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DEVELOPMENT OF A METHOD FOR NONDESTRUCTIVE TESTING OF FRUITS USING SCANNING LASER VIBROMETRY (SLV)

C. Santulli, G. Jeronimidis
Centre for Biomimetics, University of Reading, UK[1]

ABSTRACT

Quality control on fruits requires reliable methods, able to assess with reasonable accuracy and possibly in a non-destructive way their physical and chemical characteristics. More specifically, a decreased firmness indicates the presence of damage or defects in the fruit or else that the fruit has exceeded its "best before date", becoming unsuitable for consumption. In high-value exotic fruits, such as mangoes, where firmness cannot be easily measured from a simple observation of texture, colour changes and unevenness of fruits surface, the use of non-destructive techniques is highly recommendable.

In particular, the application of Laser vibrometry, based on the Doppler effect, a non-contact technique sensitive to differences in displacements inferior to the nanometre, appears ideal for a possible on-line control on food.

Previous results indicated that a phase shift can be in a repeatable way associated with the presence of damage on the fruit, whilst a decreased firmness results in significant differences in the displacement of the fruits under the same excitation signal. In this work, frequency ranges for quality control via the application of a sound chirp are suggested, based on the measurement of the signal coherence. The variations of the average vibration spectrum of a grid of points, or of point-by-point signal velocity allows the *go-no go* recognition of "firm" and "over-ripe" fruits, with notable success in the particular case of mangoes. The future exploitation of this work will include the application of this method to allow on-line control during conveyor belt distribution of fruits.

INTRODUCTION

In recent years, Laser Doppler vibrometry (LDV) has been applied in different sectors e.g., automotive (3D vibration dynamics, brake discs squealing) [1], aerospace (characterisation of defects on composite structural parts of aircrafts [2], analysis of micro-motors for satellites [3]), and sensors development (calibration of piezoelectric sensors [4]). NDT research applications included a broader range of issues, among which is restoration of artworks, where vibrometry was found useful for locating and measuring structural detachments from the substrate and delamination of paint layers [5]: a similar delamination monitoring was also possible on composite materials [6].

The high spatial resolution of LDV, especially scanning Laser vibrometry, enables also measuring the vibration response and possibly evaluating the mechanical properties of highly dampened materials, such as composites and biological materials (e.g., wood, vegetable tissue). An approach to vibrometry as a non-destructive method requires individuating the vibration "signature" of the structure considered, and evaluating the effect of structural modifications on the vibration response.

On fruits, over-ripeness results in reduced firmness, which in turn has a complex relation with mechanical properties, in particular Young's modulus of the fruits [7]**.** Traditional methods for firmness measurement involve a visual or manual inspection, or the use of destructive techniques, typically measuring the resistance of fruits to penetration via a punch. For quality discrimination purposes, it is therefore crucial to evaluate the response via NDT inspection, of a "good" (ripe) and "defective" (over-ripe) fruit.

These techniques, however, have limited accuracy, so that recently methods based on the analysis

[1] Whiteknights – Reading RG6 6AY (United Kingdom)
E-mail: c.santulli@rdg.ac.uk, Tel.: 0044-118-3788564 Fax: 0044-118-9313327

of multiple variables e.g., refractory index, colour, acidity and penetrometric data [8]. However, chemometric methods can only be applied on a limited number of fruits. This appears to be of limited significance e.g., when checking the quality of exotic fruits with stony endocarp, such as mangoes, which can have a degree of ripeness widely variable, even in the same batch of fruits.

In the last years, a number of non-destructive methods for firmness evaluation in fruits have also been proposed, including ultrasonics [9], nuclear magnetic resonance (NMR) [10], Laser spectroscopy [11] and photoluminescence [12]. Recent studies using Laser vibrometry on fruits include firmness measurements on some apples varieties [13], on kiwis [14] and persimmons [15].

Here, a non-destructive method is proposed, which appears to be able to monitor the variations of the "vibration signature" on fruits from three largely diffused cultivars, Royal Gala apples, Rosa mangoes and cherry tomatoes, to give an indication of the quality degradation of fruits, due to over-ripeness. This work is aimed at preparing a possible application of the control on the conveying line, with an initial go-no go discrimination philosophy, and the use of a limited number of points, in order to minimise the selection time.

