=0.0
ICX=0.0
ICT=0.0
Y=ICY
N=E*(SDOT-Y1DOT)+K*(S-Y)

DYNAM
NOSORT

5 IF(STEP.EQ.0.0.AND.KEEP.EQ.0.0)RETURN
IF(STEP.EQ.0.0.AND.KEEP.EQ.1.)GO TO 35
IF(SW.1.0)7,7,6
6 IF(N)40,40,10
7 IF(S-Z)10,10,20

* PARTICLE IN CONTACT
10 SDOT=W*A*COS(W*TIME)
Y2DOT=N/M-G*COS(BETA)
N=E*(SDOT-Y1DOT)+K*(S-Y)
SW=2.0
GO TO 30

* PARTICLE FLOATING
20  SDOT=Y1DOT-K/B*(S-Y)
    Y2DOT=-G*COS(BETA)
    N=0.0
    SW=0.0
    GO TO 30
* ALGEBRAIC SOLUTION OF THE PARTICLE IN THE AIR
40  GY=G*COS(BETA)
    YMAX=Y+Y1DOT**2/(2*GY)
    IF(YMAX .LT. A) GO TO 20
    IF(Y1DOT .LT. 0.0) GO TO 20
    Y=A
    T1=Y1DOT/GY
    T2=SQRT(2*(YMAX-A)/GY)
    T=T1+T2
    Y1DOT=-SQRT(2*GY*(YMAX-A))
    GX=-G*SIN(BETA)
    X=X+(GX/2) *T**2+XDOT*T
    XDOT=XDOT+GX*T
    S=Y
    COUNT=COUNT+1
    SW=0
    TIME=TIME+T
    Z=A*SIN(W*TIME)
    CALL SUBZ(T,KEEP,TIME,TIMEX,TNEXT,TLAST,TPRINT)
    WRITE(6,31) YMAX,S,Z,X,XDOT,Y,Y1DOT
31  FORMAT(/,F12.6,F12.6,1X,F12.6,2X,F12.6,2X,F12.6,2X,
               F12.6,F12.6)
    WRITE(6,32)
32  FORMAT('O')
* MEMORY STORAGE
    YY=Y
    YY1DOT=Y1DOT
    XX=X
    XXDOT=XDOT
    SS=S
    THET=THETAD
    TT=TIME
35  STEP=0.0
    RETURN
* MEMORY RECALL
    Y=YY
    Y1DOT=YY1DOT
    X=XX
    XDOT=XXDOT
    S=SS
    THETAD=THET
7   TIME=TT
    STEP=1.0
    RETURN
* INTEGRATING SECTION
30  Z=A*SIN(W*TIME)
IF(ABS(S-Y),LT., 0002) S=Y  
EPSLON=SQRT(2*R*(S-Y))

SORT
Y1DOT=INTGRL(ICY,Y2DOT)  
Y=INTGRL(ICY,Y1DOT)  
S=INTGRL(ICS,SDOT)  
ZX=-A*COS(W*TIME)  
ZDOT=A*W*SIN(W*TIME)  
F=MU*N*GAMMA  
COMPAR=ZDOT-XDOT-R*THETAD  
GAMMA=FCNSW(COMPAR,-1.0,0.0,1.0)  
X2DOT=F/M-G*SIN(BETA)  
XDOT=INTGRL(ICXD,X2DOT)  
X=INTGRL(ICX,XDOT)

THET2D=2.5*F/(M*R)+2.5*EPSLON*N/(M*R**2)*KAPPA  
THETAD=INTGRL(ICT,THET2D)  
KAPPA=FCNSW(THETAD,1.0,0.0,-1.0)

TERMINAL
COUNT=0.0

TIMER DELT=.00003, PRDEL=.0004, FINTIM=3.0
FINISH COUNT=10
PRINT S,Y,X,XDOT,Y1DOT,N,F
END
STOP

SUBROUTINE SUBZ(T,KEEP,TIME,TIMEX,TNEXT,TLAST,TPRINT)
TIMEX = TIMEX + T
TNEXT = TNEXT + T
TLAST = TLAST + T
TPRINT = TPRINT + T
RETURN
END

/*
//
Appendix A-4

Definition of Symbols Used in Digital Programs

A = half amplitude of the vibrating plate, cm
ANGLE = the plate's angle of tilt, degrees
B = dashpot coefficient, N - s/cm
BETA = the plate's angle of tilt, radians
COMPAR = dummy variable that determines if the tomato is rolling with positive or negative angular displacement, cm/s
COUNT = counter that counts the number of times the program goes through the algebraic portion of the program
EPSLON = distance normal force if offset due to rolling resistance, cm
F = friction force on the vibrating plate, N
G = gravitational acceleration = 980.66 cm/s²
GAMMA = dummy variable that puts the correct sign on F
GX = - G * sin (Beta)
GY = G * cos (Beta)
ICS = initial displacement of the tomato's surface measured perpendicular to the plate, cm
ICT = the initial condition of the tomato's angular displacement, rad
ICX = initial displacement of the tomato's center of gravity measured parallel to the plate, cm
ICXD = initial velocity of the tomato's center of gravity parallel to the plate, cm/s
ICY = initial displacement of the tomato's center of gravity measured perpendicular to the plate, cm
ICYD = initial velocity of the tomato's center of gravity measured perpendicular to the plate, cm/s
K = spring coefficient N/cm
KEEP = it is set by the CSMP program and is passed to update, its value = 1 when an integration step has been completed but = 0 at points within step.
M = mass of the tomato, kg
MU = coefficient of friction
N = normal force between the plate and the tomato, N
R = radius of the tomato, cm
S = displacement of the tomato's surface measured perpendicular to the plate, cm
SDOT = velocity of the tomato's surface perpendicular to the plate, cm/s
STEP = dummy variable used in determining the location of the integration procedure within the integration interval
SUBZ = subroutine which updates time after going through the algebraic solution section
SW = a dummy variable used in determining whether the particle is in contact or if it is floating
T = total time from departure until Y = A, sec
T₁ = time it takes for the tomato to just leave the surface to the time it takes to get to YMAX, sec
\( T_2 = \) time it takes for the tomato to go from YMAX to \( Y=A \), sec

