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APPLICATION OF VIBRATIONAL TECHNIQUES IN DETERMINATION OF DYNAMIC PROPERTIES OF AGRICULTURAL PRODUCTS - STATE OF THE ART

Silas T.A.R. Kajuna [1],   **Gauri S. Mittal**[2]   **and   Valerian C.K. Silayo**[3]

[1] Senior Lecturer and corresponding author, [3] Lecturer
Department of Agricultural Engineering and Land Planning
Sokoine University of Agriculture
P.O. Box 3179, Phone 4216, Morogoro, Tanzania
e-mail: kajuna@suanet.ac.tz

[2] Professor,
School of Engineering, University of Guelph, Guelph, Ontario Canada, N1G 2W1
e-mail: mittal@net2.eos.uoguelph.ca

Abstract

Vibration is one of the techniques employed in the determination of dynamic properties of fruits and vegetables. It entails generation of a mechanical or acoustic vibrational signal which is propagated through the flesh of the agricultural material. A transducer is either attached or held close to the specimen to monitor the propagation of the signal through the specimen. The manner in which the signal is transmitted through the material is analyzed, and the dynamic properties of the specimen which relate to its firmness or its internal being are derived. The technique has been around for the past 30 years or so.

This paper examines the evolvement in the use of the vibrational technique in determination of dynamic properties of agricultural materials (especially fruits and vegetables), and critically discusses the successes and failures of the technique over the past three decades. It points out and discusses the advantages associated with the technique vis-a-vis other testing techniques.

Introduction

The vibrational characteristics of fruits and vegetables are governed by their elastic modulus (firmness), mass and geometry. Therefore, it is possible to evaluate their firmness and other properties based on vibrational characteristics[1]. For many fruits, firmness is highly related to quality, for example peaches, as indicated by a Magness-Taylor firmness test [2] or by the ground colour [3]. Measured firmness of fruits is the basis of quality standards in the USA and Europe [4].

Vibration is one of the techniques which have been employed by various researchers to determine the dynamic properties of agricultural materials, especially fruits and vegetables. The vibrational technique involves the application of either mechanical vibrations [5,6] or sonic (acoustic) waves [7]. The mechanical vibrations could be excited by either a mechanical vibrator, or an impact on to an agricultural material to send vibrational waves through the flesh of the material. The acoustic signals could be excited by any sound wave generating mechanism, such as a loudspeaker [8], or by impacting a product [9]. The vibrational signals are propagated through the specimen, and they are picked and recorded by a sensor or transducer which is either attached (by some

Table 1. Table of natural frequencies and other parameters for various agricultural products as obtained by various researchers.

Researcher(s)	Product	Mode of vibration	1st Natural Frequency (Hz)	2nd natural frequency (Hz)	Other properties determined	Remarks
1 Finney et al.,(1967)	Sliced bananas	Acoustic resonance	375-448	---	Elastic Modulus	---
2 Abbott et al., (1968)	Sliced and intact apples	Acoustic resonance	---	600-800	Youngs Modulus, Stiffness Coeff.	3rd was >1000Hz.
3 Hamman and Carroll (1971)	Intact muscadine grapes	Non-destructive mechanical vibration	100-200	---	---	---
4 Finney et al., (1978)	McIntoshi apples Delicious apples Stayman apples	Non-destructive sonic resonance	350	970	Firmness index (f^2 m)	---
5 Yong and Bilanski (1979)	Red Delicious intact apple	Non-destructive mechanical resonance	110	900	---	Freely Vibrating fruit
6 Yamamoto et al., (1980)	Delicious apples Water melon	Impact vibration By pendulum	610-820 130-180	---	Damping factor (150/s, to 250/s; Peak frequency)	---
7 Peleg et al. (1990)	Intact avocado	Non-destructive Mechanical vibration 200-220 for soft	280-300 for hard fruits	610 - 820 Hz) 1700-1800 (hard) 1000-1300 (soft)	firmness index	---
8 Peleg (1993)	Intact apple	Non-destructive Mechanical vibration	---	---	Firmness sensitivity Index	---
9 Peleg et al., (1993)	Intact melon	Non-destructive Mechanical vibration	---	---	Firmness depicted By Peleg Firmness Test (PFT)	---
10 Huarng et al .(1993)	Intact apples	Impact vibration to obtain acoustic signals	820	1260	---	3rd one was 1500
11 Liljedahl and Abbot (1994)	Delicious apples	Sonic vibrations	200-400	600-1000	---	---
12 Kajuna et al., (1996);and (1998)	Intact plantains	Non-destructive Mechanical vibration	50 soft 100 hard	200 soft 300 hard	Damping, Critical damping, Stiffness	Freely vibrating fruit

means) to the specimen, or is held very close to the specimen. The recorded signal(s) is normally processed and analyzed in order to reflect the dynamic properties of the material in question.

