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# INFLUENCE OF THE APPLE DEFECT ON THE FREQUENCY RESPONSE SPECTRA DURING NONDESTRUCTIVE ACOUSTIC SENSING OF FRUIT FIRMNESS

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A b s t r a c t. In this paper, the spherical mode shapes corresponding to the resonant peaks in the frequency response spectrum were obtained. The apple defect was made by either injecting the reagent HCl into the apple or by making holes in the apple. It was found that the apple defect may split one $S_{20}$ peak into two or even more $S_{20}$ peaks in the frequency spectrum. The effect relies on the location and size of the defect in the apple as well as the measurement position of the impact and the response sensors. In the presence of the defect, this technique becomes unreliable in firmness evaluation, however it could possibly be used for the indication of the existence of the defect inside the apple.

K e y w o r d s: apple defect, firmness, mode shape, nondestructive sensing

## INTRODUCTION

Nondestructive acoustic sensing of fruit firmness has been based on the derivation of the resonant frequency from the response spectrum of the fruit under vibration. Application of this technique requires detailed understanding of the dynamic behaviour of the fruit. So far, considerable theoretical and experimental research has been carried out for the investigation of the dynamic behaviours of the fruit [1-7,9-15]. It was concluded that a vibrating fruit may exhibit two classes of the mode shapes denoted as torsional mode and spherical mode. The former is characterised by the tangential vibration while the latter by the radial vibration. With the interest of the acoustic sensing of the vibration response signal, the spherical modes were paid more attention. The resonant frequency $f$ of the lowest spherical mode was found to be related by the stiffness factor $f^2m^{2/3}$ to the fruit firmness, where $m$ is the fruit mass.

Inhomogeneity of the fruit appears in the form of quality difference at various regions inside the fruit. In the physical sense, these regions may differ in the firmness. For fruits like apples, peaches, pears, pineapples, melons etc., the quality among the skin, flesh and core is considerably different. Such kind of inhomogeneity is the characteristic of the fruit itself, and therefore is definite. It lies in each individual fruit, and constitutes the structure of the fruit. At the same time, due to infection, disease, injury or whatever, there exists for some fruits local small soft regions. Such kind of inhomogeneity is uncertain, unpredictable and can be referred to as the fruit defect.

Inhomogeneity is one of the factors affecting the dynamic behaviours of the fruit. Based on a 3-media elastic sphere model, Cooke [7] suggested that the flesh-to-skin ratios have larger influence for the torsional modes while the core-to-skin ratios are important for the spherical modes. By means of the finite element method, Chen *et al.* [3,4] found for apples and pineapples that the change of the firmness in the core, flesh and skin does not vary the vibration patterns of these modes, but may change their frequency sequence. The torsional modes are the most sensitive to the firmness in the skin while the spherical modes are the most sensitive to the firmness in the flesh. It was also found for melons that the watercore inside the melon may change the vibrational patterns of these modes. The extending of the watercore along the radial direction mainly caused the spherical modes to change or even disappear while the extending of the watercore along the tangential direction mainly caused one torsional mode to split into more torsional modes [5].

The previous investigation was mainly aimed at the inhomogeneity of the core, flesh and skin by some theoretical means. A little theoretical work was also carried out concerning the fruit defect. However, no experimental research on the influence of the inhomogeneity on the dynamic behaviour of the fruit has ever been reported. One of the reasons is supposed to be the difficulty of simulating the inhomogeneity inside the fruit. It was observed by Duprat *et al.* [8] that some apples tend to have more resonant peaks in the frequency spectra after several months of cold air storage. This tendency can be attributed to the appearance of the apple defect. On one side, the fruit defect may sometimes cause the difficulty in deriving the resonant frequency from the spectrum for firmness evaluation. On the other side, there is an increasing demand to have some nondestructive ways for detecting the fruit defects.

This work is a primary experimental effort to see how the fruit defect affects the dynamic behaviours. The objectives are to (1) analyse the mode shapes corresponding to the main resonant peaks in the frequency spectrum, (2) establish methods for simulating the fruit defect, and (3) investigate the influence of the fruit defect on the frequency spectrum.