\( \text{THET2D} = \) the angular acceleration of the tomato, rad/sec^2

\( \text{THETAD} = \) the angular velocity of the tomato, rad/sec

\( \text{TIME} = \) total accumulative time, sec

\( \text{TIMEX} = \) the value of time passed to update for evaluation of derivatives at various points within the step

\( \text{TLAST} = \) is the value of time at the beginning of an integration step

\( \text{TNEXT} = \) the value of time at the end of an integration step

\( \text{TPRINT} = \) the next point in time that solution values are to be printed out

\( W = \) frequency of the vibrating plate, rad/sec

\( X = \) displacement of the tomato's center of gravity measured parallel to the plate, cm

\( \text{XDOT} = \) velocity of the tomato's center of gravity parallel to the plate, cm/s

\( \text{X2DOT} = \) acceleration of the tomato's center of gravity parallel to the plate, cm/s^2

\( Y = \) displacement of the tomato's center of gravity measured perpendicular to the plate, cm

\( \text{Y1DOT} = \) velocity of the tomato's center of gravity perpendicular to the plate, cm/s

\( \text{Y2DOT} = \) acceleration of the tomato's center of gravity perpendicular to the plate cm/s^2

\( \text{YMAX} = \) maximum bounce height of the tomato, cm

\( Z = \) displacement of the plate measured parallel to the plate, cm

\( \text{ZX} = \) displacement of the plate measured parallel to the plate, cm

\( \text{ZXDOT} = \) velocity of the plate measured parallel to the plate, cm/s^2
Appendix B

B-1 Fixation procedure used to prepare tomato samples for scanning electron microscope.
Appendix B-1

Fixation procedure used to prepare tomato samples for scanning electron microscope.

1. Place cut tissue pieces in 3.6 percent glutaraldehyde/phosphate buffer solution for one and one-half hours, (no liquid changes) at room temperature.
   A. To obtain phosphate buffer of pH 7.2:
      \[ A = 0.1 \text{ M } \text{K}_2\text{HPO}_4 \]
      \[ B = 0.1 \text{ M } \text{Na}_2\text{HPO}_4 \]
   B. Glutaraldehyde comes as a 25 percent solution. Use a 1:6 ratio, glutaraldehyde solution: buffer solution to obtain a 3.6 percent glutaraldehyde / buffer of pH 7.

2. Rinse with distilled water for one-half hour: change water once.

3. Place tissue in 1 percent \( \text{Os}_2\text{O}_4 \) for two hours (no liquid change) and refrigerate.
   A. \( \text{Os}_2\text{O}_4 \) comes as 1/4 gm of crystals. Dissolve (under hood) in 25 mls. of double distilled water.
   B. Place only a few drops over the tissue; refrigerate.

4. Rinse with distilled water for one-half hour: change water once.
5. Put tissue through a dehydration series of varying concentrations of ethanol:

   10 percent,       25 percent,       50 percent,
   75 percent,       95 percent,       100 percent

Place tissue in each concentration for one-half hour; change liquid after 15 minutes.

6. Place tissue in a 50:50 solution of absolute ethanol and amyl acetate for one-half hour with one change of liquid.

7. Place tissue in 100 percent amyl acetate and hold until material can be critically point dried.
Appendix C

Electro-dynamic Shaker Results

C-1  Response of Heinz 1350 tomatoes on electro-dynamic shaker

C-2  Effect of amplitude on sorting for Ohio 7624 tomatoes on electro-dynamic shaker

C-3  Effect of plate angle of tilt on sorting for Ohio 7624 tomatoes on electro-dynamic shaker

C-4  Effect of vibratory frequency on sorting for Ohio 7624 tomatoes on electro-dynamic shaker

C-5  Effect of amplitude on sorting for Ohio 7669 tomatoes on electro-dynamic shaker

C-6  Effect of plate angle of tilt on sorting for Ohio 7669 tomatoes on electro-dynamic shaker

C-7  Effect of operating frequency on sorting for Ohio 7669 tomatoes on electro-dynamic shaker
### Table C-1
Response of Heinz 1350 Tomatoes on Electro-dynamic Shaker

Tilt of Plate (θ₁, Figure 19) = 3°

<table>
<thead>
<tr>
<th>Amplitude (peak to peak)</th>
<th>0.127 cm</th>
<th>Red</th>
<th>Green</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freq.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>40</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>60</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>70</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>75</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>80</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>90</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>Move up (slower than setting 90 Hz A=0.1 in)*</td>
<td>Bounce down</td>
<td></td>
</tr>
<tr>
<td>110</td>
<td>Move up faster than with Freq. = 100 Hz*</td>
<td>Bounce down</td>
<td></td>
</tr>
<tr>
<td>120</td>
<td>Move up faster than with Freq. = 110 Hz*</td>
<td>Bounce not so high</td>
<td></td>
</tr>
<tr>
<td>130</td>
<td>Move up faster than with Freq. = 120 Hz*</td>
<td>Bounce not so high if positioned right will slide up</td>
<td></td>
</tr>
</tbody>
</table>

Tilt of Shaker (θ₂, Figure 19) = 70°

<table>
<thead>
<tr>
<th>Amplitude (peak to peak)</th>
<th>0.254 cm</th>
<th>Red</th>
<th>Green</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freq.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>40</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>60</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>70</td>
<td>Move up faster than run at freq. = 60 *</td>
<td>Bounces down</td>
<td></td>
</tr>
<tr>
<td>75</td>
<td>Move up very fast* 4&quot; in air</td>
<td></td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>Move up faster than run at freq. = 70 *</td>
<td>Bounces down</td>
<td></td>
</tr>
<tr>
<td>90</td>
<td>Move up faster than run at freq. = 80 *</td>
<td>Bounces down</td>
<td></td>
</tr>
</tbody>
</table>

*No rotation

Date tomatoes harvested and tested: 8-31-76
Appendix C-2

Effect of amplitude on sorting for Ohio 7624 tomatoes on electro-dynamic shaker

Vibratory Frequency = 100 Hz
Plate angle of tilt (θ₁, Figure 19) = 3°
Tilt angle of shaker (θ₂, Figure 19) = 70°

