Paper No. 936542

AN ASAE MEETING PRESENTATION

EFFECT OF IMPACTING MASS ON FIRMNESS SENSING OF FRUITS

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Written for presentation at the
1993 International Winter Meeting
sponsored by
THE AMERICAN SOCIETY OF AGRICULTURAL ENGINEERS

Chicago, Illinois
December 14 - 17, 1993

SUMMARY:

There has been an increased interest in using impact techniques for sensing firmness of fruits and vegetables. When an impacter is used to impact a fruit, the impacting mass is an important parameter which affects both the impact signal and fruit damage. Results of theoretical analysis and tests conducted on two varieties of pears indicate that lowering the impacting mass results in amplifying the measured signal, reducing sensing errors, and minimizing damage to the fruit.

KEYWORDS: **Impact, fruit firmness, quality evaluation, sorting, nondestructive, pears**

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INTRODUCTION

The force response of an elastic sphere impacting a rigid surface is governed by the impacting velocity, mass, radius of curvature, elastic modulus, and Poisson's ratio of the sphere. Researchers have found that the impact of a fruit on a rigid surface can be closely modeled by the impact of an elastic sphere and that the firmness of a fruit has a direct effect on the impact force response. Nahir et al. (1986) reported that when tomatoes are dropped from a 70 mm height onto a rigid surface, the impact force response is highly correlated with fruit weight and fruit firmness. They subsequently developed an experimental tomato grading machine which, by measuring and analyzing the impact force response of the fruit, can separate tomatoes on the basis of weight and color. Delwiche et al. (1987) analyzed impact forces of peaches striking a rigid surface and found that certain impact force characteristics were highly correlated with the fruit's elastic modulus and penetrometer measurements of flesh firmness. A single lane firmness sorting system was developed which used the index F/t^2 (where F and t are the peak impact force and the time required to reach peak force, respectively) to sort peaches and pears into hard, firm, and soft categories (Delwiche et al., 1989). A problem inherent to the technique of dropping the fruit on a force sensor is that the impact force is also a function of the mass and radius of curvature of the fruit. Therefore, a large variation in these two parameters will affect the accuracy in firmness measurement.

A different approach is to impact the fruit with a small spherical impacter of known mass and radius of curvature and measure the acceleration of the impacter. The advantage of this method is that the measured impact-acceleration response is independent of the fruit mass and is less sensitive to the variation of the radius of curvature of the fruit. This technique was first described by Chen et al.(1985) and was used by researchers in Spain for sensing fruit firmness (Jarén et al., 1992; Correa et al., 1992). Ruiz-Altisent et al. (1993) developed a system which used the impact parameters to classify fruits (apples, pears, and avocados) into different firmness groups.

When an impacter is used to impact a fruit, the impacting mass is an important parameter which affects both the impact signal and fruit damage. The objective of this study is to determine theoretically and experimentally the effect of the impacting mass on firmness sensing of fruits.

THEORETICAL DEVELOPMENT

The impact of a spherical impacter on a fruit can be modeled by the impact of a rigid sphere on an elastic sphere. In such an impact, the dynamic response of the impacter is a function of the masses, elastic moduli, Poisson's ratios, radii of curvatures, and the relative (approaching) velocity of the two objects. Based on the theoretical analysis of two impacting spheres given by Timoshenko and Goodier (1951), the magnitude of the peak impact force, F, acting on each body can be expressed as:

$$F = \left(\frac{5}{4} \frac{V^2}{n_1} \right)^{\frac{3}{5}} n^{\frac{2}{5}} \qquad [1]$$

V = relative velocity of approach of both spheres

$$n_1 = \frac{m_1 + m_2}{m_1 m_2}$$

$$n=\frac{4}{3}\frac{E}{\left(1-\mu^2\right)}\left[\frac{R_1R_2}{\left(R_1+R_2\right)}\right]^{\frac{1}{2}}$$

m_1 = mass of impacter
m_2 = mass of fruit
R_1 = radius of impacter
R_2 = radius of curvature of fruit surface
μ = Poisson's ratio of fruit
E = modulus of elasticity of fruit