The challenge to the scientists has always been to come up with a non-invasive and non-destructive vibrational technique for the determination of the dynamic properties of agricultural materials. The ideal situation which the scientists should seek to achieve is that, if the specimen is tested in a non-destructive manner, then it should be available for either human consumption, or for fresh marketing, or even be allowed to continue growing on the mother plant if it was found to be immature at the time of testing. Unfortunately, reported literature has not addressed itself to this.

Vibrational tests with a view to measuring the properties of fruits and vegetables, particularly their degree of ripeness, were first introduced in 1942. However, the subsequent two decades saw little if any significant information published on the same [10]. Vibrational testing started to pick up during the late nineteen sixties, when Finney [11] used sonic technique to evaluate the changes in ripeness of bananas; and Abbot et al., [12] applied acoustic vibrations to determine the properties of both sliced and whole specimens of apples. The technique gained momentum in the nineteen seventies [5, 13, 4] and nineteen eighties [15, 16] and has continued to be explored further in the 1990's [17,18,19]

The objective of this paper is to examine how the application of vibrational technique has unrolled in the past three decades, and the impact it has had on the fruit and vegetable handling industry. It critically discusses the achievements plus the bottlenecks

encountered in the process. It also projects on the future and potential of the technique in the determination of dynamic properties of agricultural materials.

Types of vibrational tests

There are two main types of vibration testing, namely, resonance vibration and random vibration techniques [20]. In resonance testing, the material (or part of the material) is vibrated through a range of frequencies until the vibration hits the natural frequency. The latter is then used in calculation of such other parameters as the Young's Modulus of Elasticity [11] and the damping properties [6].

Finney and Norris [21] showed that the

$$E = 4 \rho f_1^2 L^2 \quad (1)$$

Young's Modulus of elasticity (E) of a cylindrical specimen could be determined from the equation
where ρ is the density of the specimen, f_1 is the longitudinal natural frequency and L is the length of the specimen. Since f_1 depends on boundary conditions of the cylinder, the cylinder must be supported at the centres with the ends of the cylinder left free to vibrate, and the cylinder must be excited longitudinally from the ends.
Kajuna et al.,[6] vibrated intact plantain fruits

$$C = \frac{C_c}{2 \sqrt{\left[\dfrac{Y}{X}\right]^2 - 1}} \quad (2)$$

to the natural frequency after which the damping of the fruits was obtained from equation 2,

where C is the damping of the fruit, C_c is the critical damping and Y/X is the amplitude ratio (where X and Y are, respectively, the input and output functions).

The natural frequency technique has been used by various researchers to determine the dynamic properties of various products, for example, Finney and Norris [21] on apples; Abbott et al., [12] on apples; Stephenson et al., [8] on tomatoes; Hamman et al., [13] on blueberries; Yong and Bilanski [5] on apples; Liljedahl and Abbot [22] on apples; Kajuna [18], Kajuna et al., [6] and Kajuna et al., [19] on plantains.

In the random vibration technique, the vibrations tend to excite all resonances within the material simultaneously [23]. Through proper use of filtering techniques, interaction effects of resonances may be combined over a small region of the frequency spectrum, thereby averaging the vibration response signal. This technique, however, has not been very popular, and a thorough search of literature has revealed that only one researcher [23] has used it on apples.

Instrumentation used in vibrational techniques

Vibrational techniques of testing the dynamic properties of agricultural materials and correlating these tests with the sensory evaluations of the texture of the materials have been used extensively by various researchers. Finney and Norris [21] used a vibrational instrumentation to determine the resonances of intact apples from which such dynamic properties as Young's Modulus of elasticity of the fruit were determined. The instrumentation entailed strapping the fruit on to a vibration exciter using pliable clay and an elastic band, while the vibrational signal was picked by the accelerometer attached at the top of the fruit (Figure 1)
The same instrumentation (Figure 1) was