<table>
<thead>
<tr>
<th>Amplitude (cm) (peak to peak)</th>
<th>Red Tomato Motion</th>
<th>Green Tomato Motion</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0762</td>
<td>Moves up slowly (no rotation)</td>
<td>Bounces up</td>
</tr>
<tr>
<td>0.1270</td>
<td>Moves up faster than with A = 0.0762 cm (no rotation)</td>
<td>Bounces up</td>
</tr>
<tr>
<td>0.1778</td>
<td>Moves up faster than with A = 0.1270 cm (no rotation)</td>
<td>Bounces up</td>
</tr>
<tr>
<td>0.2032</td>
<td>Moves up faster than with A = 0.1778 cm (no rotation)</td>
<td>Bounces up</td>
</tr>
</tbody>
</table>

Date tomatoes harvested and tested: 9-1-76.
Appendix C-3

Effect of plate angle of tilt on sorting for Ohio 7624 tomatoes on electro-dynamic shaker

Vibrating Frequency = 100 Hz
Plate angle of tilt ($\theta_1$, Figure 19) = 3°
Tilt angle of shaker ($\theta_2$, Figure 19) = 70°

<table>
<thead>
<tr>
<th>Plate angle of tilt, $\theta_1$ (deg)</th>
<th>Red Tomato Motion</th>
<th>Green Tomato Motion</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Moves up, no rotation</td>
<td>Bounces up</td>
</tr>
<tr>
<td>1</td>
<td>Moves up slower than with $\theta_1 = 0°$ *</td>
<td>Bounces either direction</td>
</tr>
<tr>
<td>2</td>
<td>Moves up slower than with $\theta_1 = 1°$ *</td>
<td>Bounces up</td>
</tr>
<tr>
<td>3</td>
<td>Moves up slower than with $\theta_1 = 2°$ *</td>
<td>Bounces up</td>
</tr>
<tr>
<td>4</td>
<td>Moves up slower than with $\theta_1 = 3°$ *</td>
<td>Bounces down</td>
</tr>
<tr>
<td>5</td>
<td>Moves up slower than with $\theta_1 = 4°$ *</td>
<td>Bounces up</td>
</tr>
<tr>
<td>6</td>
<td>Moves up slower than with $\theta_1 = 5°$ *</td>
<td>Bounces either direction</td>
</tr>
<tr>
<td>7</td>
<td>Moves up slower than with $\theta_1 = 6°$ *</td>
<td>Bounces up</td>
</tr>
<tr>
<td>9</td>
<td>Tomato stays still</td>
<td>Bounces up</td>
</tr>
<tr>
<td>10</td>
<td>Moves down</td>
<td>Bounces either direction</td>
</tr>
</tbody>
</table>

* no rotation. Date tomatoes harvested and tested: 9-1-76
Appendix C-4

Effect of vibratory frequency on sorting for Ohio 7624 tomatoes on electro-dynamic shaker

Amplitude of vibration (peak to peak) = .254 cm
Plate angle of tilt ($\theta_1$, Figure 19) = 3°
Tilt angle of shaker ($\theta_2$, Figure 19) = 70°

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Red Tomato Motion</th>
<th>Green Tomato Motion</th>
</tr>
</thead>
<tbody>
<tr>
<td>70</td>
<td>Moves up slowly, no rotation</td>
<td>Bounces up</td>
</tr>
<tr>
<td>80</td>
<td>Moves up faster than with Frequency=70 Hz*</td>
<td>Bounces up</td>
</tr>
<tr>
<td>90</td>
<td>Moves up faster than with Frequency=80 Hz*</td>
<td>Bounces up</td>
</tr>
<tr>
<td>100</td>
<td>Moves up faster than with Frequency=90 Hz*</td>
<td>Bounces up</td>
</tr>
<tr>
<td>110</td>
<td>Moves up faster than with Frequency=100 Hz*</td>
<td>Bounces up</td>
</tr>
</tbody>
</table>

* no rotation. Date tomatoes harvested and tested: 9-1-76
Appendix C-5

Effect of amplitude on sorting for Ohio 7669 tomatoes on electro-dynamic shaker

Vibratory frequency = 90 Hz
Plate angle of tilt ($\theta_1$, Figure 19) = 3°
Tilt angle of shaker ($\theta_2$, Figure 19) = 70°

<table>
<thead>
<tr>
<th>Amplitude (cm) (peak to peak)</th>
<th>Red Tomato Motion</th>
<th>Green Tomato Motion</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0508</td>
<td>Moves up, no rotation</td>
<td>Bounces up</td>
</tr>
<tr>
<td>0.1016</td>
<td>Moves up faster than $A = 0.0508$ cm</td>
<td>Bounces up</td>
</tr>
<tr>
<td></td>
<td>(no rotation)</td>
<td></td>
</tr>
<tr>
<td>0.1524</td>
<td>Moves up faster than $A = 0.1016$ cm</td>
<td>Bounces either</td>
</tr>
<tr>
<td></td>
<td>(no rotation)</td>
<td>direction</td>
</tr>
<tr>
<td>0.2032</td>
<td>Moves up faster than $A = 0.1524$ cm</td>
<td>Bounces down</td>
</tr>
<tr>
<td></td>
<td>(no rotation)</td>
<td></td>
</tr>
<tr>
<td>0.2540</td>
<td>Moves up faster than $A = 0.2032$ cm</td>
<td>Bounces down</td>
</tr>
<tr>
<td></td>
<td>(no rotation)</td>
<td></td>
</tr>
<tr>
<td>0.2794</td>
<td>Moves up faster than $A = 0.2540$ cm</td>
<td>Bounces down</td>
</tr>
<tr>
<td></td>
<td>(no rotation)</td>
<td></td>
</tr>
</tbody>
</table>

Date tomatoes harvested and tested: 9-1-76
Appendix C-6

Effect of plate angle of tilt on sorting for Ohio 7669 tomatoes on electro-dynamic shaker

Amplitude of vibration (peak to peak) = 0.127 cm
Vibratory frequency = 90 Hz
Tilt angle of shaker ($\theta_2$, Figure 19) = 70°

