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INFLUENCE OF THE APPLE PROPERTIES ON RELIABILITY OF IMPACT EXCITATION IN FREQUENCY MEASUREMENTS OF APPLES

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A b s t r a c t. Impact excitation and frequency response measurements look promising as a nondestructive firmness measurement for apple. In this work the influence of the apple properties including firmness, local shape, damping and Poisson's ratio on the impact excitation is studied on the basis of a force model and using the excitation frequency and the internal stress as criteria. The change of the elastic modulus between 2 to 12 MPa, weight between 100 to 250 g, and coefficient of restitution below 0.8 does not influence the reliability of the excitation using the optimal excitation parameters. When the radius of the local shape in the contact surface of an apple is far less than 31 mm, the impact may not excite the spherical mode and even cause damage to the apple. Suggestions are given for the location of the impact excitation on the apple surface. Poisson's ratio is found to have little influence on the impact excitation.

K e y w o r d s: apple, impact excitation, frequency response, fruit firmness

INTRODUCTION

Resonant frequency of an intact fruit is a nondestructive parameter reflecting the fruit firmness. After several decades of research, detailed understanding of the fruit behaviour during frequency measurement has been obtained by the discovery of the existence of two basic types of mode shapes designated as torsional mode and spherical mode [1-3,6-8,11,17-18, 20]. Their resonant frequency f is related to the flesh firmness of the fruit via the stiffness factor $f^2 m^{2/3}$ with m being the fruit mass.

Meanwhile, efforts have also been made to develop instrumental systems for frequency measurements [1,9,19]. These years, the measurement systems are improved for practical purpose in two aspects. One is the use of microphones to replace accelerometers for non-contact measurement of response signal, which means that the spherical modes turn out to be the only type able to be detected. Another improvement is the use of an impact signal to replace swept sinusoid and random signal for fast excitation of the spherical modes. This improvement makes on-line automatic measurement possible.

Mechanical excitation has been the only impact means to excite the fruit, which was performed by releasing an impact mass on to the fruit surface [2,4,19]. Yamamoto *et al.* [19] used a ball pendulum with a wooden ball of 8.5 g in weight and 24 mm in diameter attached to the end of a string of 84 mm in length to excite apples and watermelons. Amstrong *et al.* [2] used in their measurement of apples a hammer consisting of a wax ball of 20 mm in diameter attached to the end of a steel rod to induce vibrations. Under the condition that the lowest spherical mode of an apple, with the average property of 175 g in weight, 8 MPa in Young's modulus and 80 mm in the diameter of the equator, is excited without any potential damage to the fruit, the optimal excitation parameters are given as: the weight of the hammer of 10 g, the initial contact velocity of 1.4 m/s, elastic modulus of the hammer in the contact area more than 40 MPa, the contact surface being flat [5]. This is the only work done so far concerning the reliability of the impact excitation system.

Real apples vary considerably in their properties. The objective of this research is to investigate if the optimal excitation parameters derived with respect to a single apple of average quality remain reliable in the case of the apples that differ in properties including firmness, shape at the contact area, damping, Poisson's ratio and so on.

METHODS

A force model with hysteresis damping

This research is based on a force model with hysteresis damping and two criteria for reliable excitation. Figure 1 shows an example of the excitation signal measured by a force