adopted by Finney [24] and Stephenson et al., [8] to determine the mechanical resonance in red delicious apples and tomatoes respectively, which they related to the texture of the fruits. The first resonant frequency for red delicious apples that was obtained by Finney [24] using this instrumentation (Figure 1) was found to have a mean of 318 Hz while the second natural frequency was in the range of 832 Hz (Table 1). It is important to note that the orientation of the fruit with respect to principle axis is
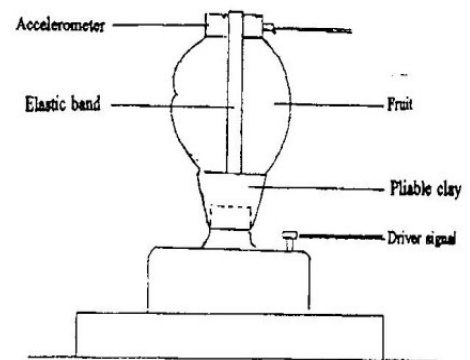

Fig. 1. Instrumentation for determination of vibrational properties of fruits [21]

likely to affect the results obtained. Thus, for detecting varietal differences in apples (or other fruits), it is advisable to keep the same orientation of the fruits.

A criticism was raised by Abbott et al., [17] who argued that the use of pliable clay by Finney [10] and Finney [24] as a contact medium between the fruit and the shaker mechanism was time consuming and the clay was sticking to the fruit. They [17] advocated the use of floral clay as it provided the best contact, and maintained that it provided best transmission of vibrational energy.

However, the instrumentation was further criticised by Yong and Bilanski [5] who used a freely vibrating red delicious apple on a vibration exciter to determine the vibrational characteristics of the fruits. They reported that the first resonant frequency for the apples

ranged between 100 and 150 Hz, less than half of the results reported by Finney [24]. This range of variation of the natural frequencies is apparently large (i.e. 100 to 150 Hz), possibly due to the heterogeneity of tissues of agricultural materials as opposed to homogeneity of other engineering materials, such as steel. They [5] argued that any artificial means used to hold the fruit down to the vibrating table, such as the use of elastic band and pliable clay in Figure 1, alters the natural spring constant of the fruit thereby affecting the first natural frequency. The second natural frequency, however, was similar to that reported by Finney [24].

The Young and Bilanski [5] instrumentation was modified and used by Kajuna et al., [19] to determine the dynamic properties of intact plantains (Figure 2). In this instrumentation, Kajuna et al., [19] used two accelerometers, namely, the input signal accelerometer and the light-weight response accelerometer. The input signal accelerometer recorded the vibration of the mechanical exciter from which the input amplitude was deduced. The response accelerometer was attached on to the plantain fruit and recorded the signal that was transmitted through it, from which the response amplitude was deduced.

The instrumentation used by Peleg et al., [25]

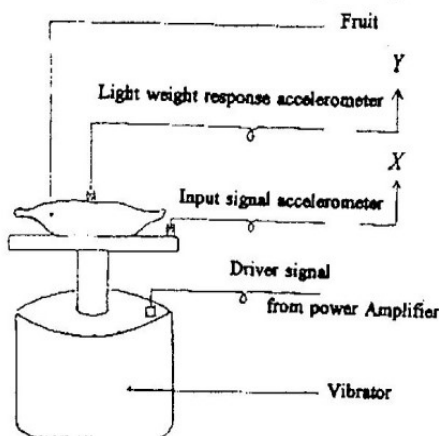

Fig.2. Freely vibrating fruit on a mechanical

vibrator [19]

and Peleg [26] to determine the firmness of melons, was similar in arrangement to the one used by Yong and Bilanski [5] and Kajuna et al., [19]. Rather than using the resonance technique to analyze the mechanical properties, Peleg [26] used a direct firmness index, termed Peleg Firmness Test, (PFT), given by equation 3. where Xi and Xo are the r.m.s. values of the input and output accelerations respectively.

The technique was successful in detecting the

$$PFT = \frac{\ddot{X}_0}{\ddot{X}_0 - \ddot{X}_i} \qquad (3)$$

differences in firmness for singly tested melons [25].