The maximum deformation, D, of the fruit can be written as:

$$D=\left(\frac{5}{4}\frac{V^2}{nn_1}\right)^{\frac{2}{5}} \qquad [2]$$

And the time required to reach peak force can be expressed as:

$$t = 1.47\ D/V \qquad [3]$$

Assuming negligible gravitational effect (about 2%), one can express the peak acceleration, A, of the impacter as:

$$A = F/m_1 \qquad [4]$$

The ratio of A/t, often used as a firmness index, can be expressed as follows:

$$A/t = 0.68\ FV/Dm_1$$

$$= 0.8954\ V^{1.4}\frac{1}{m_1}\left(\frac{m_1m_2}{m_1+m_2}\right)^{0.2}\left(\frac{E}{1-\mu^2}\right)^{0.8}\left(\frac{R_1R_2}{R_1+R_2}\right)^{0.4} \qquad [5]$$

EXPERIMENTAL PROCEDURE

Tests were conducted to compare the results of firmness sensing obtained with two impacters with different masses. An impact tester (Fig. 1) similar to that described by Chen et al. (1985) was used. The impacter has a 0.019-m diameter spherical tip. The impacting mass, drop height, and acceleration history were recorded for each impact. Two experiments were conducted -- one at the Polytechnic University in Madrid, Spain, and one at the University of California in Davis, California.

Test procedure in Spain. Conferencia pears harvested from a commercial orchard were brought back to the laboratory in Madrid. One box of 30 fruits was stored at 20 °C and another box of 30 fruits was stored at 0 °C in order to produce a wider range of fruit firmness. After three days the fruits were brought out from storage, and impact tests were made after the temperature of the fruits reached room temperature. Four impacts were made at 4 locations along the largest circumference of the fruit using two impacters of 20 g and 50 g mass, respectively, and two drop heights of 2 cm and 4 cm for each impacter. Fruit firmness (not flesh failure strength as measured by the Magness-Tayor method) was measured by compressing the fruit with a 19-mm diameter spherical indenter at a deformation rate of 20 mm/min. The deformation at 10 N compression force was recorded, and the elastic modulus, E, was determined from the following equation (Timoshenko and Goodier, 1951) :

$$E = \frac{3}{4} \frac{F(1-\mu^2)}{D^{1.5}} \left(\frac{R_1 + R_2}{R_1 R_2} \right)^{0.5} \qquad [6]$$

The values of μ and R_2 were assumed constant at 0.49 and 0.035 m, respectively.

Test procedure in California. Bartlett pears harvested from a commercial orchard in Lake County were brought back to Davis. One box of approximately 30 fruits were stored at 20 °C and a second box was stored at 0 °C. After two days the first box was also moved into the 0 °C room. After both boxes were stored at 0 °C for an additional week they were moved into the 20 °C room, and 5 fruits from each box were taken out on the first, third, and fifth days for testing. Impact tests were similar to those made in Spain except that the mass of the lighter impacter was 10 g instead of 20 g. Fruit firmness was measured by compressing the fruit with a 9.5-mm diameter spherical indenter at a deformation rate of 100 mm/min. The compression force at 1.0 mm was used to calculate the value of E using equation [6].

RESULTS AND DISCUSSION

Results of Theoretical Analysis

The following parameters were used in the theoretical analysis: $R_1 = 0.01$ m; $R_2 = 0.035$ m; $\mu_2 = 0.49$; $V = 0.886$ m/s (equivalent to a 4 cm drop height); E = 0.7 MPa for soft fruit and 7.0 MPa for firm fruit.

Based on these parameters and equation [1], we calculated the values of peak force for different impacting masses when they were dropped onto a soft and a firm fruit. Figure 2 shows that, as the impacting mass varies from 0.01 kg to 0.05 kg, the peak force on the soft fruit increases from 6.3 N to 14.8 N, and that on the firm fruit increases from 16.2 N to 42.5 N. Since high impact force is associated with increased fruit damage, this result suggests that a light impacter should be used to avoid fruit damage.