<table>
<thead>
<tr>
<th>$\theta_1$ (Deg.)</th>
<th>Red Tomato Motion</th>
<th>Green Tomato Motion</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Moves up, no rotation</td>
<td>Bounces up</td>
</tr>
<tr>
<td>2°</td>
<td>Moves up slower than $\theta_1 = 0^\circ$, no rotation</td>
<td>Bounces either direction</td>
</tr>
<tr>
<td>5°</td>
<td>Moves up slower than $\theta_1 = 2^\circ$, no rotation</td>
<td>Bounces down</td>
</tr>
<tr>
<td>7°</td>
<td>Moves up slower than $\theta_1 = 5^\circ$, no rotation</td>
<td>Bounces down</td>
</tr>
<tr>
<td>9°</td>
<td>Rolls down</td>
<td>Bounces down</td>
</tr>
</tbody>
</table>

Date tomatoes harvested and tested: 9-1-76
Appendix C-7

Effect of operating frequency on sorting for Ohio 7669 tomatoes on electro-dynamic shaker

Amplitude of vibration (peak to peak) = 0.127 cm
Plate angle of tilt ($\theta_1$, Figure 19) = 3°
Tilt angle of shaker ($\theta_2$, Figure 19) = 70°

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Red Tomato Motion</th>
<th>Green Tomato Motion</th>
</tr>
</thead>
<tbody>
<tr>
<td>70</td>
<td>Stays still</td>
<td>Bounces down</td>
</tr>
<tr>
<td>80</td>
<td>Moves up, no rotation</td>
<td>Bounces down</td>
</tr>
<tr>
<td>90</td>
<td>Moves up faster than Frequency = 80, no rotation</td>
<td>Bounces down</td>
</tr>
<tr>
<td>100</td>
<td>Moves up faster than Frequency = 90, no rotation</td>
<td>Bounces up</td>
</tr>
<tr>
<td>110</td>
<td>Moves up faster than Frequency = 100, no rotation</td>
<td>Bounces up</td>
</tr>
</tbody>
</table>

Date tomatoes harvested and tested: 9-1-76
Appendix D

Prototype Sorter

D-1 Dynamic displacement of the aluminum plate on the prototype sorter.

D-2 Response of red Ohio 7669 tomatoes on prototype sorter with a circular forcing function.

D-3 Response of green Ohio 7669 tomatoes on prototype sorter with a circular forcing function.

D-4 Response of red tomatoes on prototype sorter with straight line motion on $45^\circ$ angle measured from the horizontal.

D-5 Response of green tomatoes on prototype sorter with straight line motion on $45^\circ$ angle measured from the horizontal.
 Appendix D-1

Dynamic displacement of the aluminum plate on the prototype sorter.
Appendix D-2

Response of red Ohio 7669 tomatoes on prototype sorter with a circular forcing function.

<table>
<thead>
<tr>
<th>Angle (Degrees)</th>
<th>0°</th>
<th>1°</th>
<th>2°</th>
<th>3°</th>
<th>4°</th>
<th>5°</th>
<th>6°</th>
<th>7°</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>0</td>
<td>No</td>
<td>Did not move</td>
<td>0</td>
<td>Roll down plate</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.7</td>
<td>1/4&quot;</td>
<td>Bouncing up</td>
<td>1/4&quot;</td>
<td>No</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.0</td>
<td>1/4&quot;</td>
<td>No</td>
<td>Bouncing up</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.3</td>
<td>1/4&quot;</td>
<td>No</td>
<td>Bouncing up</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.7</td>
<td>1/4&quot;</td>
<td>No</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.0</td>
<td>1/2&quot;</td>
<td>Figure up</td>
<td>2°</td>
<td>Bouncing up</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.7</td>
<td>1/2&quot;</td>
<td>No</td>
<td>Bouncing generally up</td>
<td>1/2&quot;</td>
<td>Stay in one to 1&quot; up or place</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.0</td>
<td>1/2&quot;</td>
<td>Figure 25 to 1&quot; up</td>
<td>1/2&quot;</td>
<td>Rolls down 1&quot; down</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.3</td>
<td>0°-1&quot;</td>
<td>Figure 25 up or slide</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.5</td>
<td>Soft-0° Figure 25 Hard-1/2&quot; 25 Soft-up Hard-down bounces</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.7</td>
<td>0°-1/2&quot; Figure 25 up</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.7</td>
<td>0° Figure 25 up</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.8</td>
<td>0° Figure 25 up</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.8</td>
<td>0° Figure 25 up</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Amplitude of aluminum plate shown in D-1 as a function of frequency.

*Bloom end or stem end located up plate will go up plate, otherwise rolls down.
Appendix D-3
Response of green Ohio 7669 tomatoes on prototype sorter with a circular forcing function.

<table>
<thead>
<tr>
<th>Angle (Degree)</th>
<th>0°</th>
<th>10°</th>
<th>20°</th>
<th>30°</th>
<th>40°</th>
<th>50°</th>
<th>60°</th>
<th>70°</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.0</td>
<td>0</td>
<td>No</td>
<td>Did not move</td>
<td>0</td>
<td>Rolls down</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16.7</td>
<td>1/2″</td>
<td>-</td>
<td>Bouncing down</td>
<td>1/2″</td>
<td>Rolls Bouncing down</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20.3</td>
<td>1/2″</td>
<td>-</td>
<td>Bouncing down</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>21.3</td>
<td>1/2″</td>
<td>Erratic Generally bouncing up</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>24.7</td>
<td>1/2″</td>
<td>Rolls Bouncing down</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25.0</td>
<td>1/2″-1″</td>
<td>Erratic Up or down</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>28.7</td>
<td>1″</td>
<td>Erratic bouncing up</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>31.7</td>
<td>1″</td>
<td>Erratic bouncing up</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>34.3</td>
<td>2″-3″</td>
<td>Erratic bouncing up</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>35.0</td>
<td>3″-4″</td>
<td>Erratic Bouncing down</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>38.3</td>
<td>3″-4″</td>
<td>Erratic Bouncing up</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>41.7</td>
<td>3″-4″</td>
<td>Erratic Bouncing up</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>45.0</td>
<td>3″-4″</td>
<td>Erratic Bouncing down</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>48.3</td>
<td>4″</td>
<td>Erratic Bouncing down</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Amplitude of aluminum plate shown in D-1 as a function of frequency.
Appendix D-4

Response of red tomatoes on prototype sorter with straight line motion on 45° angle measured from the horizontal.

Amplitude of Aluminum Plate Shown in Figure D-1 as a Function of Frequency.  