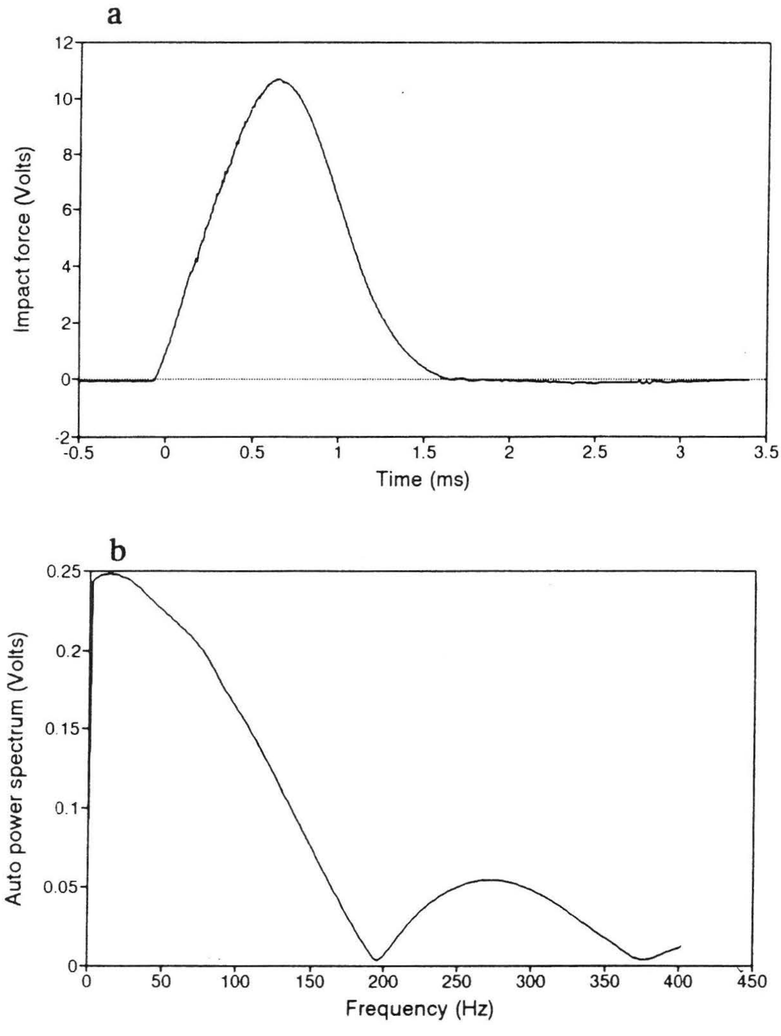

Fig. 1. An example of the impact excitation signal from measurement: time domain force (**a**) and frequency domain power spectrum (**b**).

transducer fixed at one end of a small hammer when the hammer impacts an apple. During the compression phase, the impact force increases from zero to a maximum value, and in the subsequent separation phase the maximum impact force decreases back to zero (Fig. 1a). Due to the viscoelastic texture of the apple, the impact force curve is unsymmetric with the change of the force being sharper in the compression phase than in the separation phase (Fig. 1a). In the frequency domain, the corresponding energy spectrum of the impact force is distributed in several ranges referred to as lobes (Fig. 1b). Describing the apple texture as a Kelvin-Voigt model, such an impact force can be approximated by a force model with hysteresis damping used by Lankarani in the case of the impact of multibody systems [13]:

$$F = K\,\delta^{2/3}\left[1 + \frac{3}{4}(1-e^2)\,\frac{\dot{\delta}}{\dot{\delta}_o}\right] \quad (1)$$

where F is the impact force, K is a parameter related to the elastic modulus, Poisson's ratio and the radius of both spheres, δ and $\dot{\delta}$ are the deformation and deformation rate of the apple in the contact area during impact, $\dot{\delta}_o$ is the initial contact velocity of the hammer, e is the coefficient of restitution of the apple. In the case of the optimal excitation parameters, Eq. (1) can be further expressed as:

$$F = \frac{4}{3}\,\frac{E_2 R_2^{1/2}}{1-\nu_2^2}\,\delta^{2/3}\,[1 + 0.536\,(1-e^2)\,\dot{\delta}\,] \quad (2)$$

where R_2 is the radius of the apple in the contact area, E_2 is the elastic modulus and ν_2 is the Poisson's ratio of the apple flesh. Concerning the hysteresis damping, the compression pressure p_o at the centre of the contact area [12] can be given as:

$$p_o = \frac{2a}{\pi R_2}\,\frac{E_2 R_2^{\;1/2}}{1-\nu_2^2}\,[1 + 0.536\,(1-e^2)\,\dot{\delta}] \quad (3)$$

with a - the radius of the contact area.

In an impact excitation experiment, the apple was supported in its lower part, and excited by the hammer on its top [4]. For such a set-up, the impact force F can be expressed according to Newton's law as:

$$F = m_1\,(g - \ddot{\delta}) = 0.01\,(g - \ddot{\delta}) \quad (4)$$

where m_1 is the weight of the hammer, and the suggested optimal value is 0.01 kg; $\ddot{\delta}$ is the acceleration of the hammer during impact. Combining Eqs (2) and (4) yields:

$$\ddot{\delta} = g - \frac{400}{3}\,\frac{E_2 R_2^{\;1/2}}{1-\nu_2^2}\,\delta^{2/3}$$

$$[1 + 0.536\,(1 - e^2)\,\dot{\delta}] \quad (5)$$

Equation 4 is a nonlinear second-order differential equation. In order to calculate the impact force F, Eq. (4) is first solved numerically for δ, $\dot{\delta}$, and $\ddot{\delta}$ by using FORTRAN computer language performed in a Vax8520. The time domain force representation is then derived from Eqs (2) or (4). The frequency domain force representation is the Fast Fourier transform (FFT) of the force in time domain.

From the above equations, we may note that the apple properties including firmness represented by the elastic modulus E_2, local shape in the contact area represented by the radius R_2, damping represented by the coefficient of restitution e and Poisson's ratio ν_2 have direct influence on the character of the impact force.

Criteria for reliable impact excitation

Reliable excitation should guarantee that the lowest spherical mode is excited. As can be seen from Fig. 1b, the energy of the impact force is mainly concentrated in two frequency lobes. The spherical mode of an apple can not be excited if its resonant frequency falls in the frequency where exists a valley between two neighbouring lobes. For a mechanical excitation system, the energy in the second lobe was found to be easier to be used for exciting the spherical mode [5]. Two points with their magnitude as much as half of the maximum value of the lobe are selected and defined as half power points, and the frequency range between these two points is defined as half power range. In order to excite the spherical mode, the half power frequency range should involve the resonant frequency. This is the first criterion for reliable excitation.

