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Teodor Tiplica, Pierre Vandewalle, Sylvain Verron, Cécile Grémy-Gros, Emira Mehinagic

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T. Tiplica*, P. Vandewalle, S. Verron*, C. Grémy-Gros*, E. Mehinagic****

** LASQUO – ISTIA – University of Angers, 62, avenue Notre Dame du Lac, 49000 Angers, France*
*** Ecole Supérieure d'Agriculture, Groupe de Recherche en Agro-industrie sur les Produits et les Procédés (GRAPPE), 55 rue Rabelais, B.P. 30 748, 49007 Angers Cedex 01, France*

Abstract

This article shows that acoustic measurement can be a useful tool to discriminate different apple batches with a low error rate. Starting from the spectrum of the signal recorded by a microphone after the impact of a small hammer on the fruit, 18 key features were identified and used for the classification of apples belonging to 10 different varieties. A capability study of the gage has been done and the results show that the measuring instrument is repeatable and reproducible for the resonance frequency and amplitude of the signal. The prospects of this study are interesting in the context of automatic sorting of fruits.
Keywords: Acoustic measure, spectral analysis, classification, discriminant analysis, R&R test, non-destructive test, apples, texture.

Résumé

Dans cet article on montre que les mesures acoustiques peuvent être utilisées avec succès afin de discriminer différentes espèces de pommes et ceci avec un taux d'erreur réduit. A partir du spectre du signal enregistré par un microphone après l'impact d'un petit marteau sur le fruit, 18 caractéristiques clé ont été identifiées et utilisées pour la classification des pommes appartenant à 10 variétés différentes. Une étude de capabilité du dispositif expérimental utilisé a été réalisé et les résultats obtenus montrent que l'appareil de mesure et répétable et reproductible au niveau de l'amplitude et de la fréquence de résonance du signal. Les perspectives de cet étude sont intéressantes dans le contexte du tri automatique des fruits.
Mots clés: Mesure acoustique, analyse spectrale, classification, analyse discriminante, test R&R, test non destructif, pommes, texture.

1. Introduction

Elaborating simple, reliable and rapid non destructive systems to evaluate and guarantee the quality of fruits is nowadays one of the most important topics of research in this field. In the last decades, different acoustic techniques based in the acoustic resonance have been developed in order to measure the quality of fruits: firmness, external and internal defaults, diseases, changes during the shelf life, etc.

Firmness is commonly considered as an indicator of the state of maturity of fruit. Traditionally firmness evaluation is done by invasive techniques. Many studies have been carried out to identify the relationship between invasive measures (penetrometry, compression, chemical composition, sensory etc.) and non-destructive measures [4], [18], [20], [29], [30], [31], [35], [38], [41], [42]. Non-destructive techniques using acoustic characteristics have been applied for measuring the firmness of several fruits such as apples [2], pears [16], [25], melons [37], kiwifruits [1], tomatoes [8], [17], pineapples [9] and mandarins [26].

Several stiffness coefficients are used to estimate the firmness of fruits. Among them, the most used for round shaped fruits is the stiffness coefficient proposed by Abbott et al. [3] and Cooke and Rand [14]: $S = f^2 \cdot m^{2/3}$ where f is the resonance frequency also called dominant frequency (corresponding to the greatest amplitude in the spectra) and m is the mass of the product. Pathaveerat et al. [31] are using the third resonant frequency for the stiffness coefficient ($f_3^2 \cdot m^{2/3}$ where f_3 is the frequency corresponding to the third greatest amplitude of the acoustic spectrum).

Acoustic measurements have also allowed to identify external defaults in eggs [10], pistachio nuts [32] and internal defaults in pears [34], watermelons [4], [19], cheese [13] and potatoes [23].

The use of acoustic impulse response is increasing as a valuable tool to evaluate changes during harvest and postharvest [16], [27], [35]. For apples tested on trees a poor correlation exists between stiffness and firmness [44], while during shelf life an increased correlation of fruit flesh firmness and stiffness appears. Stiffness coefficient ($f_3^2 \cdot m^{2/3}$), specific gravity, and soluble solids content appeared to be the most important parameters for distinguishing the

level of maturity of pineapples and the marbled fruits [31]. However previous studies showed that the stiffness factor was useful to classify freshly harvested from stored apples, but was not efficient enough to discriminate the ripeness degrees of some apple varieties [38].
In the different research works mentioned before and concerning the fruits quality, different acoustic parameters have been determined such as dominant frequency, maximum amplitude or band magnitude. It was proved that an important correlation exists between the first resonance frequency and the fruit mass [22]. The first resonance frequency also depends on the water status of the fruit and the pectin transformation during the shelf life [15], [44]. In order to better compare different fruits spectra, some authors have defined a normalized spectrum by dividing the amplitude at each frequency by the maximum amplitude of the spectrum [20], [24], others have calculated the band magnitude by summing the weighted amplitudes of the normalized spectra for a specified frequencies range [19], [20], [24], [36]. The number of band magnitude depends on the product [13], [19].