<table>
<thead>
<tr>
<th>Angle:</th>
<th>10°</th>
<th>30°</th>
<th>45°</th>
<th>50°</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Freq: Hz:</strong></td>
<td>17.0</td>
<td>17.0</td>
<td>17.0</td>
<td>17.0</td>
</tr>
<tr>
<td><strong>Bounce Height:</strong></td>
<td>1/4&quot;</td>
<td>1/4&quot;</td>
<td>1/4&quot;</td>
<td>1/4&quot;</td>
</tr>
<tr>
<td><strong>Rotate:</strong></td>
<td>No, if goes up plate rolls down</td>
<td>No, if goes up plate rolls down</td>
<td>No, if goes up plate rolls down</td>
<td>No, if goes up plate rolls down</td>
</tr>
<tr>
<td><strong>Up or Down:</strong></td>
<td>Up or down</td>
<td>Up or down</td>
<td>Up or down</td>
<td>Up or down</td>
</tr>
<tr>
<td><strong>Freq: Hz:</strong></td>
<td>19.2</td>
<td>41.7</td>
<td>41.7</td>
<td>41.7</td>
</tr>
<tr>
<td><strong>Bounce Height:</strong></td>
<td>1/4&quot;</td>
<td>1/2&quot;</td>
<td>1/2&quot;</td>
<td>1/2&quot;</td>
</tr>
<tr>
<td><strong>Rotate:</strong></td>
<td>No, if goes up plate rolls down</td>
<td>Up or down</td>
<td>Up or down</td>
<td>Up or down</td>
</tr>
<tr>
<td><strong>Up or Down:</strong></td>
<td>Up or down</td>
<td>Down</td>
<td>Down</td>
<td>Down</td>
</tr>
<tr>
<td><strong>Freq: Hz:</strong></td>
<td>65.0</td>
<td>65.0</td>
<td>65.0</td>
<td>65.0</td>
</tr>
<tr>
<td><strong>Bounce Height:</strong></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>Rotate:</strong></td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td><strong>Up or Down:</strong></td>
<td>Up</td>
<td>Up</td>
<td>Up or stays still</td>
<td>Up or Down</td>
</tr>
<tr>
<td><strong>Freq: Hz:</strong></td>
<td></td>
<td></td>
<td></td>
<td>71.7</td>
</tr>
<tr>
<td><strong>Bounce Height:</strong></td>
<td></td>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td><strong>Rotate:</strong></td>
<td></td>
<td></td>
<td></td>
<td>No, if goes up plate</td>
</tr>
<tr>
<td><strong>Up or Down:</strong></td>
<td></td>
<td></td>
<td></td>
<td>Up or Down</td>
</tr>
</tbody>
</table>
Appendix D-5

Response of green tomatoes on prototype sorter with straight line motion on 45° angle measured from the horizontal.

<table>
<thead>
<tr>
<th>Angle:</th>
<th>1°</th>
<th>3°</th>
<th>4°</th>
<th>5°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hz:</td>
<td>17.0</td>
<td></td>
<td></td>
<td>17.0</td>
</tr>
<tr>
<td>Bounce Height:</td>
<td>1/4&quot;</td>
<td></td>
<td></td>
<td>1/2&quot;</td>
</tr>
<tr>
<td>Rotate:</td>
<td>No, if goes up plate rolls down</td>
<td></td>
<td></td>
<td>No, if goes up plate rolls down</td>
</tr>
<tr>
<td>Up or Down:</td>
<td>Up or mainly down</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hz:</td>
<td>19.2</td>
<td></td>
<td></td>
<td>41.7</td>
</tr>
<tr>
<td>Bounce Height:</td>
<td>1/4&quot;</td>
<td></td>
<td></td>
<td>1&quot;-2&quot;</td>
</tr>
<tr>
<td>Rotate:</td>
<td>No, if goes up plate rolls down</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Up or Down:</td>
<td>Up or mainly down</td>
<td></td>
<td></td>
<td>Down</td>
</tr>
<tr>
<td>Hz:</td>
<td>41.7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bounce Height:</td>
<td>1&quot;</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rotate:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Up or Down:</td>
<td>Down</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hz:</td>
<td>65.0</td>
<td>65.0</td>
<td>65.0</td>
<td>71.7</td>
</tr>
<tr>
<td>Bounce Height:</td>
<td>3&quot;-4&quot;</td>
<td>3&quot;-4&quot;</td>
<td>3&quot;-4&quot;</td>
<td>3&quot;-4&quot;</td>
</tr>
<tr>
<td>Rotate:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Up or Down:</td>
<td>Up</td>
<td>Up</td>
<td>Up or down</td>
<td>Down</td>
</tr>
</tbody>
</table>
Appendix E

Coefficient of Friction Results

E-1 Effect of harvest date on the coefficient of kinetic friction for Ohio 7669 tomatoes.

E-2 Coefficient of kinetic friction data for partially-ripe Campbell-28 tomatoes.

E-3 Coefficient of kinetic friction data for partially-ripe Chico III tomatoes.

E-4 Effect of normal force on the coefficient of kinetic friction on Ohio 7669 tomatoes.

E-5 Effect of tomato variety on the coefficient of kinetic friction.

E-6 Effect of wiping surface of Ohio 7669 tomatoes with ether on coefficient of kinetic friction.

E-7 Effect of wiping surface of Ohio 7669 tomatoes with acetone on the coefficient of kinetic friction.

E-8 Effect of the surface of plate on coefficient of kinetic friction.
Appendix E

Coefficient of Friction Results

(continued)

E-9 Coefficient of kinetic friction data for Ohio 7669 tomatoes run at plate velocity = 6.248 cm/sec.

E-10 Coefficient of kinetic friction data for Ohio 7669 tomatoes run at plate velocity = 20.117 cm/sec.
Appendix E-1

Effect of harvest date on the coefficient of kinetic friction for Ohio 7669 tomatoes.