The values of peak acceleration, A, calculated from equation [4], were plotted in Figure 3. The peak acceleration increases from 850 m/s^2 to 1618 m/s^2 when the impacting mass is reduced from 0.05 kg to 0.01 kg for the firm fruit. Since the acceleration signal is the primary measured parameter in firmness sensing, it is desirable to use a lighter impacter because it generates a stronger acceleration signal that is easier to detect and has lower noise-to-signal ratio. In addition to the increase in acceleration, the spread between the peak acceleration obtained with the soft fruit and that obtained with the firm fruit also increases as the impacting mass decreases. This is another desirable feature for firmness sensing. Figure 3 also shows an acceleration curve for a firm fruit that is allowed to move freely during the impact (not fixed). The difference between this curve and that of the fixed fruit decreases as the impacting mass decreases, indicating that the error due to a small movement of the fruit is less critical when a smaller impacting mass is used. This factor is quite important for on-line sorting where it is difficult to hold the fruit stationary during the impact sensing.

The impacting mass has even a greater effect on the firmness index A/t (Fig. 4). The values of A/t for both the firm and soft fruits, as well as the spread of A/t between the two fruits, increase more than threefold when the impacting mass is reduced from 0.05 kg to 0.01 kg. Clearly the firmness index is more sensitive to the change in fruit firmness when a lighter impacter is used. The closeness between the curve for the fixed fruit and that for the free-to-move fruit indicates that the firmness index, A/t, is not sensitive to how the fruit is held during impact sensing.

Experimental Results

The results of tests on Bartlett pears are shown in Figures 5 and 6. Figure 5 shows the relationships between peak acceleration and the firmness (E value) of the fruits for the four combinations of impacting mass and drop height. For the same drop height the peak acceleration of the 10-g impacter is about twice as high as that of the 50-g impacter. In addition, the slope of the regression line, which is the rate of change of the acceleration with respect to fruit firmness, for the 10-g impacting mass is greater than that for the 50-g mass.

Figure 6 shows the relationships between the firmness index, A/t, and the E value. For each drop height, the value of A/t obtained with the 10-g impacter is about 3 times as big as that obtained with the 50-g impacter, and the rate of change of A/t with respect to E for the 10-g impacter is more that 3 times as high as that for the 50-g impacter.

Similar results were also obtained from tests conducted in Spain with Conferencia pears. Figure 7 shows similar increases in both the values of A/t and the slopes of the regression lines as the impacting mass was reduced from 50 g to 20 g.

Table 1 presents a summary of the experimental results. The 10-g impacter did not cause any damage to any of the Bartlett pears tested. The 20-g impacter did not bruise any Conferencia pears at 2 cm drop height but caused bruises to 26% of the fruits at 4 cm drop height. The 50-g impacter damaged 32% of the Conferencia pears and 53% of the Bartlett pears when it was dropped from a 2 cm distance. At 4 cm drop height, nearly all of the fruits were bruised by the 50-g impacter.

The result in Table 1 shows that lighter impacters can be dropped from a greater height without causing fruit damage. Since the error in drop height setting is a constant absolute value (e. g., ±1 mm), increasing the drop height would further reduce sensing errors.

CONCLUSIONS

Both theoretical and experimental results point to the following desirable features associated with low impacting mass:

1. It increases the strength of the measured acceleration signal, thereby facilitating easier detection and minimizing noise-to-signal ratio.
2. It increases both the magnitude of the calculated firmness index, A/t, and the rate of change of A/t with respect to the fruit firmness, E.
3. It minimizes the error due to movement of the fruit during the impact.
4. It minimizes fruit damage caused by the impact.

Therefore, in firmness sensing of fruits, the mass of the impacter should be kept as low as possible, but not too low as to affect the control of the impacting velocity.

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Table 1. Summary of Experimental Results. The values of intercept, slope, and R^2 correspond to the regression lines in Figures 6 and 7.