Acoustic signals may contain more information about the physical or chemical properties of the tested product than the single firmness. Most of previous studies have concentrated their efforts on few particular points of the acoustic signal (dominant frequency, maximum amplitude or band magnitude). In order to better explore the capability of this technique, the global acoustic signal is explored in this study. We concentrated our efforts on two particular aspects:

1. How to evaluate the capability of the experimental device to give reliable data?
2. How to identify in the spectral signal of different varieties of apples some particular characteristics relevant for the disparities in the internal structure of these fruits, permitting them to be discriminated easily?

2. Experimental device

Elastic properties of biological tissues gave a vibrational behavior, which is used as an indicator of their internal characteristics [12]. Different non-destructive techniques were developed to observe this behavior: the product may be hit with a small hammer [22], dropping onto an impact plate [33], submitted to an ultrasonic pulser [6] or laser Doppler vibrometer [39]. The stiffness was reported to be correlated with apple fruit textural parameters such as the Young modulus [27] and fruit firmness [16] measured by referenced penetrometric measures, or with water status [27].
In our case, the first above-mentioned technique where the fruit is positioned to receive an impact with a small hammer, which generates an acoustic signal detected by a microphone positioned near the fruit (Figure 1), was used. The hammer is very light and its extremity is spherical so the fruit is not damaged after the impact.

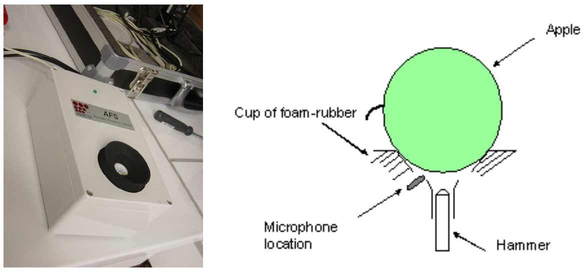

Figure 1. The experimental device (AFS, Aweta)

Modal analysis on spherical products like apples has shown that the best signal is produced when the response is recorded at 0° or 180° from the impact place [7], [28], [35]. This signal is registered, processed and transformed by the experimental device (AFS, Aweta, next term Nootdorp, The Netherlands).
Fast Fourier Transform (FFT) of the signal is performed on the acoustic signature to obtain power spectrum and identify characteristic frequencies [40], [42]. The statistical tool used in this study in order to exploit the spectral data mentioned before is the discriminant analysis viewed as a supervised classification method [21].

3. Experimental strategy

To assess whether the data provided by acoustic measurement can be used successfully to discriminate different apple varieties (Antares, Ariane, Braeburn, Cameo, Elstar, Jubile, Pink Lady, Reineta Armonique, Red Delicious, Temptation), 100 apples were analysed. With the experimental device 10 measurements were done on each of four sides of each fruit: on the sun face, the face opposite to that exposed to the sun (or shade side) and the two intermediary sides (Figure 2).

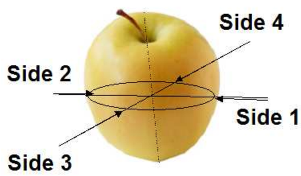

Figure 2. The four measured sides of the apple

In this way 40 measurements per fruit were collected, and then 4000 measures based on 100 fruits tested were recorded. As stated previously by a measurement we mean the frequency spectrum of the acoustic signal that is automatically generated by the software (Figure 3). The spectral range corresponding to low frequencies (between 0 and 3500 Hz) was explored because this range is most informative about the different characteristics of a given varieties. Fourteen characteristic points of the spectral curve, presented in figure 3, were used for the classification:

- **A_{max1}** - maximum amplitude of the first pike of the spectral curve.
- **F_{max1}** - the frequency corresponding to A_{max1}.
- **A_{max2}** - maximum amplitude of the second pike of the spectral curve.
- **F_{max2}** - the frequency corresponding to A_{max2}.
- **A_{min1}** - the minimum amplitude between A_{max1} and A_{max2}.
- **F_{min1}** - the frequency corresponding to A_{min1}.
- **A_{max3}** - maximum amplitude of the third pike of the spectral curve.
- **F_{max3}** - the frequency corresponding to A_{max3}.
- **A_{min2}** - the amplitude of the minimum between A_{max2} and A_{max3}.
- **F_{min2}** - the frequency corresponding to A_{min2}.
- **A_{max4}** - maximum amplitude of the fourth pike of the spectral curve.
- **F_{max4}** - the frequency corresponding to A_{max4}.
- **A_{min3}** - the amplitude of the minimum between A_{max3} and A_{max4}.
- **F_{min3}** - the frequency corresponding to A_{min3}.

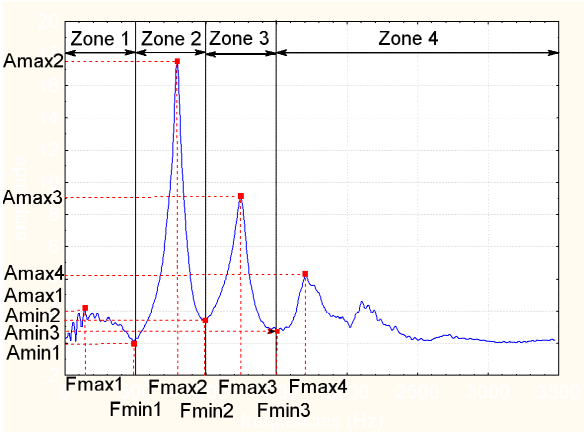

Figure 3. Some key characteristic points of the spectral curve of an apple

Moreover four new parameters, corresponding to the areas of four zones demarcated as in figure 3, were calculated from the spectral curve (Energy1, Energy2, Energy3 and Energy4). These 18 parameters were used as descriptors for the discriminant analysis (DA) to classify the fruits according to their varieties.

Figure 4 shows that a fairly large variability exists in spectra for repeated measures on the same side of the same fruit. This variability occurs predominantly at the level of spectral amplitudes and it is less pronounced at the frequencies level. One possible explanation for this phenomenon could be an impact force of the hammer which is not constant from one measurement to the other. In any case, to overcome this drawback, the decision was taken to conduct our study not on the individual spectral curves but on a median spectral curve that is most representative for the repeated tests on the same side of the same fruit.

In order to be the least influenced in further processing of data by the presence of outliers (values that deviate substantially from the rest of the data distribution), the median and not the mean was chosen.

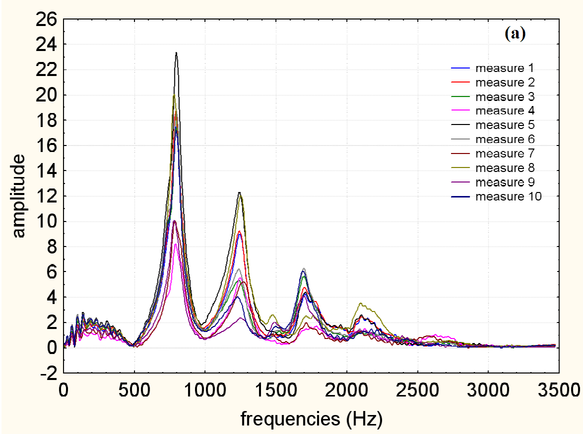

Figure 4. Variability of the spectra for repeated measurements on the same side of the same fruit

In case of few data and the differences between the extreme values and the rest of the data are significant, the median is an estimator of central tendency more relevant than the average when outliers are present.

4. Capability study of the measurement system

For this study we wanted to know if the measurement system previously described is able to perform the requested measurements. The characteristics studied on the spectrum of signals were some key points such as frequencies and the corresponding amplitudes.

In order to reduce the impact of natural apple variability (flesh composition, kernel, circularity, etc.), it was decided to realize a R&R study on a kind of standard spherical objects such as tennis balls. Several reasons have motivated us to make this choice: the perfect circular shape of the balls, the greater homogeneity of the internal environment of the balls (no nucleus, more uniform density), as well as the same volume, weight, etc. Indeed if the experimental device is capable for measurements on the tennis balls, it should be also used with success to distinguish various apples because the higher variability of the fruits.