<table>
<thead>
<tr>
<th>Location, Tomatoes From</th>
<th>OSU's Horticulture Farm</th>
<th>OARDC's Northwestern Branch</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date Tested</td>
<td>8-12-77</td>
<td>8-23-77</td>
</tr>
<tr>
<td>Average μ</td>
<td>.74</td>
<td>.73</td>
</tr>
<tr>
<td>Highest μ</td>
<td>1.12</td>
<td>.96</td>
</tr>
<tr>
<td>Lowest μ</td>
<td>.54</td>
<td>.59</td>
</tr>
<tr>
<td>Number Tested</td>
<td>17</td>
<td>20</td>
</tr>
<tr>
<td>Variance</td>
<td>.0245</td>
<td>.0100</td>
</tr>
<tr>
<td>Average μ</td>
<td>.87</td>
<td>.88</td>
</tr>
<tr>
<td>Highest μ</td>
<td>1.27</td>
<td>1.25</td>
</tr>
<tr>
<td>Lowest μ</td>
<td>.65</td>
<td>.59</td>
</tr>
<tr>
<td>Number Tested</td>
<td>8</td>
<td>12</td>
</tr>
<tr>
<td>Variance</td>
<td>.0410</td>
<td>.0535</td>
</tr>
<tr>
<td>Average μ</td>
<td>.57</td>
<td>.71</td>
</tr>
<tr>
<td>Highest μ</td>
<td>.99</td>
<td>1.13</td>
</tr>
<tr>
<td>Lowest μ</td>
<td>.39</td>
<td>.51</td>
</tr>
<tr>
<td>Number Tested</td>
<td>8</td>
<td>12</td>
</tr>
<tr>
<td>Variance</td>
<td>.0457</td>
<td>.0389</td>
</tr>
<tr>
<td>Average μ</td>
<td>1.98</td>
<td>1.61</td>
</tr>
<tr>
<td>Highest μ</td>
<td>2.57</td>
<td>2.73</td>
</tr>
<tr>
<td>Lowest μ</td>
<td>1.30</td>
<td>.93</td>
</tr>
<tr>
<td>Number Tested</td>
<td>17</td>
<td>22</td>
</tr>
<tr>
<td>Variance</td>
<td>.1493</td>
<td>.1750</td>
</tr>
<tr>
<td>Average μ</td>
<td>1.93</td>
<td>1.77</td>
</tr>
<tr>
<td>Highest μ</td>
<td>2.66</td>
<td>3.13</td>
</tr>
<tr>
<td>Lowest μ</td>
<td>1.58</td>
<td>1.11</td>
</tr>
<tr>
<td>Number Tested</td>
<td>8</td>
<td>16</td>
</tr>
<tr>
<td>Variance</td>
<td>.1300</td>
<td>.3635</td>
</tr>
<tr>
<td>Average μ</td>
<td>1.85</td>
<td>1.44</td>
</tr>
<tr>
<td>Highest μ</td>
<td>2.42</td>
<td>1.95</td>
</tr>
<tr>
<td>Lowest μ</td>
<td>1.20</td>
<td>.93</td>
</tr>
<tr>
<td>Number Tested</td>
<td>8</td>
<td>16</td>
</tr>
<tr>
<td>Variance</td>
<td>.1466</td>
<td>.0923</td>
</tr>
</tbody>
</table>

- Aluminum plate clean and dry.
- Velocity of Al. plate = 5.79 cm/sec.
Appendix E-2

Coefficient of kinetic friction data for partially-ripe Campbell-28 tomatoes.

<table>
<thead>
<tr>
<th>Tomato</th>
<th>Red surface of tomato touching aluminum plate</th>
<th>Green surface of tomato touching aluminum plate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>μ Blossom End</td>
<td>μ Side</td>
</tr>
<tr>
<td>1</td>
<td>.84</td>
<td>1.36</td>
</tr>
<tr>
<td>2</td>
<td>1.01</td>
<td>1.40</td>
</tr>
<tr>
<td>3</td>
<td>1.25</td>
<td>1.54</td>
</tr>
<tr>
<td>4</td>
<td>.71</td>
<td>1.11</td>
</tr>
<tr>
<td>5</td>
<td>1.63</td>
<td>1.96</td>
</tr>
<tr>
<td>6</td>
<td>1.80</td>
<td>2.47</td>
</tr>
<tr>
<td>7</td>
<td>.81</td>
<td>1.63</td>
</tr>
<tr>
<td>8</td>
<td>.78</td>
<td>1.38</td>
</tr>
<tr>
<td>9</td>
<td>.73</td>
<td>1.23</td>
</tr>
<tr>
<td>10</td>
<td>.76</td>
<td>1.01</td>
</tr>
<tr>
<td>11</td>
<td>2.11</td>
<td>.93</td>
</tr>
</tbody>
</table>

Tomatoes harvested and tested on 9-7-77.

Velocity of aluminum plate = 5.79 cm/sec.

Plate clean and dry.
Appendix E-3

Coefficient of kinetic friction data for partially-ripe Chico III tomatoes.

<table>
<thead>
<tr>
<th>Tomato</th>
<th>Red surface of tomato</th>
<th>Green surface of tomato</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>touching aluminum plate</td>
<td>touching aluminum plate</td>
</tr>
<tr>
<td>1</td>
<td>.48</td>
<td>.74</td>
</tr>
<tr>
<td></td>
<td>.48</td>
<td>1.19</td>
</tr>
<tr>
<td>2</td>
<td>.75</td>
<td>1.13</td>
</tr>
<tr>
<td></td>
<td>.53</td>
<td>.68</td>
</tr>
<tr>
<td>3</td>
<td>1.62</td>
<td>1.53</td>
</tr>
<tr>
<td></td>
<td>.83</td>
<td>2.87</td>
</tr>
<tr>
<td>4</td>
<td>.85</td>
<td>1.35</td>
</tr>
<tr>
<td></td>
<td>1.00</td>
<td>2.35</td>
</tr>
<tr>
<td>5</td>
<td>.95</td>
<td>1.44</td>
</tr>
<tr>
<td></td>
<td>.66</td>
<td>1.38</td>
</tr>
<tr>
<td>6</td>
<td>1.01</td>
<td>1.28</td>
</tr>
<tr>
<td></td>
<td>1.01</td>
<td>1.24</td>
</tr>
<tr>
<td>7</td>
<td>.81</td>
<td>.64</td>
</tr>
<tr>
<td>8</td>
<td>1.13</td>
<td>1.53</td>
</tr>
<tr>
<td></td>
<td>.74</td>
<td>1.64</td>
</tr>
<tr>
<td>9</td>
<td>.76</td>
<td>1.74</td>
</tr>
<tr>
<td></td>
<td>.82</td>
<td>1.03</td>
</tr>
<tr>
<td>10</td>
<td>1.02</td>
<td>1.28</td>
</tr>
</tbody>
</table>

Tomatoes harvested and tested on 9-7-77.