## EXPERIMENTAL TECHNIQUES

Several 75 to 80-mm-diameter Granny apples recently harvested and imported from Chile were used. The apples were measured for the frequency response spectra and mode shapes before and after some defect was made.

### Measurement of mode shapes

As shown in Fig. 1, 20 points around the equator of each apple were measured, where point 2 to 10 and point 12 to 20 were equally distributed at an interval of 15°, point 2 and 20 were 30° apart from point 1, point 10 and 12 were 30° apart from point 11. The apple was excited by an impact at point 1. Two small condense type MCE-2500 microphones, with one fixed at point 11 and another placed in sequence from point 1 to 20, were used to measure the response signals simultaneously. The signals were then fed into a Nicolet-310 digital oscilloscope which was connected via a IEEE-488 interface to a SX386 personal computer where the time-domain signals were transferred into the frequency spectra by using a program coded in Quick Basic. All the spectra were saved and processed for the mode shapes.

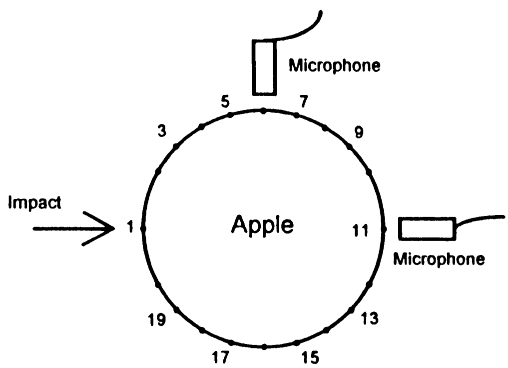


**Fig. 1.** Relative positions of the impact, microphones and 20 measurement points along the equator of an apple.

The method for deriving the mode shapes from the measured spectra was the same as that used by Huarng *et al.* [10]. A mode shape corresponding to a resonant peak in the frequency spectra was determined by the relative vibration amplitude and phase angle difference at these 20 points. The relative vibration amplitude at each point was obtained by dividing the Fourier transformed magnitude of the resonant peak by the corresponding Fourier transformed magnitude of the peak at the reference point 11. The phase angle difference was obtained by abstracting the phase at each point by the phase at the reference point. The relative vibration amplitude determined the radial displacement while the phase angle difference indicated the polarity of each point. If the absolute value of the phase angle difference was less than 90°, the polarity of this point was the same as that of the reference point 11. It was inverse when the absolute value was larger than 90°.

### Method for making the apple defect

Two methods were used for the simulation of the apple defect. One was by injecting the reagent HCl of 18 % vol. into different parts of the apple. After about 30 min, the injected region became very soft. Another was by making holes directly on the apple. The hole can be regarded as a defect region with zero firmness.

## RESULTS AND DISCUSSION

### Frequency spectra and mode shapes

Figure 2 shows the frequency response spectrum measured at the reference point 11 of an apple without defect. It is similar to the frequency response spectra measured by others [6,10,11]. There exist three resonant peaks at 740 Hz, 1120 Hz and 1460 Hz, respectively with the lowest frequency peak at the largest amplitude and the highest frequency peak at the smallest amplitude. The mode shapes corresponding to these three resonant peaks are illustrated in Fig. 3, where the middle dotted circle of each mode represents the original circle of the equator whose relative vibration amplitude is 0, the outer and the inner dotted circle represent the basic circles with the relative vibration amplitude of 1. The zone between the middle and the outer circle has the positive polarity while the zone between the inner and the middle circle has the negative polarity. The solid lines denote the mode shapes at one extreme deformation of the apple equator.