Reliable excitation should also guarantee that the apple does not suffer any damage during impact. It was reported that fruit damage occurs when the shear stress inside the apple exceeds the yield shear stress of the apple tissue [10,14,15]. During impact, the maximum shear stress is about $0.31p_o$, and it occurs inside the apple at a distance of 0.48 a from the contact surface along the central line [12]. Therefore, the second criterion for reliable excitation is that the maximum shear stress has to be below the yield shear stress of the apple.

RESULTS AND DISCUSSION

The apple is irregular in the shape. Its firmness and damping may change with the maturity. All these parameters are uncontrollable during the frequency measurement. These variations may influence the impact excitation using the optimal excitation parameters.

Influence of firmness

Figure 2 illustrates the influence of the apple firmness on the impact force. When excited with the optimal excitation parameters, the impact force on harder apples has a shorter time duration and a higher peak force (Fig. 2a). Correspondingly its energy appears to be at a higher frequency range (Fig. 2b). The peak value and the shape of the second lobe do not change obviously.

For Jonagold apples the elastic modulus may vary from 12 MPa to 2 MPa, depending on the maturity stage. The weight may range between 100 g and 250 g [5]. The spherical resonant frequency of the apple and the corresponding half power range at the above firmness range are illustrated in Fig. 3a where the dashed lines correspond to the resonant frequencies of the spherical mode at two extreme weights of 100 g and 250 g respectively. The resonant frequency of other Jonagold apples falls in between these two dashed lines. These are the results of the finite element simulation [5]. The range between the solid lines represents the half power range obtained under the optimal excitation parameters. The yield shear stress from measurements and the maximum shear stress during the impact are shown in Fig. 3b.

As the apple becomes softer, its resonant frequency decreases. Meanwhile the half power range moves towards lower frequency. It may also be noted that the resonant frequency drops a little more than the half power range during the ripening of the apple. For hard apples with the elastic modulus of 12 MPa, the resonant frequency range is situated in the upper part of the half power range. For soft apples with the elastic modulus of 2 MPa, the resonant frequency range is situated in the lower part of the half power range. The fact that the two dashed lines are always kept within the solid lines indicates that the impact under the optimal excitation parameters can excite the spherical mode of the Jonagold apples in the considered weight and firmness range.

From Fig. 3b it can be noted that both the yield shear stress and the maximum shear stress decrease with the ripening of the apple, and the latter decreases a little more. The impact excitation will not cause any damage to the apples in different ripeness stages since the maximum shear stress never exceeds the yield value.

It can be concluded that the apple firmness may affect the impact force. However, this influence does not reduce the reliability of the impact excitation since the change of the impact force coincides with the change of the apple properties such as the resonant frequency and the yield shear stress.

Influence of shape in contact area

The shape in the contact area of an apple can be characterized by the two principle radii