Velocity of aluminum plate = 5.79 cm/sec.

Plate clean and dry.
Appendix E-4

Effect of normal force on the coefficient of kinetic friction on Ohio 7669 tomatoes.

<table>
<thead>
<tr>
<th>Red Side</th>
<th>Normal Force Applied: 0.0 grams</th>
<th>104.3 grams</th>
<th>267.1 grams</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average $\mu$</td>
<td>.74</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>Highest $\mu$</td>
<td>.99</td>
<td>1.52</td>
</tr>
<tr>
<td></td>
<td>Lowest $\mu$</td>
<td>.41</td>
<td>.67</td>
</tr>
<tr>
<td></td>
<td>Number Tested</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>Variance</td>
<td>.0268</td>
<td>.0405</td>
</tr>
<tr>
<td>Red Blossom End</td>
<td>Average $\mu$</td>
<td>.78</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>Highest $\mu$</td>
<td>1.19</td>
<td>1.57</td>
</tr>
<tr>
<td></td>
<td>Lowest $\mu$</td>
<td>.45</td>
<td>.61</td>
</tr>
<tr>
<td></td>
<td>Number Tested</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>Variance</td>
<td>.0671</td>
<td>.0768</td>
</tr>
<tr>
<td>Red Stem End</td>
<td>Average $\mu$</td>
<td>.87</td>
<td>1.16</td>
</tr>
<tr>
<td></td>
<td>Highest $\mu$</td>
<td>1.14</td>
<td>1.78</td>
</tr>
<tr>
<td></td>
<td>Lowest $\mu$</td>
<td>.51</td>
<td>.87</td>
</tr>
<tr>
<td></td>
<td>Number Tested</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>Variance</td>
<td>.0253</td>
<td>.0644</td>
</tr>
<tr>
<td>Green Side</td>
<td>Average $\mu$</td>
<td>1.83</td>
<td>2.03</td>
</tr>
<tr>
<td></td>
<td>Highest $\mu$</td>
<td>2.64</td>
<td>2.91</td>
</tr>
<tr>
<td></td>
<td>Lowest $\mu$</td>
<td>.69</td>
<td>1.17</td>
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<td>.1157</td>
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- Tomatoes harvested and tested on 9-6-77.
- Velocity of aluminum plate = 5.79 cm/sec.
- Plate clean and dry.
Appendix E-5

Effect of tomato **variety** on the coefficient of kinetic friction.

<table>
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<th>Campbell-28</th>
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<td></td>
<td>8-23-77</td>
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<td>8-30-77</td>
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<td>.78</td>
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<td>.96</td>
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<td>1.17</td>
</tr>
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<td>.33</td>
<td>.53</td>
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<td>18</td>
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<td>.0025</td>
<td>.0359</td>
</tr>
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<td>.83</td>
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<td>.64</td>
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<td>18</td>
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<td>Variance</td>
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<td>.0050</td>
<td>.0465</td>
</tr>
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<td></td>
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<td>.76</td>
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<td>.96</td>
</tr>
<tr>
<td>Lowest $\mu$</td>
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<td>.45</td>
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<td>16</td>
<td>18</td>
</tr>
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<td>Variance</td>
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<td>.0031</td>
<td>.0253</td>
</tr>
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<td></td>
<td></td>
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<td>1.61</td>
<td>.88</td>
<td>1.38</td>
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<td>Highest $\mu$</td>
<td>2.73</td>
<td>2.05</td>
<td>2.06</td>
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<td>.53</td>
<td>.92</td>
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<td>Total Number of Runs</td>
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<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Variance</td>
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<td>.1385</td>
<td>.0925</td>
</tr>
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<td></td>
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<td>1.49</td>
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<td>1.95</td>
<td>2.05</td>
<td>1.99</td>
</tr>
<tr>
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<td>.48</td>
<td>.58</td>
</tr>
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<td>Total Number of Runs</td>
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<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Variance</td>
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<td>.1391</td>
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<td></td>
<td></td>
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<td>1.24</td>
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<td>2.42</td>
<td>1.91</td>
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<tr>
<td>Lowest $\mu$</td>
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<td>.87</td>
<td>.78</td>
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<td>Total Number of Runs</td>
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<td>16</td>
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<tr>
<td>Variance</td>
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Appendix E-6

Effect of wiping surface of Ohio 7669 tomatoes with ether on coefficient of kinetic friction

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<td>μ Ether</td>
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<tr>
<td>.48</td>
<td>.76</td>
<td></td>
</tr>
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<td>.82</td>
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<td></td>
</tr>
<tr>
<td>.85</td>
<td>1.17</td>
<td></td>
</tr>
<tr>
<td>.80</td>
<td>1.65</td>
<td></td>
</tr>
<tr>
<td>.57</td>
<td>.78</td>
<td></td>
</tr>
<tr>
<td>.45</td>
<td>.62</td>
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<td>.67</td>
<td>.90</td>
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<td>.73</td>
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<td>.73</td>
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</tr>
<tr>
<td>.51</td>
<td>.66</td>
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<td>Average μ</td>
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<td>.92</td>
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<td>1.65</td>
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<td>.62</td>
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</tr>
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Side of tomato touching plate.
Plate clean and dry.
Plate velocity = 5.79 cm/sec.
Date harvested and tested: 9-28-77.
Appendix E-7

Effect of wiping surface of Ohio 7669 tomatoes with acetone on the coefficient of kinetic friction.

<table>
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<td>$\mu$ Acetone</td>
<td>$\mu$ No Acetone</td>
<td>$\mu$ Acetone</td>
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<tr>
<td>0.57</td>
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<td>2.31</td>
<td>3.22</td>
<td></td>
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<tr>
<td>0.83</td>
<td>0.98</td>
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<td>2.80</td>
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<td>1.17</td>
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<td>3.59</td>
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</tr>
<tr>
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<td>2.94</td>
<td>3.75</td>
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</tr>
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<td>0.77</td>
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<td>2.82</td>
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<tr>
<td>0.87</td>
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<td>1.98</td>
<td>3.50</td>
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</tr>
<tr>
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<td></td>
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<td>2.74</td>
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</tr>
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<td>2.53</td>
<td>3.22</td>
</tr>
<tr>
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<td>1.42</td>
<td>3.59</td>
<td>3.75</td>
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<tr>
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<td>1.68</td>
<td>2.80</td>
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Date harvested and run: 9-15-77
Place velocity = 5.79 cm/sec
Plate clean and dry.
Side of tomato touching plate.
Appendix E-8

Effect of the surface of plate on coefficient of kinetic friction.