Mode (a) corresponds to the lowest resonant peak. It is characterised by out of phase extension and contraction in two perpendicular

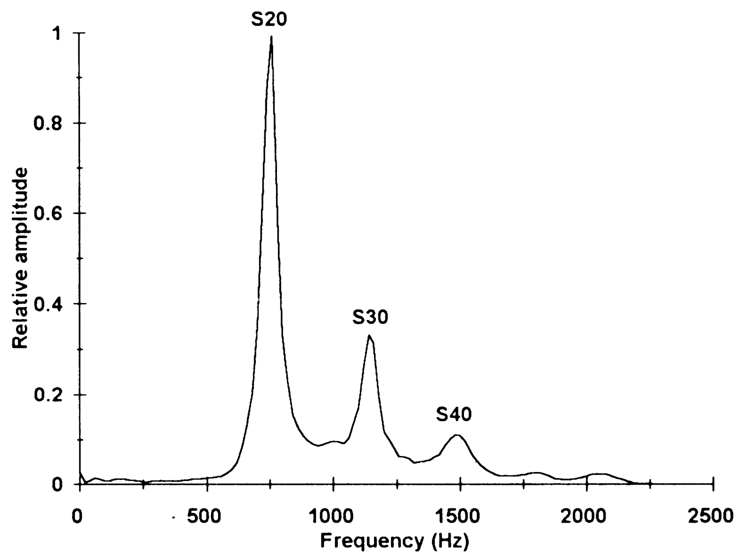


**Fig. 2.** Frequency response sectrum of an apple.

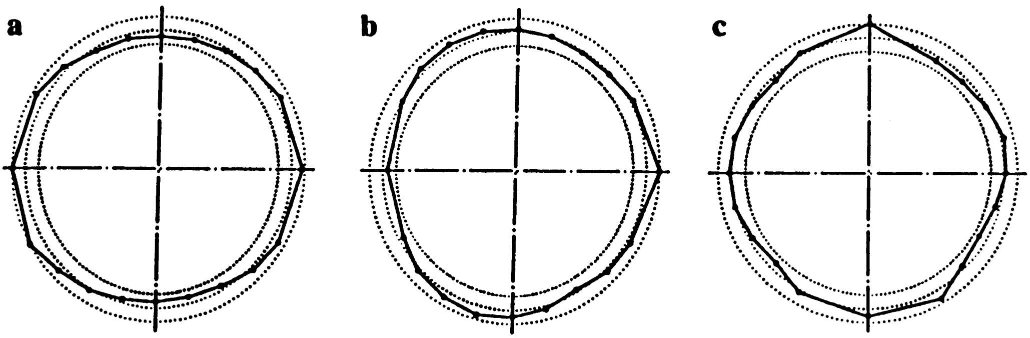


**Fig. 3.** Spherical mode shapes corresponding to the resonant peaks in Fig. 2: a- $S_{20}$ mode at 740 Hz; b - $S_{30}$ mode at 1120 Hz ; c - $S_{40}$ mode at 1460 Hz.

directions. As the parts of the equator near point 1 and point 11 extend to the positive zone, the parts near point 6 and point 16 contract to the negative zone, and vice versa. It happens for the equator to have two parts in the positive zone and two parts in the negative zone at one time. There exist 4 points at which the solid line crosses with the middle dotted circle. These points do not move during vibration, therefore are referred to as the nodal points. Such kind of mode is called the first type spherical mode shape, and is designated as $S_{20}$.

Mode (b) corresponds to the second resonant peak. It is characterised by three parts in the positive zone and three parts in the negative zone at one time. There are 6 nodal points in the equator. This mode is called the second type spherical mode shape, and is designated as $S_{30}$.

Mode (c) corresponds to the third peak. It is characterised by four parts in the positive zone and another four parts in the negative zone at one time, as well as 8 nodal points. Since the equator of the real apple is not an ideal circle, the measured mode shows a little unsymmetry. It is referred to as $S_{40}$.

The above three modes and their correspondence to the first three peaks in the frequency spectrum were the same as those measured by Huarng *et al.* [10]. In Kimmel *et al.*'s measurement [11], the first peak was related to the rigid body vibration, and the second and the third peak were related respectively to an $S_{20}$ mode and an $S_{30}$ mode. The first peak in this case was due to their measurement setup.