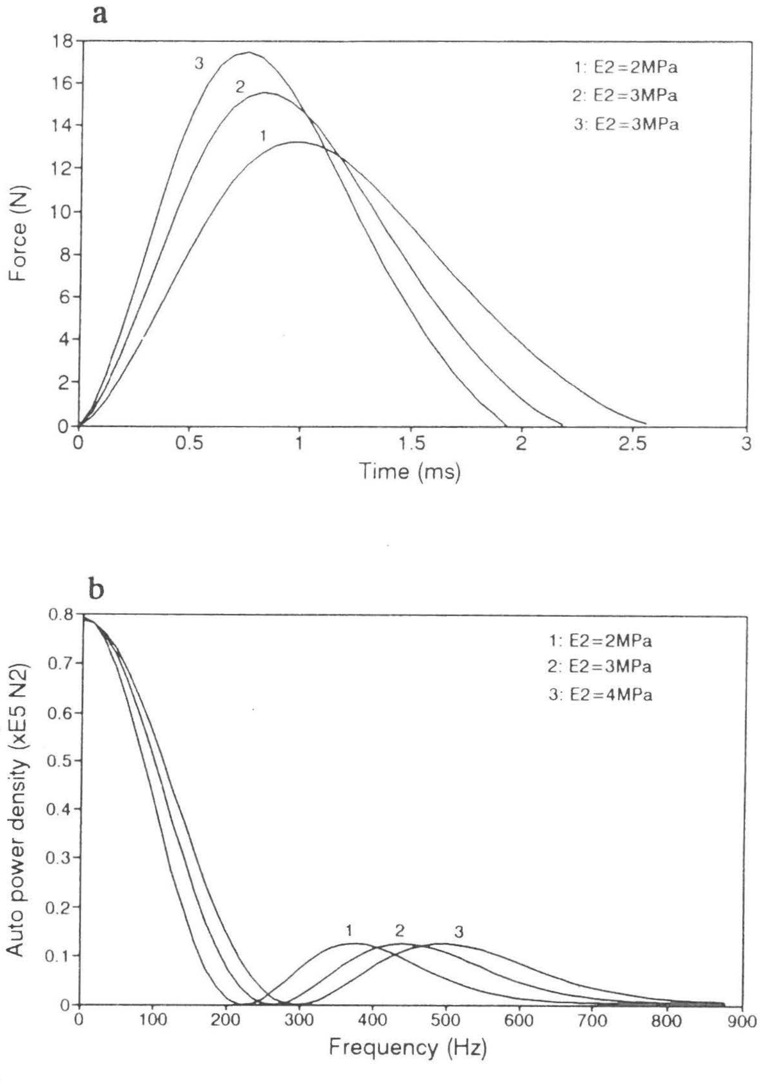

Fig. 2. Influence of the elastic modulus of the apple on the impact excitation signal: time (**a**) and frequency (**b**) domain.

of curvature in mutually orthogonal planes. For simplicity, we regard the local surface as a part of a sphere. Its shape can thus be simply depicted by the radius of the sphere, designated as R_2. Normally an apple with a bigger mass has a larger R_2. The local shape may differ considerably in different locations on one apple with R_2 being larger near the equator than at the two ends. R_2 is also uncertain to a certain extent due to the irregularity of the apple shape.

Figure 4 shows the influence of R_2 on the impact force. When impacted with the optimal excitation parameters, the local shape with a bigger R_2 gives an impact force with a shorter time duration and a higher peak force. The impact force is more sensitive to the local shape as R_2 is smaller than 40 mm. From the frequency domain spectrum, it is noticed that R_2 does not influence the peak value of the lobes, but may vary the position and shape of these

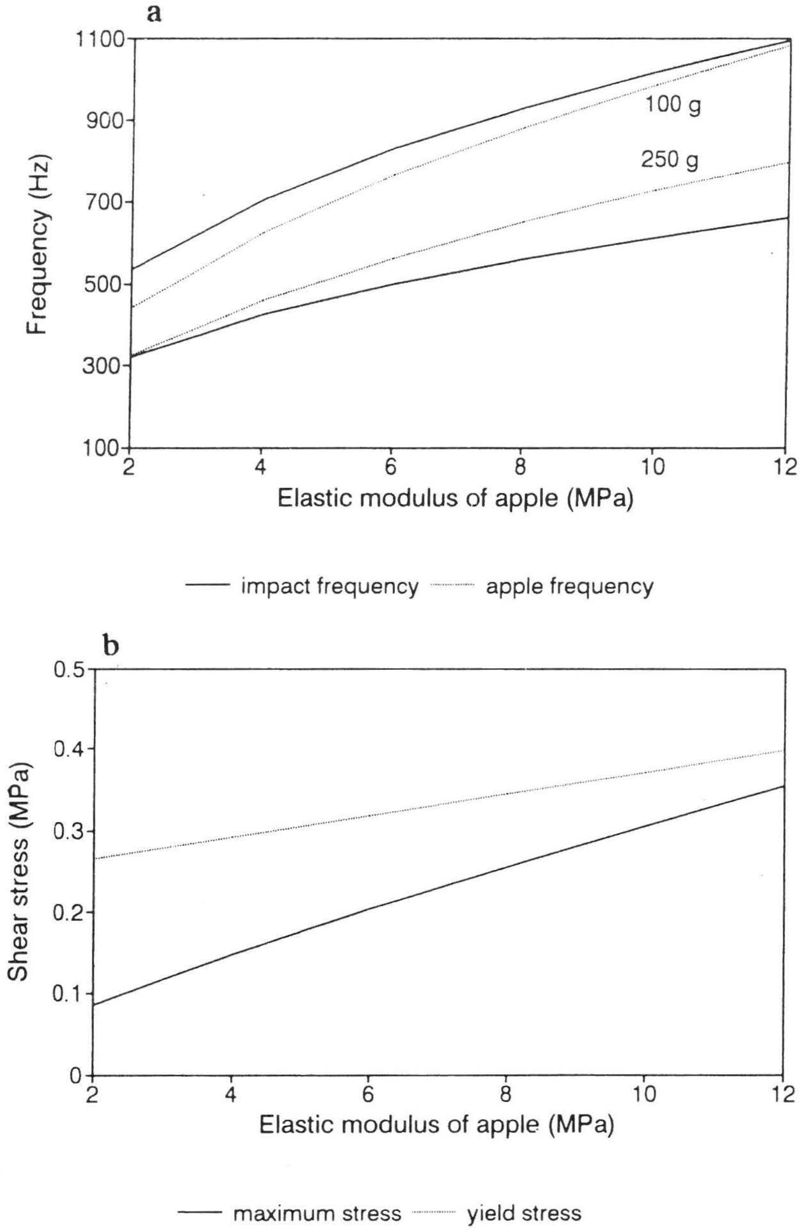

Fig. 3. Influence of the elastic modulus of the apple on the half power range (**a**) and on the shear stress during impact (**b**).

lobes. A bigger R_2 corresponds to a second lobe with a wider frequency distribution at a higher frequency range.