Another instrumentation that has been used to determine the properties of fruits and vegetables, is shown in Figure 3. It is a
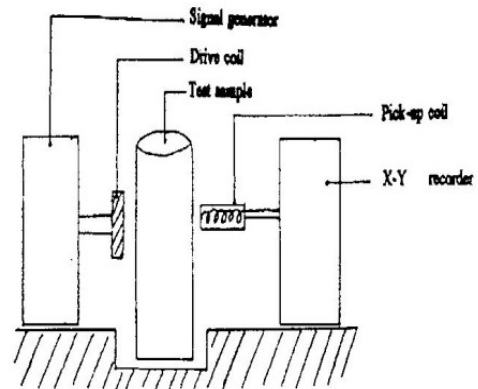
schematic arrangement of an acoustic technique where the sound waves, generated Figure 3. Schematic representation of an acoustic instrumentation for measurement of the natural frequency in a specimen of an agricultural material (Modified from Abbot et al., [12]).

by a loudspeaker, are propagated through the sample (but without touching the sample) and the signal is picked and processed by a sensor (which also does not touch the sample) on the opposite side of the test specimen.

Advantages of vibrational testing

Vibrational testing techniques for determination of the dynamic properties of agricultural materials, offer advantages over most other mechanical tests. Firstly, the time of testing is very short, and therefore, a variety of wide temperatures and frequencies can be scanned within a practical time frame [27]. Secondly, other tests, for example quasi-static are slow, and may lead to deterioration of the samples being tested. Thirdly, apart from being rapid, the vibrational technique is advantageous in that it is non- invasive, and, in some cases, non-destructive.

Classification of dynamic testing

Morrow and Mohsenin [28] classified the methods of dynamic testing of the properties of agricultural materials into four categories, namely 1. Direct measurement of stress and strain 2 Transducer Methods 3. Resonance methods and 4. Wave propagation methods. These methods were discussed in detail by Rao and Griffin [27]. However, this classification appears to be misleading, because the 'direct measurement of stress and strain methods' involves the use of transducers in order to determine the signals generated. So do the resonance methods, where the transducers are also required to register the resonance condition. The wave propagation methods may also employ the resonance technique in order to determine such other mechanical properties as the elastic modulus, as was determined by Finney [11]. Equally, the wave propagation methods will also need the use of transducers as exemplified by Mizrach et al, [16] who

determined the wave propagation velocity and attenuation properties of fruit and vegetable tissues by ultrasonic excitation. (Their approach however, involved the use of cut samples, a method which is destructive.)

It is suggestible here, that the correct classification of dynamic testing techniques for the properties of agricultural materials be as follows: 1.Destructive techniques and 2. Non-destructive techniques.

The destructive techniques are the ones which destroy a product, for example, the use of penetrometer for firmness testing [25, 26]. Once a product has been involved in a test, it can not be available for marketing. These involve such techniques and cutting cubes and cylinders of agricultural samples for impact and vibrational testing. The destructive techniques may include impact vibration such as simulation of multilayer transportation in-transit damage of fruits and vegetables during truck transportation.

The non-destructive dynamic testing techniques on the other hand, involve techniques which, after the tests, the specimen may be available for re-use or marketing. These involve such techniques as low-level mechanical vibration methods, ultrasonic techniques, low-level impacts, Nuclear Magnetic Resonance (NMR) imaging, optical reflectance , and the use of instrumented spheres (Kajuna and Bilanski, 1991).

Dynamic properties that can be derived from vibrational tests

(i) Stiffness coefficient

In order to obtain an index for the determination of the vibrational properties of agricultural materials, the *stiffness coefficient*, (or index of firmness) defined by $(f_{n=2})^2 m$, (where $f_{n=2}$ stands for the second lowest resonant frequency, while m is the mass of the

fruit) was proposed by Abbot et al., [12] and adopted by other researchers [10,14,24] to estimate the dynamic elastic properties of the fruit flesh and to measure maturity. It was argued that this index was highly correlated with texture and Finney et al., [14] reported that the index decreased progressively with storage time for apples stored at 0°C. The index was proposed in order to compensate effectively for the fruit mass or size. However, Cooke [30] used the vibrational data obtained by Abbott et al., [12] and Finney [10, 24] to test the validity of this stiffness index. Through linear regression, Cooke [30] demonstrated that the stiffness coefficient should be modified to $(f_{n=2})^2 m^{2/3}$ and argued that the new coefficient generally reduced the variations about the regression. Peleg et al., [31] further discredited the $(f_{n=2})^2 m$ index by arguing that computation of this index requires weighing each product and finding its resonant frequency, which is not a simple task in real time classification, since most products have more than one resonant

$$K = m\omega_n^2 \qquad (4)$$

frequency.