It is obvious that the mode shape at a lower frequency peak is simpler in the deformation and has less nodal points. The mode shape tends to become more complex at a higher frequency peak. In the practical sense, the simple mode is easier to measure and less sensitive to the measurement location at the equator. In the previous research, the $S_{20}$ mode was found to be the most important in reflecting the fruit firmness, and its resonant frequency $f$ was widely used in the stiffness factor $f^2m^{2/3}$ for calculating the fruit firmness.

## Influence of the apple defect on the frequency spectrum

Figure 4 shows the frequency response spectra of a Granny apple, where curve 1 was measured from the original apple and curve 2 was measured 30 min after 0.88 g of HCl was injected into the apple. The injected part is very soft, and its location and size are illustrated in Fig. 5. The created apple defect amounts to about 2.5 % of the total weight of the apple. As a result, the $S_{20}$ peak at 740 Hz in curve 1 is split into two $S_{20}$ peaks with one at 600 Hz and another at 740 Hz in curve 2. The $S_{30}$ peak at 1120 Hz does not split but shifts to about 1000 Hz. It is verified that the existence of the apple defect split one spherical

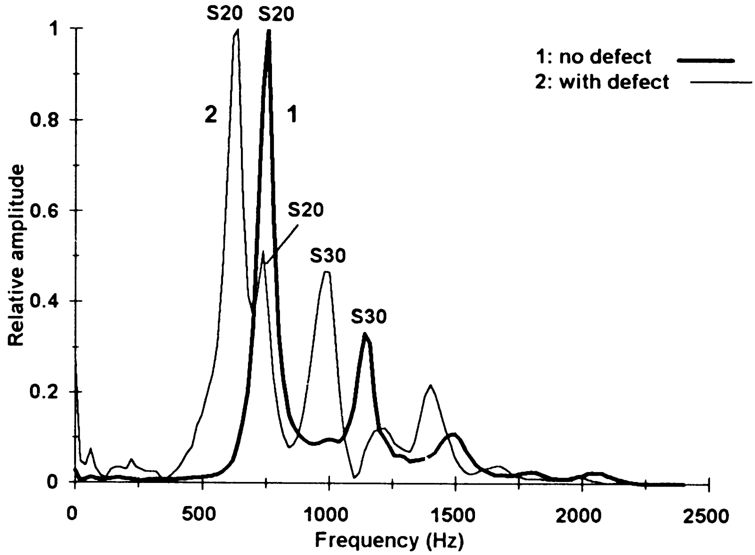


**Fig. 4.** Influence of the apple defect on the frequency response spectrum.

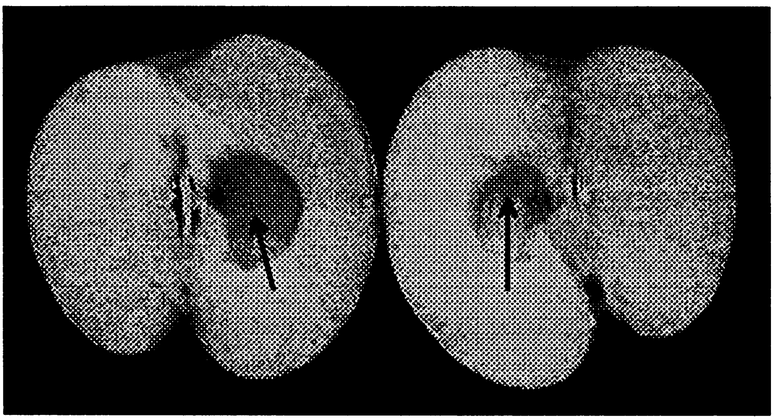

**Fig. 5.** Location and size of the defect indicated by the arrows.

mode to more modes, causing more resonant peaks in the frequency spectrum. In this case using the lower frequency (600 Hz) in the stiffness factor may cause about 25 to 30 % difference in the evaluated firmness.