Figure 5 illustrates the change of the half power range and the maximum shear stress with R_2. The impact under the optimal excitation parameters on the apple surface where R_2 is larger than 31 mm will excite the spherical mode of the apple without causing any damage. The impact may possibly be unable to vibrate the spherical mode, and furthermore cause some damage to the apple when striking

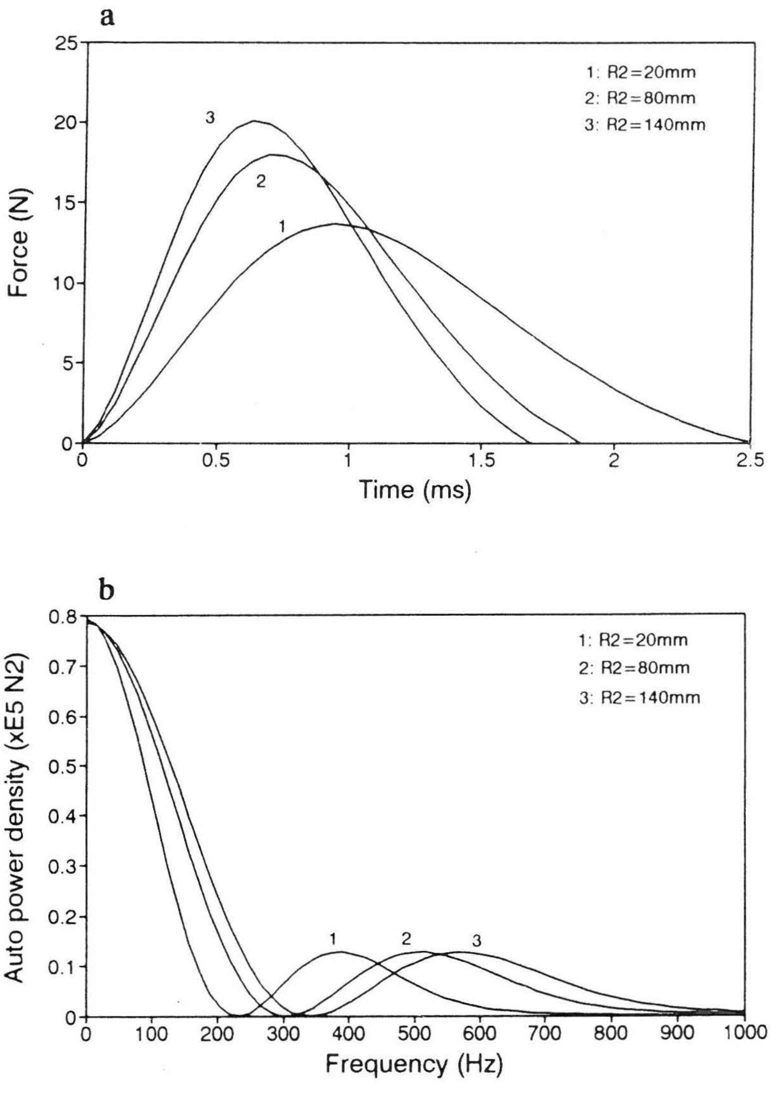

Fig. 4. Influence of the radius of the apple shape in the contact area on the impact excitation signal in time (**a**) and frequency (**b**) domain.

the apple surface where R_2 is much smaller than 31 mm. In this case, the resonant frequency range is fully or partly outside the half power range, and the maximum shear stress during impact probably exceeds the yield shear stress. For this reason, it is important that the apple is oriented during the measurement so that the impact can be applied near the equator. It is also suggested to avoid striking the apple surface where a small elevation or surface irregularity exists.

Influence of coefficient of restitution

The viscosity of the apple can be expressed alternatively by its damping or by the coefficient of restitution, either of which can be calculated from the other [12]. A higher coefficient of restitution corresponds to a lower damping value. For an elastic body where the coefficient of restitution equals 1, the damping is 0.