(ii) Stiffness

The stiffness, K, has been defined as a measure of firmness in a fruit, and is an indirect reflection of its elasticity. It may be presented as a function of fruit mass and its natural frequency as follows [18]

In intact plantain fruits, the stiffness was found to decrease from 8456.2 N/m for green and hard fruits to 2465.5 N/m for yellow and soft fruits [18]. Bower and Rohrbach [32] reported the stiffness constant for berries to lie between 8320 and 9700 N/m.

(iii) Natural frequency

The natural frequency of a material, is the frequency of vibration at which the material will go to resonance. This is an important parameter in the vibrational properties of fruits and vegetables, because it is used in derivation of such other properties as elastic modulus [21], the stiffness and critical damping [6] and stiffness index [12].

(iv) Damping ratio

The damping ratio is the ratio of the damping coefficient of a material to its critical damping. The critical damping is the damping of a material such that its mass would move from its extended position to its static equilibrium position in the minimum time without oscillating [33]. It has been reported [24] that as a fruit softens, its viscous or damping properties may increase. Kajuna et al., [6] reported that as intact plantain fruits ripened, there was a significant increase $(p < 0.01)$ in the damping ratio of the fruits.

v) Attenuation coefficient

Attenuation is a term used in acoustics to describe the progressive decrease in the amplitude and eventual fading away of the vibrational signal. Mizrach et al., [7] used an acoustical instrumentation to determine the degree of wave attenuation in melon tissue. They reported that the attenuation coefficient, α, could be expressed by eq. 5, where L = thickness of the melon tissue, A_L = wave

$$A_L = A_o Exp(-\alpha L) \qquad (5)$$

amplitude at L, A_o = wave amplitude of transmitter. They reported that the acoustical attenuation of a transmitted pulse strongly

increased with the depth of the fruit sample.

Sarkar and Wolfe [34] used a set of instrumentation to determine the attenuation coefficients of various materials including tomatoes, oranges and husked corn. They reported that the total loss (attenuation and reflection) could be calculated from the using eq. 6 below:

$$T = 20\log_{10}\frac{A_T}{A_t} \qquad (6)$$

where T is the total loss, A_T is the amplitude of through-transmitted energy and A_t is the amplitude of transmitted energy without the test material being placed between the two sensing transducers. They concluded that the loss due to attenuation was linearly dependent on the thickness of a given material, while the reflection loss was independent of the material thickness. They related the attenuation coefficient, the material thickness and reflection loss, B, to the total loss as follows:

$$T = \alpha L + B \qquad (7)$$

Effect of peel on the vibrational behaviour of fruits and vegetables

In an endeavour to find out if the skin of a fruit or vegetable has an effect on its vibrational properties, some researchers have ventured in to such a study.

Abbot et al., [12] vibrated and recorded the resonance of intact and pealed apple fruits. They found that the second resonant frequency decreased sharply after peeling, and concluded that the skin helped to reinforce and stiffen the structure to a marked degree.

Armstrong et al., [35] used a wax ball of 20mm diameter to strike on to an apple fruit and the acoustic signal emitted by the apple was recorded by a microphone positioned near the equator of the apple. Through Fast Fourier Transform (FFT) of the signal, the natural frequencies of intact Paula Red and Golden Delicious apples were determined. Thereafter, the skin was cut by a shallow, multibladed knife over the apples surface and the tests repeated. They found that apples cut in this manner had stable lower natural frequencies than did intact fruits, which was a further proof that the skin exerted an influence on the vibrational properties of the fruits by reducing the resonant frequency.

On the contrary, Liljedahl and Abbot [22] obtained different results. They used sonic transmissions through intact apples in order to measure, among other parameters, the resonant modes of intact Delicious and Golden Delicious apples. The sonic signal exciter consisted of an electromagnetic vibrator, on to which the apple was laid on its cheek. An accelerometer was attached on top of the fruit and used to detect the vibration of the fruit. After determination of the natural frequency of the intact fruits, the same fruits were cut with successive slits ≤ 1 mm deep using a razor along the latitudes and longitudes of the fruits but no tissues were removed. The vibrational spectrum was again recorded after each cut. They reported that the initial slit through the skin (single stem-to-calyx cut) frequently caused a slight increase (0.5 to 1%) in the resonant frequencies while subsequent cut had negligible effects on the resonant frequencies.