Ten tennis balls were analysed three times by three operators. The obtained results are presented in tables 1 and 2 for the amplitude (A_{max}) and frequency (F_{max}) corresponding to the maximum on the spectral curve (Figure 5). Table 1 shows that the experimental system used is capable (capability index = 0.77%) of measuring the frequency corresponding to the maximum on the spectral curve. However the capability index related to the amplitude (21.4%) is at the limit of acceptability (table 2). This is principally related to the high variability percentage of repeatability (19.4%). One possible explanation for this undesirable phenomenon is that the force of the hammer is not constant from one test to another. The measuring system could be improved by introducing a regulating system for the impact force of the hammer.

	Estimated standard deviation	Estimated variance	% of R&R	% of Total
Repeatability	0.84	0.71	86.04	0.66
Reproducibility	0.34	0.11	13.95	0.10
Piece to piece	10.34	107.10		99.22
R&R	0.91	0.83	100.00	0.77
Total	10.38	107.93		100.00

Table 1 : Results of the R&R study for the frequency F_{max}

	Estimated standard deviation	Estimated variance	% of R&R	% of Total
Repeatability	0.38	0.14	90.84	19.44
Reproducibility	0.12	0.01	9.15	1.96
Piece to piece	0.77	0.60		78.59
R&R	0.40	0.16	100.00	21.40
Total	0.87	0.76		100.00

Table 2 : Results of the R&R study for the amplitude A_{max}

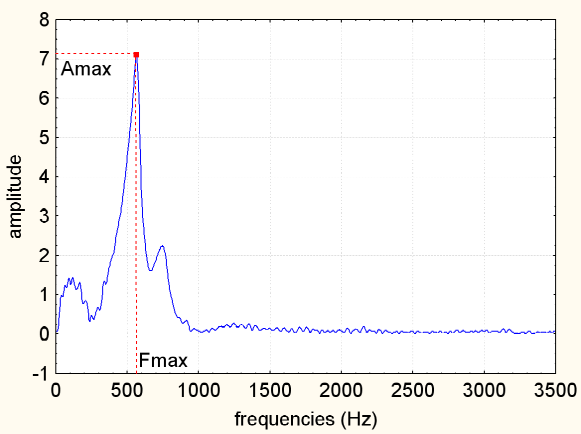

Figure 5. Amplitude (A_{max}) and frequency (F_{max}) of the maximum on the spectral curve of a tennis ball

However, the obtained results confirm that the experimental device gives reliable data that are exploitable for further tests.

5. Analysis and interpretation of results

In this paragraph the results for the discrimination of different varieties of apples are presented. A classification error of 0.25% was obtained by using the quadratic discriminant analysis (QDA). This misclassification rate was calculated taking into account all the 400 measures, (i.e. 10 fruits/varieties × 10 varieties × 4 faces/fruit). A single observation on 400 was erroneously classified by the QDA (an apple that belongs to the Cameo varieties was classified as a Red Delicious apple).This result is very encouraging because it shows that each kind of fruit has its own spectral signature, and that it is possible to distinguish the fruit varieties from some key features of the spectrum of the signal recorded by the microphone after the impact of the hammer on the fruit.

In figure 6 the projection of the 400 observations on the discriminating plan formed by the first two discriminant factors is given. One can easily see that, within the same varieties, observations are grouped by sub-sets of points (for example, Antares, Pink Lady and Cameo varieties are clearly two subgroups). This remark already gives a hint about a possible "side effect" that is the cause of the important dispersion of the points for the same fruit varieties. This phenomenon was observed for each varieties. We do not have enough evidence to clarify it. For instance, some hypotheses can be made to explain it: 1) non-homogeneities of the medium (effect of the nucleus, circular defects, etc.). 2) subtle changes in the composition of the flesh due to sunlight etc.

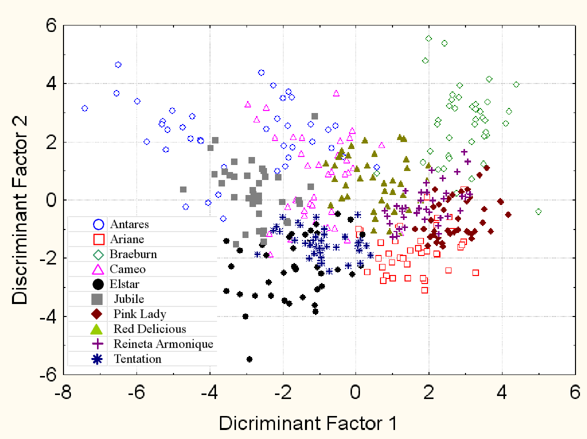

Figure 6. Projection of various apple varieties on the principal discriminating plan

Therefore, we tried to discriminate the apples based on measurements realised on the same side of fruit only (e.g. sun exposed side of the fruit). A classification error rate of 0% was obtained which means that all apples were classified correctly. In figure 7 the projections of these observations on the principal discriminating plane is presented: the separation of varieties is much clearer than before (Figure 6).