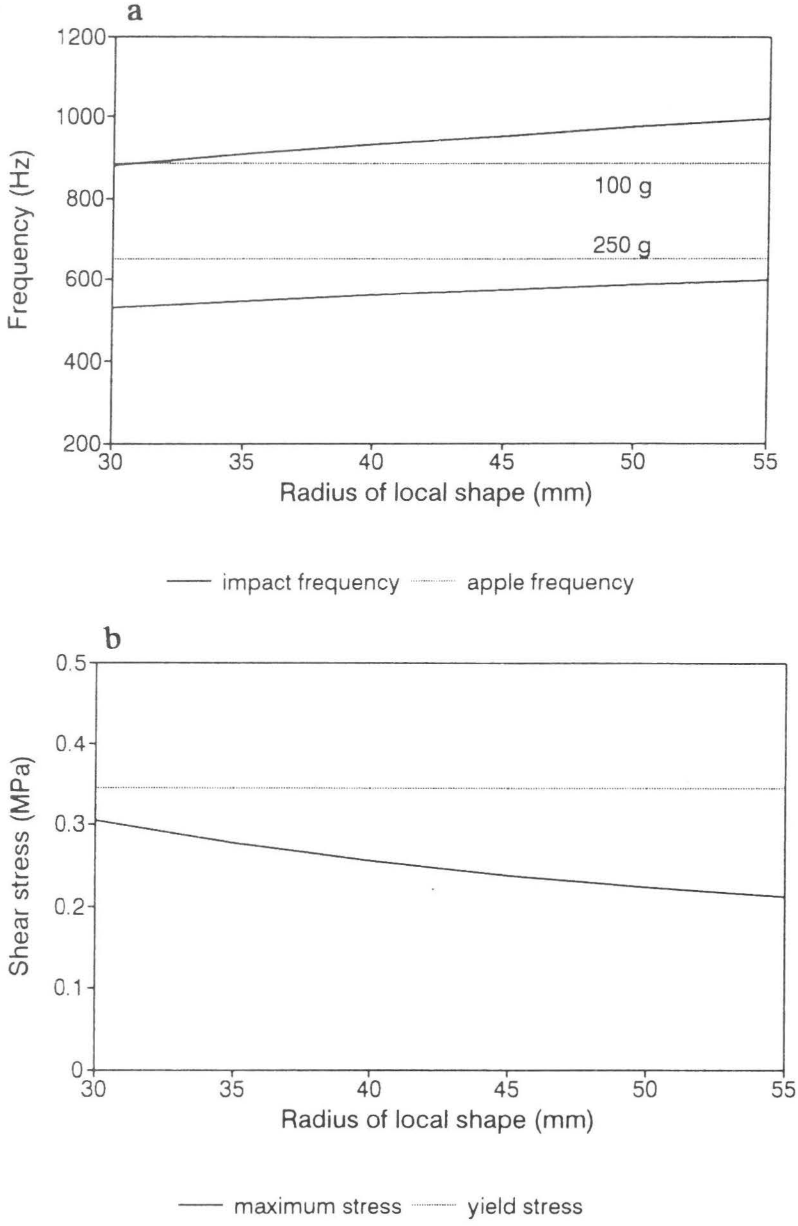

Fig. 5. Influence of radius of the apple shape in the contact area on the half power range (**a**) and on the shear stress diuring impact (**b**).

Figure 6 shows the influence of the coefficient of restitution of the apple on the impact force. Curve 1 corresponds to the impact force of a perfectly elastic apple. With the decrease of the coefficient of restitution, which happens when the apple becomes ripe, the impact force curve tends to be more unsymmetric, and the peak force value decreases (Fig. 6a). The coefficient of restitution does not change much the duration of the impact time. Figure 6b shows that coefficient of restitution may change the peak value, position and shape of the lobes.