Variety	Impacting mass g	Drop height cm	Bruised fruit %	Intercept m/s^3	Slope $m/s^3/Pa$	R^2
Conferencia	20	2	0	3.59x105	0.167	0.78
	20	4	26	8.16x105	0.182	0.73
	50	2	32	1.71x105	0.059	0.78
	50	4	79	3.40x105	0.073	0.63
Bartlett	10	2	0	5.26x105	0.189	0.85
	10	4	0	8.66x105	0.259	0.87
	50	2	53	1.53x105	0.053	0.84
	50	4	89	2.06x105	0.092	0.84

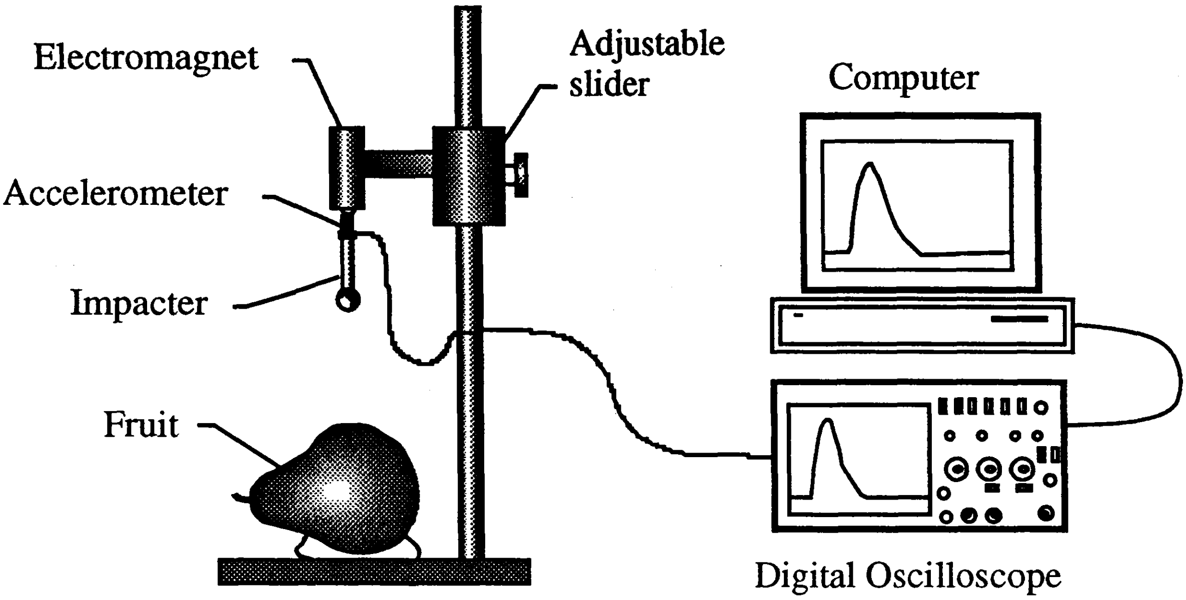

Figure 1. Impact testing system

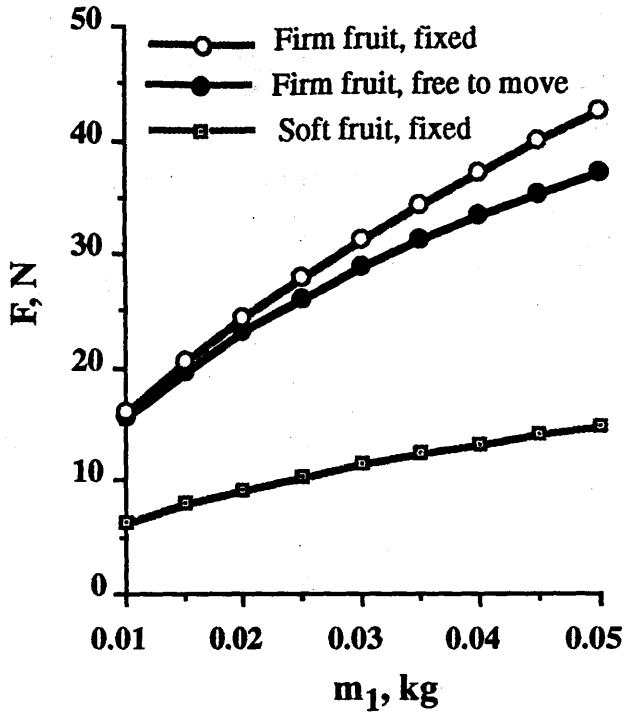

Figure 2. Relationship between theoretically calculated peak force and impacting mass.