In order to investigate the influence of the defect location on the frequency spectrum, a hole of 15 mm in diameter was made through an apple. A cylindrical flesh of half length as big as the hole was then cut from another apple of the same ripeness, and filled into the hole. The rest unfilled part of the hole can be regarded as the apple defect. Figure 6 shows the frequency spectra when the cylindrical flesh is at one side (curve 1) and in the middle of the hole (curve 2). It is obvious that two $S_{20}$ peaks at 560 Hz and 680 Hz tend to become one $S_{20}$ peak at 680 Hz when the cylindrical flesh is moved from one side to the middle of the hole. In the former position, the defect is

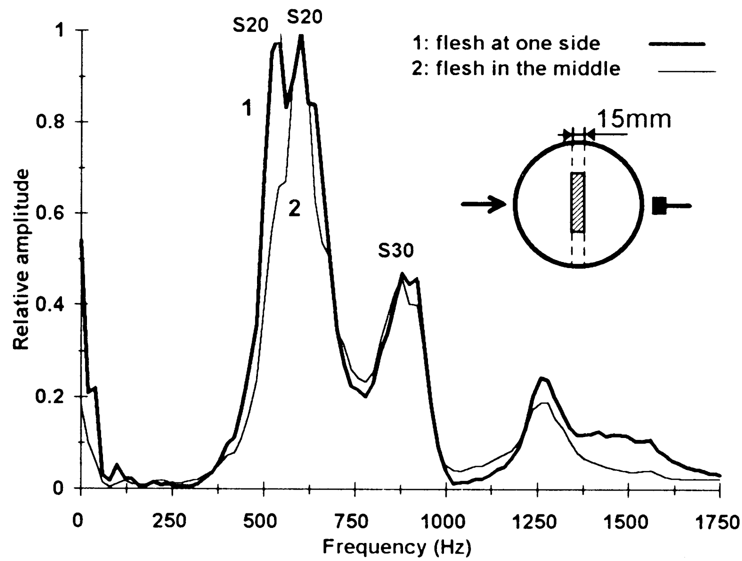


**Fig. 6.** Influence of the defect location on the frequency spectrum.

located in one side which makes the apple to be in unsymmetric structure while in the latter position, two defects are located in the two opposite sides of the apple which keeps the apple in symmetric structure. This means that the peak tends to split when the defect exists at a unsymmetric position and causes the apple to be in unsymmetric structure. In another experiment, one apple was injected with 0.8 g HCl in the inner part and another apple was injected with half of the HCl in the outer part. It was found that a smaller defect in the outer part had the same effect on the mode shapes as a bigger defect in the inner part. The defect in the outer part of an apple influences more on the frequency spectrum since it causes the apple to be more unsymmetric. It can be concluded that a defect in the outer part may have more influence on the mode shapes and two defects at the opposite side may have less influence than a defect at one side.

Whether the split mode caused by the apple defect can be measured depends also on the position of the impact excitation and response sensors, as verified in Fig. 7 where curve 1 was measured along direction 1 and curve 2 along direction 2. The microphone was always in the opposite side of the impact point. Apparently, in the former case the defect (a hole of 22.5 mm in diameter and 15 mm in depth) was located in an unsymmetric position relative to the measurement direction, and two modes at 560 Hz and 680 Hz were therefore measured. In the latter case, the defect was located in the symmetric position (along the impact-microphone line), and the small $S_{20}$ peak at 560 Hz was not measured. For another apple whose defect was made by injecting some HCl into it, two $S_{20}$ peaks at 621 Hz and 745 Hz were measured when the defect was in unsymmetric location, and only one peak at 703.8 Hz was measured when the defect was in the symmetric location. The latter peak was very similar to that of the original apple in the frequency. It can be concluded that the apple defect may cause the existence of several $S_{20}$ modes. Which mode is measured relies on the locations for the excitation and response measurements.