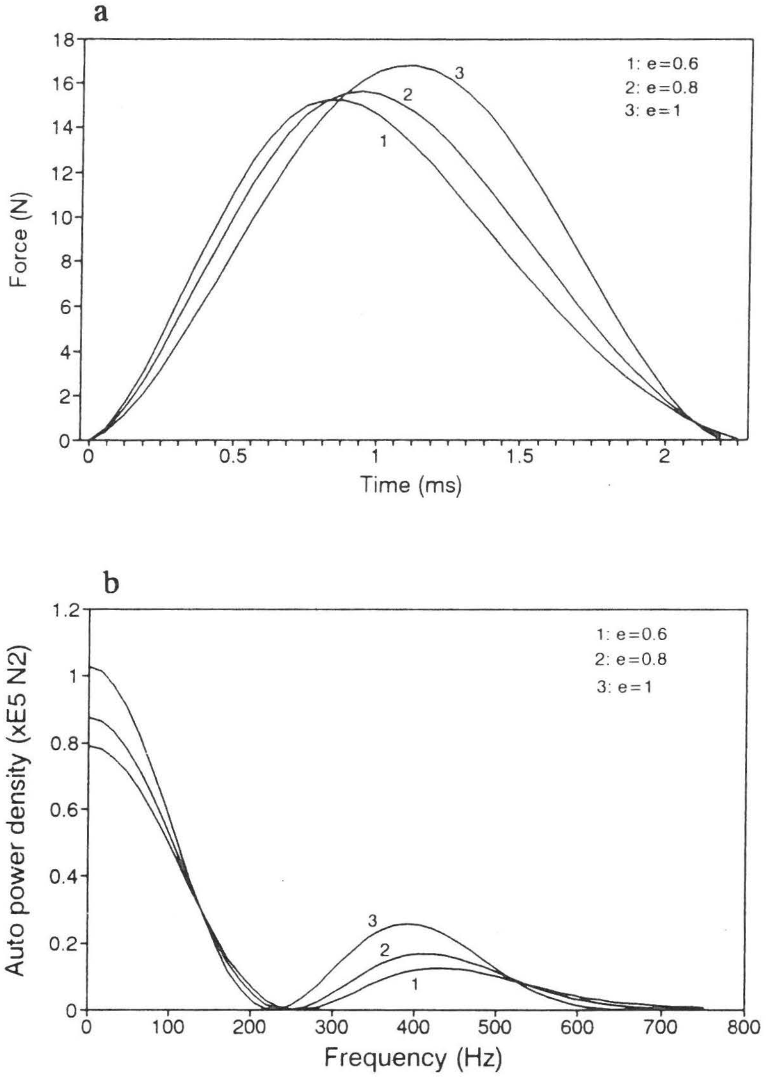

Fig. 6. Influence of the coefficient of restitution of the apple on the impact excitation signal in time (**a**) and frequency (**b**) domain.

The change of the position of the second lobe is considerably smaller compared with that caused by firmness or local shape.

The decrease in the coefficient of restitution may cause the half power range to move towards a higher frequency as well as an increase in the maximum shear stress, as exemplified in Fig. 7. When the coefficient of restitution is more than 0.8, part of the resonant frequency range, which corresponds to some smaller apples, is outside the half power range. By comparison, the influence of the viscosity on the impact signal is smaller than that of the apple firmness and the radius at the contact area. For the range of the coefficient of restitution below 0.8, the optimal excitation parameters remain feasible.

Influence of the Poisson's ratio

The Poisson's ratio of agricultural products is normally under 0.49 [16]. Figure 8 shows the influence of the Poisson's ratio on

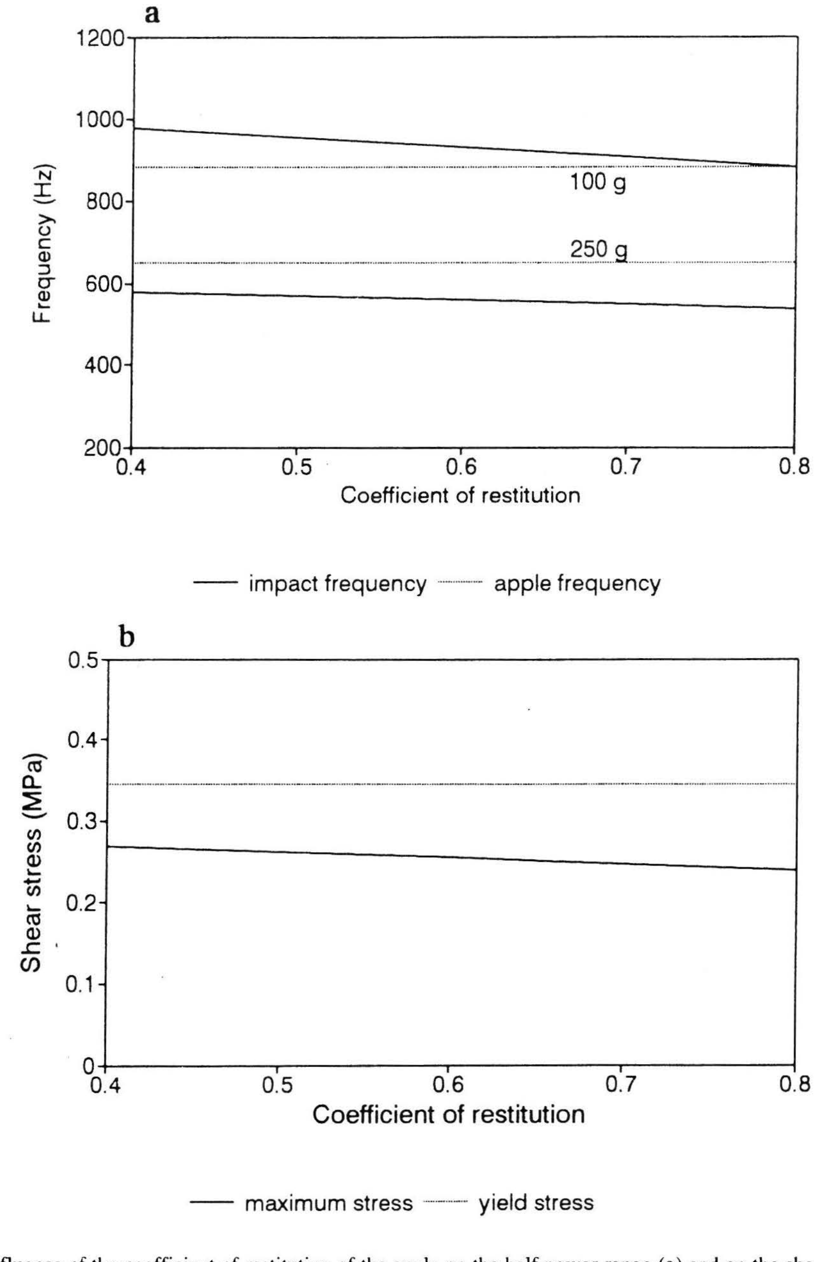

Fig. 7. Influence of the coefficient of restitution of the apple on the half power range (**a**) and on the shear stress during impact (**b**).

the impact force. It is obvious that the influence is quite small and can be ignored.