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<th>Date Tests were Run</th>
<th>Al. Plate Cleaned with Acetone</th>
<th>Al. Plate Dirty, with Tomato Juice</th>
<th>Al. Plate Wet with Water</th>
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<td>8-23-77</td>
<td>8-24-77</td>
<td>8-24-77</td>
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<td>Red Side</td>
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<td>.28</td>
</tr>
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<td>.38</td>
<td>.44</td>
</tr>
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<td>.21</td>
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<td>.0056</td>
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<td>.28</td>
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<td>.40</td>
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<td>.30</td>
<td>.19</td>
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<td>7</td>
<td>4</td>
</tr>
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<td>Variance</td>
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<td>.0007</td>
<td>.0085</td>
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<td>.25</td>
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<td>.20</td>
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<tr>
<td>Total Number of Runs</td>
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<td>7</td>
<td>4</td>
</tr>
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<td>.0055</td>
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<td>.38</td>
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<td>.60</td>
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<td>.20</td>
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<td>.0220</td>
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<td>.32</td>
<td>.48</td>
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<td>1.95</td>
<td>.37</td>
<td>.71</td>
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<td>.35</td>
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<td>4</td>
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<td>.69</td>
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<td>7</td>
<td>4</td>
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<td>.0030</td>
<td>.0515</td>
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Appendix E-9

Coefficient of kinetic friction data for Ohio 7669 tomatoes run at plate velocity = 6.248 cm/sec.

<table>
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<th>Green Tomatoes*</th>
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<td>( \mu ) Side</td>
<td>( \mu ) Side</td>
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<td>1.58</td>
<td>.70</td>
</tr>
<tr>
<td>2.13</td>
<td>.68</td>
</tr>
<tr>
<td>1.93</td>
<td>.62</td>
</tr>
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</tr>
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<td>1.80</td>
<td>.54</td>
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<tr>
<td>1.66</td>
<td>.71</td>
</tr>
<tr>
<td>2.47</td>
<td>.80</td>
</tr>
<tr>
<td>2.19</td>
<td>.87</td>
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<td>1.60</td>
<td>1.12</td>
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<td>1.30</td>
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<tr>
<td>1.86</td>
<td>.68</td>
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<td>2.57</td>
<td>.78</td>
</tr>
<tr>
<td>2.57</td>
<td>.54</td>
</tr>
</tbody>
</table>

| Average \( \mu \) | .74 | .57 | .87 |
| Highest \( \mu \) | 2.57| 2.42| 2.66|
| Lowest \( \mu \)  | 1.30| 1.20| 1.58|
| Total Number       | 17  | 8   | 8   |
| Variance           | .1493|.1466|.1300|

* Average of side, blossom and stem: \( \mu = 1.94 \)

**Average of side, blossom and stem: \( \mu = .73 \)

Date harvested and tested: 8-12-77.
Plate clean and dry.
Appendix E-10

Coefficient of kinetic friction data for Ohio 7669 tomatoes run at plate velocity = 20.117 cm/sec.

<table>
<thead>
<tr>
<th>Green Tomatoes*</th>
<th>Red Tomatoes**</th>
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</thead>
<tbody>
<tr>
<td>μ Side</td>
<td>μ Blossom</td>
</tr>
<tr>
<td>1.30</td>
<td>1.79</td>
</tr>
<tr>
<td>1.47</td>
<td>2.13</td>
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<tr>
<td>1.74</td>
<td>.72</td>
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<td>1.26</td>
<td></td>
</tr>
<tr>
<td>1.17</td>
<td></td>
</tr>
<tr>
<td>1.53</td>
<td></td>
</tr>
</tbody>
</table>

| Average μ | 1.41 | 1.55 | 1.35 | .59 | .50 | .75 |
| Highest μ | 1.74 | 2.13 | 1.65 | .86 | .53 | .93 |
| Lowest μ | 1.17 | .72 | .98 | .41 | .49 | .60 |
| Total Number Variance | 6 | 3 | 3 | 6 | 3 | 3 |

* Average of side, blossom and stem: \( \mu = 1.43 \).

**Average of side, blossom and stem: \( \mu = .61 \)

Date harvested and tested: 8-12-77.
Plate clean and dry.
Appendix F

F-1 Average dimensions and weights of processing tomatoes.
Appendix F-1

Average dimensions and weights of processing tomatoes.

<table>
<thead>
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<th>Color</th>
<th>Date Harvested and Tested</th>
<th>Equatorial Diameter (cm) 1</th>
<th>Equatorial Diameter (cm) 2</th>
<th>Axial Diameter (cm)</th>
<th>Weight (grams)</th>
<th>Total Number</th>
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<td>4.4</td>
<td>4.7</td>
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<td>33.7</td>
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<td>4.0</td>
<td>4.4</td>
<td>38.4</td>
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<td>4.4 cm*</td>
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**VARIETY - CAMPBELL 28**

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<th>Equatorial Diameter (cm)</th>
<th>Equatorial Diameter (cm)</th>
<th>Axial Diameter (cm)</th>
<th>Weight (grams)</th>
<th>Total Number</th>
</tr>
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<tbody>
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<td>4.9</td>
<td>87.3</td>
<td>9</td>
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<tr>
<td>Green</td>
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<td>5.5</td>
<td>4.7</td>
<td>76.6</td>
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**VARIETY - CHICO III**

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<th>Equatorial Diameter (cm)</th>
<th>Axial Diameter (cm)</th>
<th>Weight (grams)</th>
<th>Total Number</th>
</tr>
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<tbody>
<tr>
<td>Red</td>
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<td>4.6</td>
<td>4.7</td>
<td>6.3</td>
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<td>5.6</td>
<td>35.8</td>
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* Average of two equatorial diameters and one axial diameter.
REFERENCES CITED