To see the sensitivity of the frequency spectrum on the apple defects, holes of different diameters were made on some apples. Figure 8

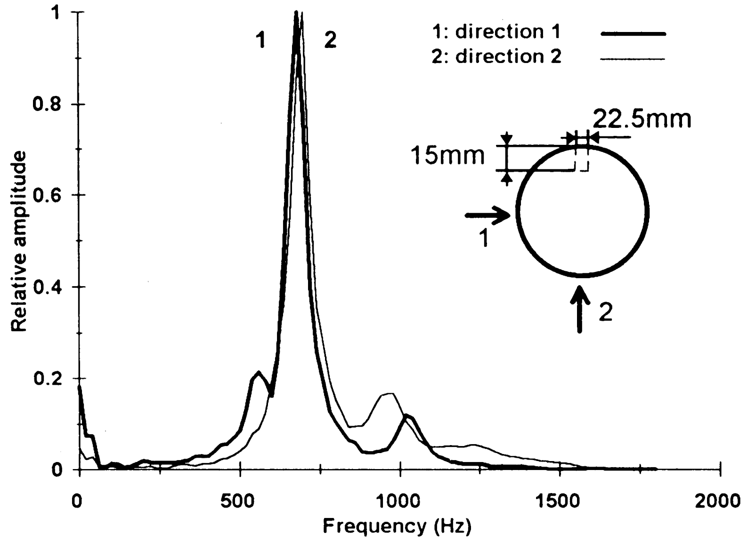


**Fig. 7.** Influence of the measurement positions on the frequency spectrum.

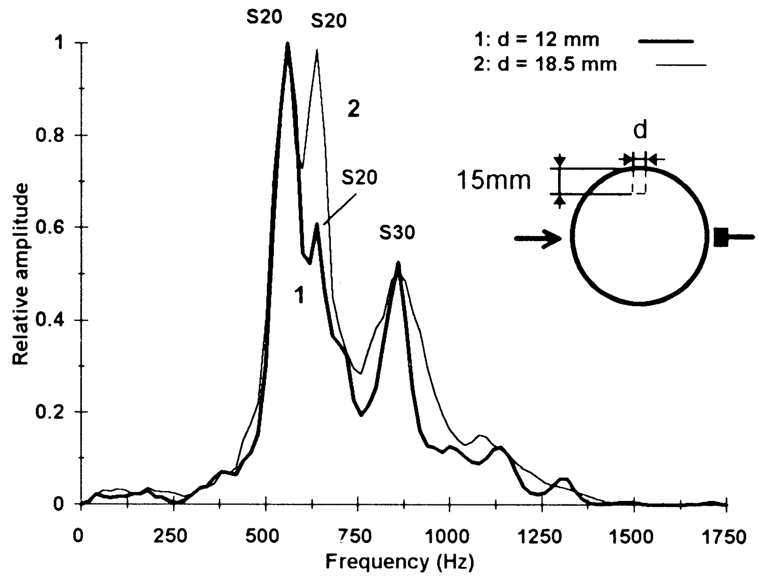


**Fig. 8.** Sensitivity of the frequency spectrum on the defect.

shows one case. The original apple had one $S_{20}$ peak at 600 Hz. When a hole was of 12 mm in diameter, the single $S_{20}$ peak began to separate to two $S_{20}$ peaks with one at 560 Hz and another at 640 Hz (curve 1). The $S_{20}$ peak at a lower frequency had a bigger amplitude. When the hole was increased to 18.5 mm in the diameter, the two $S_{20}$ peaks tended to become more clear, and in a similar amplitude (curve 2). For another apple with a single $S_{20}$ peak at 680 Hz, there appeared another small $S_{20}$ peak at 560 Hz until the hole was increased to 22.5 mm in diameter. We may note that a certain amount of the apple defect may cause one peak to split into two peaks or cause the appearance of another small peak. The amount at which the spectrum begins to change differs from apple to apple. In other words, different apple is sensitive according to the defect. When the holes were filled with the softer flesh from another riper apple, both the apples had the similar spectra to the original apples. It means that only very soft defect may cause the resonant peak to split.