CONCLUSIONS

The optimal excitation parameters were derived with respect to a single apple of average quality. This paper is a subsequent research concerning the influence of apple properties on impact excitation to see if the optimal excitation parameters stand. It is based on numerical simulation of the impact excitation using a force model with hysteresis damping.

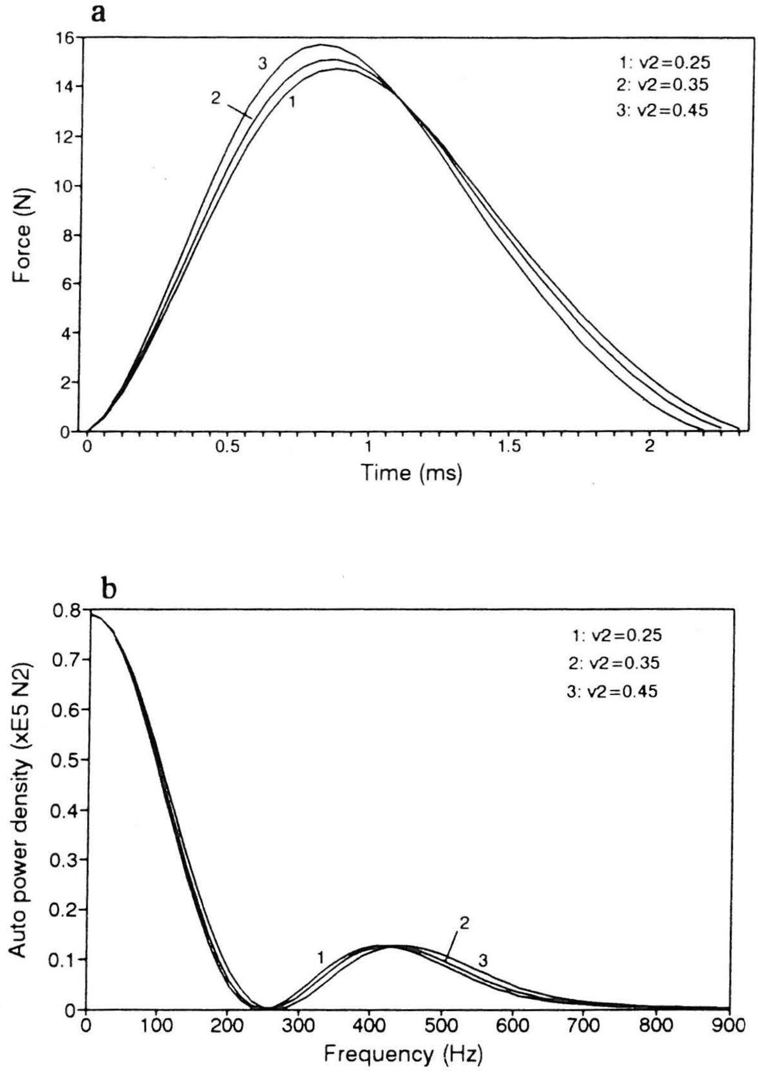

Fig. 8. Influence of the Poisson's ratio on the impact excitation signal in time (**a**) and frequency (**b**) domain.

The excitation of the spherical mode and the prevention of fruit damage are used as rules for determining the excitation reliability.

During ripening of the apple, its firmness and coefficient of restitution decrease simultaneously. The former causes the half power range to move towards a lower frequency range and the maximum shear stress to decrease. The latter has an inverse effect, and this effect is smaller compared with the former. Separate study of these two factors reveals that for apples having an elastic modulus between 2 to 12 MPa, and coefficient of restitution under 0.8, these factors do not influence the reliability of the impact excitation.

The local shape of an apple can be characterised by its radius of curvature R_2. A smaller R_2 may cause a higher frequency of the half power range and a higher value of the maximum shear stress. When R_2 is much smaller than 31 mm, the optimal excitation parameters may not vibrate the spherical mode, and meanwhile cause damage to the apple. It is suggested to impact near the equator of the apple where the surface tends to be flatter, or R_2 is larger.

The influence of the Poisson's ratio is negligible.

The weight of the apple does not directly influence the impact excitation, but may change the spherical resonant frequency. For apples weighing between 100 g and 250 g, the spherical resonant frequency is within the half power range of the frequency spectrum of the force impact.

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