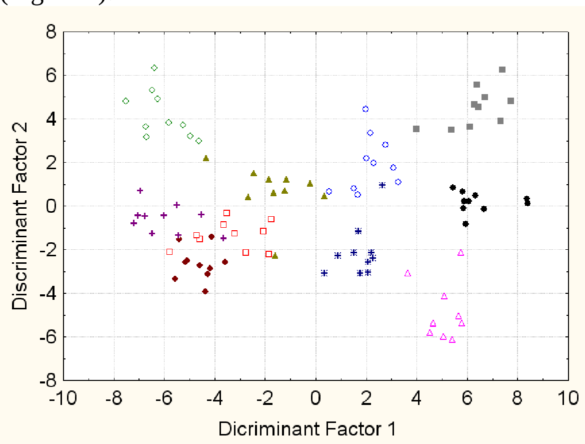

Figure 7. Projection of various apple varieties on the principal discriminating plan for measures performed on the same side

The classification error rate of 0.25% mentioned above has been obtained using the 18 descriptors and the set of all 400 observations for the construction of discriminant functions. This poses two problems: the ability of generalization and the robustness of the classifier. The generalization ability of the classifier means its ability to classify observations that have not participated to the construction of discriminant functions. So, it is wise to test the classifier by dividing the set of observations into two groups: the group of observations used to calculate the discriminant functions (also called learning sample) and the group of observations used for testing the classifier (also called test sample). In this way the ability of the classifier to generalize (i.e. to correctly classify the observations which did not contribute to the construction of discriminant functions) was tested. In table 3 the results of a study, that was conducted on the different possible divisions of the data set and their impact on the misclassification rate obtained, are presented.

k	Mean error (%)	Standard deviation (%)
5	16.50	3.24
10	15.25	6.06
20	16.25	9.98
50	14.75	10.92
100	14.75	17.44
200	15.00	25.56
300	15.00	35.77
400	14.75	35.50

Table 3 : Misclassifications according to the size of the overall learning and test samples

The data set has been divided in “k” parts of equal size. The construction of the discriminating function is then realized based on “k-1” parts and the test is done on the remaining part. The procedure was repeated “k” times and the average error and the standard deviation of the average error were calculated. For example, for k = 20, the 400 observations were divided in 20 groups of 20 observations each. Each group contains two observations of each kind of apple. The construction of discriminant factors was conducted on the basis of 19 groups (380 observations) and the test on the remaining group (20 observations). The classification error was noted. The procedure was repeated 20 times to cover all possible combinations of groups and from the 20 misclassifications errors obtained, an average error (16.25%) and a standard deviation (9.98%) were calculated. The classification errors obtained in this way are larger than the classification errors obtained on the complete set of data (0.25%). This is explained by the strong dispersion of the observations belonging to different varieties. Thus, observations quite far from their class centre which did not participate in learning led to the decrease of the dispersion of this class and their misclassification to an adjacent class with a larger dispersion. When k = 400 it is as if one excludes a single observation for the test and use the others for the construction of the discriminating function. This technique is very effective and often used in cross-validation of different classifiers, it bears the evocative name "*leave one out*".

The robustness of a classifier is related to the number of descriptors included in the model. It is well known that keeping non-informative descriptors in the model increases the classification error rate of new observations [43]. The objective is to obtain the lowest classification error of observations which did not participate to the construction of discriminant functions with the smallest number of descriptors. In table 4 the result of an ANOVA (Analysis of Variance) test for the 18 descriptors used is given. This test is designed to check whether a descriptor included in the model is significant from a statistical point of view or not. Some descriptors are more important than others for the discrimination of 10 varieties of apples. In general, the descriptor is as more important for the discrimination as the value on the column "*F exclusion*" is higher. Thus the amplitude of the third maximum on the spectral curve is the most discriminative variable for the chosen set of descriptors (F = 20.96). Then follow in order Fmax1 (absolute maximum frequency on the spectral curve), Energy4 and Energy3 (the energy absorbed in areas 4 and respectively 3 of the spectrum), etc.