### Comparison of two methods for the creation of the apple defect

In the above research, two methods for making the apple defect were used. By injecting the HCl into the apple, the caused defect is more like the real defect. However, it was found to be very difficult to inject the reagent into the apple. Therefore it is very difficult to control the shape, size and location of the defect inside the apple. This method can only provide a qualitative means for the study of the influence of the apple defect.

An alternative method for the defect was to make a hole through the apple. By filling the hole properly with the apple flesh, the apple can match the original apple. As shown in Fig. 9, curve 1 is the original spectrum and curve 2 is the spectrum after a hole of 15 mm in diameter was made through the apple, and filled with a cylindrical flesh from an apple of the same ripeness. It is obvious that the apple with the filled flesh has the similar spectrum to the original apple except for a little decrease in the resonant frequency of the $S_{20}$ peak. This implies that the apple with the filled flesh hole can match the original apple in the number of the resonant peaks. By changing the length, property and location of the filled material in the hole, the influence of the apple defect on the resonant peaks can be quantitatively studied. It was noted during experiments that the apple with filled flesh can match the original apple only when a cylindrical flesh of a larger diameter was forced into the hole.

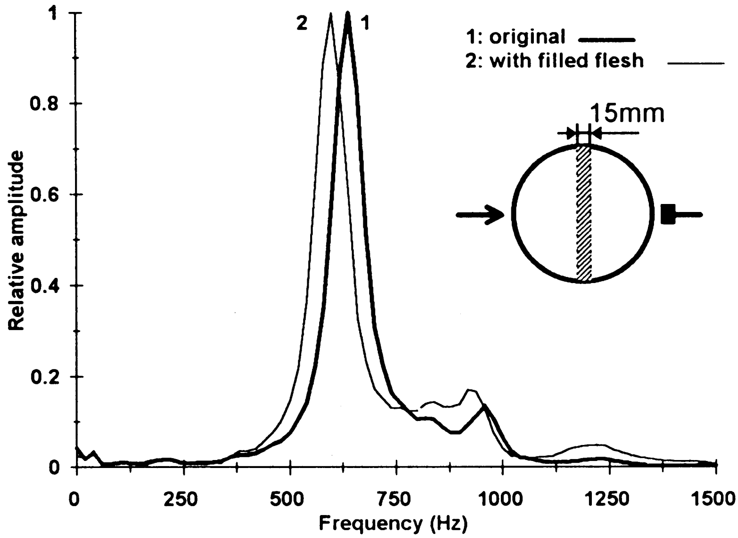


Fig. 9. Frequency spectra of an apple without hole (1) and with a filled flesh hole (2).

## CONCLUSIONS

The apple may display several resonant peaks in the frequency response spectrum when it is excited by an impact at a point in the equator and measured at the opposite side. The mode shape corresponding to the lowest frequency peak is a $S_{20}$ mode characterised by out of phase extension and contraction in the two perpendicular directions. It is simpler in the deformation and has less nodal points in comparison with the other types of the modes at the higher frequency.

The apple defect may split one $S_{20}$ peak into two or even more $S_{20}$ peaks in the frequency spectrum, this may cause considerable error in the firmness evaluation. In this case the nondestructive technique for the fruit firmness becomes unreliable. The effect depends to a certain extent on the location and size of the defect in the apple. A smaller defect in the outer part may have the same influence on the frequency spectrum as a bigger defect in the inner part. Two defects at the opposite side may have less influence than a defect at one side. For the same defect at the same location, the sensitivity of the spectrum to the defect differs from apple to apple. The frequency spectrum relies also on the measurement position of the impact and the response sensors. Due to these factors, it is really difficult to determine quantitatively the defect of an individual apple by means of this nondestructive technique. However, this technique could possibly be used to detect the existence of the defect inside the apple during storage.

Two methods for simulating the apple defect were used. By injecting the HCl into the apple, the caused defect is more like the real defect. This method can only provide a qualitative means for the study of the influence of the apple defect. An alternative method for the defect was to make a hole through the apple. By filling the hole properly with the apple flesh, the apple can match the original apple. Changing the length, property and location of the filled material in the hole makes possible the quantitative study of the influence of the apple defect.

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