Kajuna et al, [19] used an instrumentation described in Kajuna et al., [6] to study the vibrational characteristics of intact plantains. They argued that, since the skin-to-pulp ratio is considerably high, the latter could exert a substantial influence on the vibrational behaviour of the fruit. Thus, they used a two-degrees-of-freedom model, to simulate the vibration of the pulp in relation to the skin. Their model successfully separated the

vibrational effect due to the peel from that due to the pulp, and concluded that the skin exerted a pronounced effect on the vibrational properties of the intact fruit.

Although Liljedahl and Abbot [22] failed to register a substantial effect of skin on the vibration of fruits , it can be argued that perhaps it was by shear bad luck. Logically, the peel has different physiological properties from those of the pulp. The peel helps to enclose and stiffen the pulp, which can be likened to elevation of natural frequency of fruits by tight packaging.

Critical discussion

Although the vibrational approach has introduced a fairly non-destructive technique for determination of mechanical properties of agricultural materials, we can nevertheless maintain that to-date, the techniques are not all that non-destructive.

Firstly, some vibrational techniques such as those used by Abbott et al., [12] involved the use of a sample cut from an apple, and already that was a destructive approach.

Secondly, even the approaches used by Peleg et al., [25] and Peleg [26] on intact melons could not be used on a melon that is to be allowed to continue growing. The melon has to be harvested for testing. What if it is not mature enough? Can it be returned to the field to continue growing? Equally the low-level vibrational approach used by Kajuna et al., [6] and Kajuna et al., [19] on intact plantain fruits still had an inherent element of being destructive, because the plantain fruits had to be harvested first before they could be tested, and they had to be separated in to individual fingers.

Nevertheless, measurement techniques based on sonic and ultra sonic transmissions, force/deflection and vibrational responses do require coupling of transducers on to the fruit surface, and are inherently slower than those based on impact response [36] - a disadvantage.

However, in the studies conducted by Finney and Norris, [21] Abbot et al., [12] Yong and Bilanski [5] Peleg et al., [40] Kajuna et al., [6, 18], there was a good level of reproducibility of the results which were obtained for a given sample. When a different sample was tested, the results for the natural frequency showed some variations. This was due to the fact that agricultural materials (even of the same species) are made up of heterogeneous tissue. The difference in weight and age of specimen, lignin, cellulose and hemi-cellulose content are likely to give differences in the results obtained for the natural frequency.

In the opinion of the authors, a technique could be termed purely non-destructive if it could determine the properties of a fruit or vegetable non-invasively in the field, without having to harvest the product. For example, a signal-emitting device (say vibrational wave or light) could simply be held in the hand of a researcher and walk across a field while pointing the device in the direction of the growing product. In case the product(s) is found not ready for harvest, it could be allowed to continue growing naturally and its growth could be monitored by that technique until it is horticulturally mature, and is ready for harvesting. Such a technique has yet to be developed, and Delwiche and Sarig [36] reported that there is no commercial equipment for non-destructive firmness sorting of fruits or vegetables.

Importance of studying the vibrational properties of agricultural products

Kajuna et al., [6] reported that plantain fruits subjected to vibration would go to resonance in the range of 50 to 100 Hz. Such a range of frequencies should be avoided during transportation. O'Brien and Gillou [37] suggested that tight packaging of fruits would elevate the natural frequency hence the fruits resonance would be well above that of a truck. In peaches, when the truck frequency is about 10Hz, the bottom layer of fruits would have an acceleration of approximately 0.2 g (approx. 2 m/s^2). Truck frequencies of vibration have been reported to reach as high as 20 Hz, in which case top layers of fruits could have amplitudes large enough to give accelerations of up to 1 g (9.81 m/s^2), where the fruits experience weightlessness and start to abrade against each other [37].

Small fruits such as blueberries and grapes can be sorted on the basis of firmness by means of low frequency vibration [1].
Ultra-sonic techniques have been successfully used for detecting the internal being of agricultural materials. For example, Chen and Sun [1] reported that the sonic technique has been used to assess the internal soundness of fruits; and, in animals, it has been used to assess the amount of lean meat, fats and subcutaneous fats.

Finally, the vibrational approach has been used successfully by Tseng and Bilanski [38] for settling the bulk of corn.

Conclusions

The vibrational techniques have been successfully used to determine the mechanical properties of agricultural materials. Although some of the tests have been non-destructive, some of them have been destructive. But even the non-destructive ones have an inherent nature of being destructive. A lot of research work has been done on vibrational testing, but none of them has addressed itself to determination of properties of fruits and vegetables on the mother plant. If the future of vibrational techniques is to be brighter, there is a need to channel research efforts in this direction

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