	$F_{exclusion}$ (9.37)	p level
Amax1	10.83	0.000
Fmax1	19.16	0.000
Amax2	8.68	0.000
Fmax2	2.96	0.002
Amax3	20.96	0.000
Fmax3	3.44	0.000
Amax4	7.85	0.000
Fmax4	0.98	0.459
Amin1	1.96	0.042
Fmin1	12.23	0.000
Amin2	14.24	0.000
Fmin2	14.96	0.000
Amin3	4.70	0.000
Fmin3	2.99	0.001
Energy1	11.43	0.000
Energy2	13.04	0.000
Energy3	17.36	0.000
Energy4	17.71	0.000

Table 4 : Statistical significance of the descriptors for the discrimination

It is important to keep in the model only the most significant descriptors without reducing too much the precision in the classification. In figure 8 the results of a "leave one out" cross-validation study are presented. This study is realized by varying the number of descriptors from the first most significant until 18 and looking for the impact on the classification error rate. One can see that the percentage of misclassification is underestimated when evaluated on the complete data set. This is more evident as the number of descriptors is important. For the QDA, the lowest error rate is obtained for 13 descriptors (10.25%). But even with a number of 10 descriptors a comparable error rate (12.75%) is obtained. All this observations give us a good reason to think that 10 descriptors out of 18 are really significant from a statistical point of view for this study.

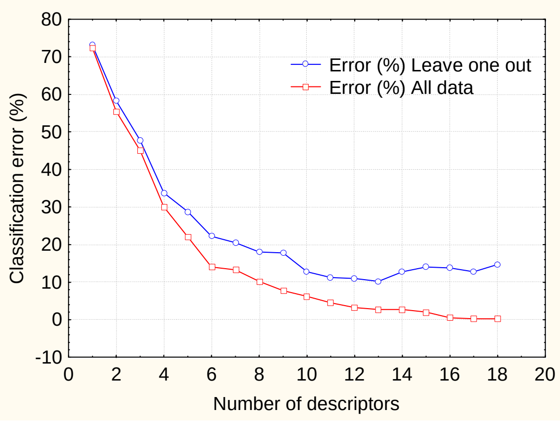

Figure 8. Influence of the number of descriptors on the classification error rate

In the table 5, these 10 descriptors are presented.

	$F_{exclusion}$ (2.58)	p level
Amax1	10.39	0.000
Fmax1	17.96	0.000
Amax2	19.12	0.000
Fmin1	14.52	0.000
Amin2	9.33	0.000
Fmin2	15.89	0.000
Energy1	12.23	0.000
Energy2	11.35	0.000
Energy3	33.91	0.000
Energy4	16.97	0.000

Table 5 : 10 most significant descriptors for the classification

6. Conclusion

The work presented in this article is only a first step in a major study on the evaluation of fruit quality by non-destructive tests. We chose to focus our attention on the acoustic measurements and we worked only on apples. A capability study has been done on the experimental device we used. This R&R study confirmed that our experimental device is quite capable to measure different key points of the spectrum of the signal recorded after the impact of a small hammer on the fruit.

The use of 18 carefully chosen spectral characteristics allows to discriminate among 10 different varieties of apples. This means that each type of apple has its own spectral signature permitting to unambiguously identify the belonging varieties of any fruit. Among the applications considered in this work we can mention, for example, the automatic sorting of apples.

We also proved that there is a "*side effect*" for apples that manifest itself by different spectral characteristics according to the chosen survey direction. This "*side effect*" was never highlighted before by other studies using acoustical measurements because they took into account only the frequency of the maximum pick on the spectra. At this moment no clear explanation about the cause of this side effect can be given, but several assumptions, that future studies will maybe confirm, can nevertheless be made: the propagation of sound waves is very dependent on the direction of propagation because of the non-homogeneities of the internal environment of the apple (shape of the nucleus, circularity, etc.); the density and composition of the environment changes after exposure to the sun, and so on.

As mentioned in the introductory part of this paragraph, this study is a first step in a larger program which aims to assess the quality of apples by non-destructive tests. A consistent database containing information from different sensorial tests and destructive test already exists. It is well-understood that each test provides, a wealth of information. We will consider undertaking further studies on the possible correlations that may exist between these tests and the acoustical technique. We will also compare the performance of the acoustical method with those of other non-destructive testing such as optical or laser tests. The goal here is to extract maximum information on fruit quality without destroying the fruit and without relying on expensive laboratory methods which require much time and dedicated resources.

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