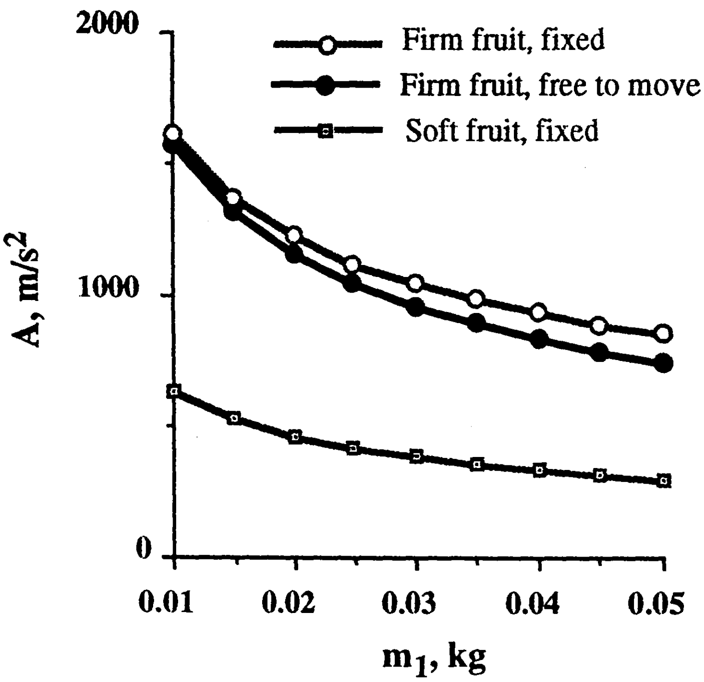

Figure 3. Relationship between theoretically calculated peak acceleration and impacting mass.

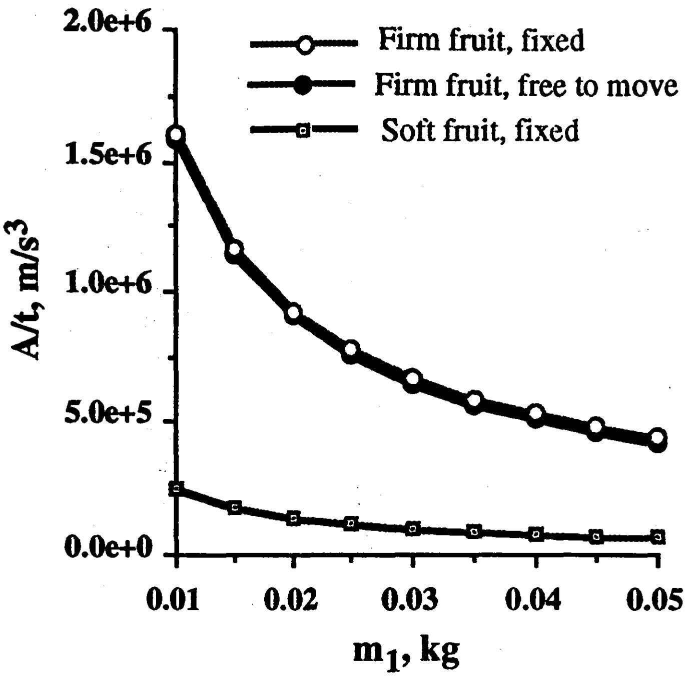

Figure 4. Relationship between theoretically calculated firmness index, A/t, and impacting mass.

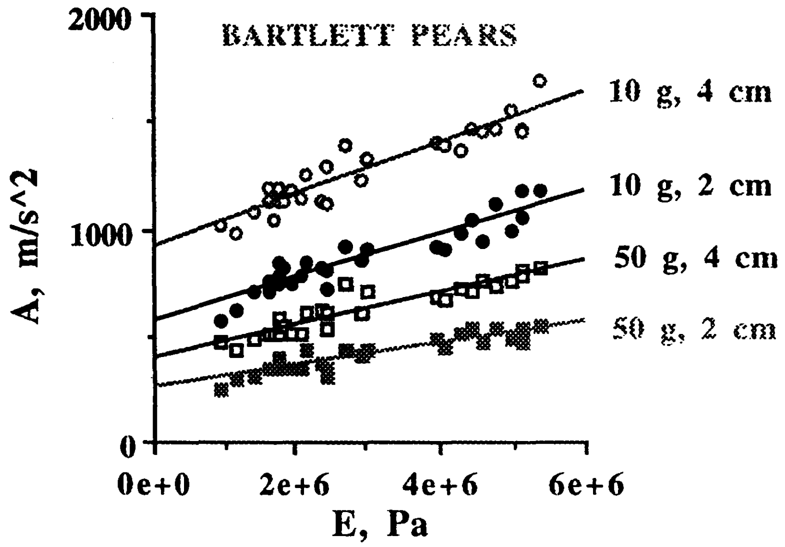

Figure 5. Results of tests on Bartlett pears showing the relationship between peak acceleration and fruit firmness, E.

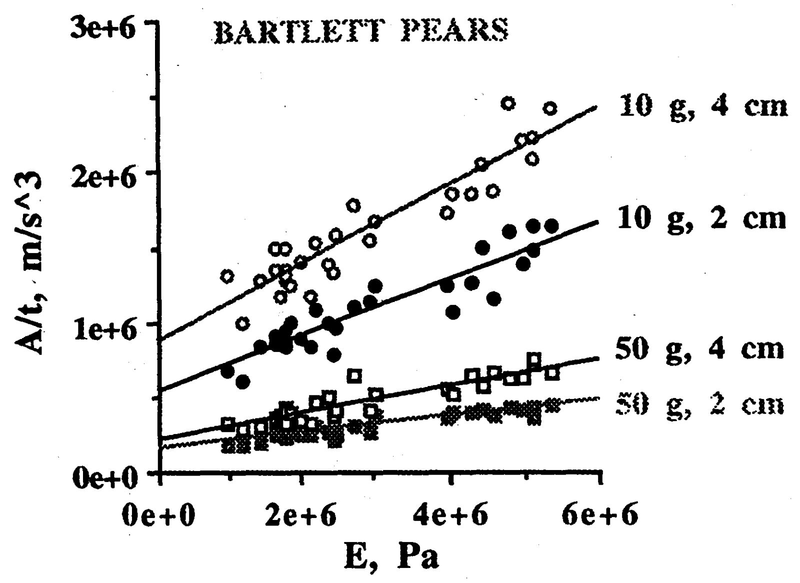

Figure 6. Results of tests on Bartlett pears showing the relationship between firmness index, A/t, and fruit firmness, E.

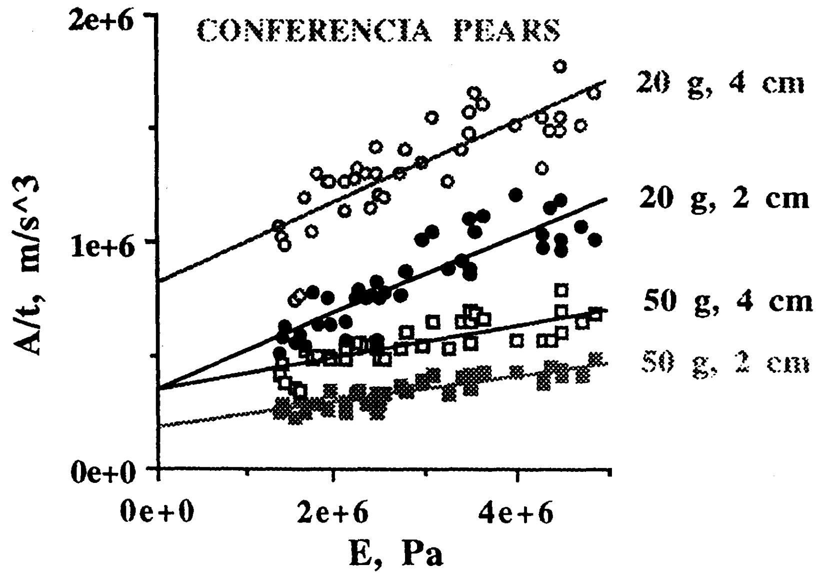

Figure 7. Results of tests on Conferencia pears showing the relationship between firmness index, A/t, and fruit firmness, E.