SCANNING LASER VIBROMETRY

Scanning Laser Doppler vibrometry (SLDV), based on an optical interferometry principle, is a sensitive and robust characterisation method, which greatly facilitates solving vibration problems since it measures the full-field surface vibration. This technique is capable of accurately measuring surface velocities of grids of points moving at frequencies of up to 30 MHz via the measurement of the Doppler shift that the beam undergoes when entering the surface of the moving body. The spatial resolution depends on the Laser beam, but digital demodulation of light can allow accurate measurements of displacements as low as $2*10^{-12}$ m for scanning speed of up to approximately 100 points/second. Obtained data are then processed and presented as response spectra and time histories 2D or 3D colour maps. SLDV is ideal in applications where it is impossible or very difficult to use standard vibration measuring devices, such as accelerometers. In quality control of fruits, the application of accelerometers may result in damage being inflicted to delicate surfaces, such as fruit skin. In addition, to perform an accurate vibration analysis, it would be necessary either to use many transducers, or to move one around the tested piece. Apart from the considerable time required for fruit inspection, online inspection would not be possible in this case.

LASER VIBROMETRY ACTIVITIES (UNIVERSITY OF READING)

Laser vibrometry activities carried out at the University of Reading included work on a number of projects, in particular on highly dampened materials (composites and biological materials) for structural and biomedical applications.

Some examples of the problems investigated with the support of Laser Doppler vibrometry include the following:

- Measurement of the variation in damping factor in some varieties of poplar wood as a result of the different fibre orientation [16]
- Study of vibration properties of composite springs for train bogies (measurement of natural resonance modes for different design configurations)
- Study of vibration properties (natural resonance modes) of different design configurations for an architectural structure (Kagome lattices) to be employed to maximise mechanical and acoustic performance (concert hall roof structure)
- Middle ear study, in collaboration with Guys and St. Thomas Hospital– London (evaluation of the optimal position of cochlear implants [17] and monitoring of drill-caused ear trauma during surgery)
- Vibration of filiform hairs in house crickets (*Acheta domesticus*) in response to induced airflow for the development of innovative bionic sensors

EXPERIMENTAL

The experimental program is aimed at evaluating the possibility of using scanning Laser vibrometry to measure firmness in fruits by monitoring the frequency spectra and signal amplitudes over grid of points evenly distributed on a surface of the fruit, supposed to be the one which is turned in the direction of the scanning laser vibrometer objective. Such an evaluation is designed to be carried out in an industrial conveying environment, therefore with fruits moved and supported from below, with no surface treatment.
The initial aim is measuring if a sufficient confidence can be obtained in discriminating fruits with a “go-no go” philosophy. In other words, it is required that the vibrometry response be sufficiently different between “acceptable” and “detective” fruits. This would enable the design of an algorithm for quality discrimination, scanning only a few points in each fruit and therefore requiring a very short time.

In order to excite fruits vibration, simulating their conveying conditions, a repeatable and completely non-destructive method was selected, using an electro-magnetic vibrator, encased in a steel structure resonant at 12000 Hz. The vibrator was fed with a broadband noise chirp from 200 to 2000 Hz, ideally with flat response in this interval, whose limits were selected to avoid disturbance from mechanical free-body vibrations of the fruits (usually centred around 100-150 Hz) and to come at the highest possible level at which a sufficient signal-to-noise ratio was measured in a previous study [18]. The chirp was produced via software by the Laser vibrometer system used, which was a PSV-300 scanning system by Polytec, fitted with a Laser beam with 100 μm diameter.

FRUITS EVALUATED

The research was centred on three fruit cultivars, Royal Gala apples (UK), Rosa Mango (Brazil) and Pachino cherry tomatoes (Italy). On each of the three cultivars, 20 fruits of the same batch were randomly obtained from supermarkets. Of these, extreme cases were taken i.e., the fruit which appeared subjectively (visual inspection and gentle squeezing by expert workers) to be the hardest and the softest were singled out to be examined in the vibrometry study. For the mangoes, also a fruit of intermediate firmness was considered, and defined as *medium*. Typical grids of scanning points are shown in Figure 1 for the three fruit cultivars studied: the totality of points yielded an optimal or at least valid signal-to-noise ratio. Distances between points varied from 3-6 mm on mangoes and apples and 1.5 to 4 mm in cherry tomatoes.

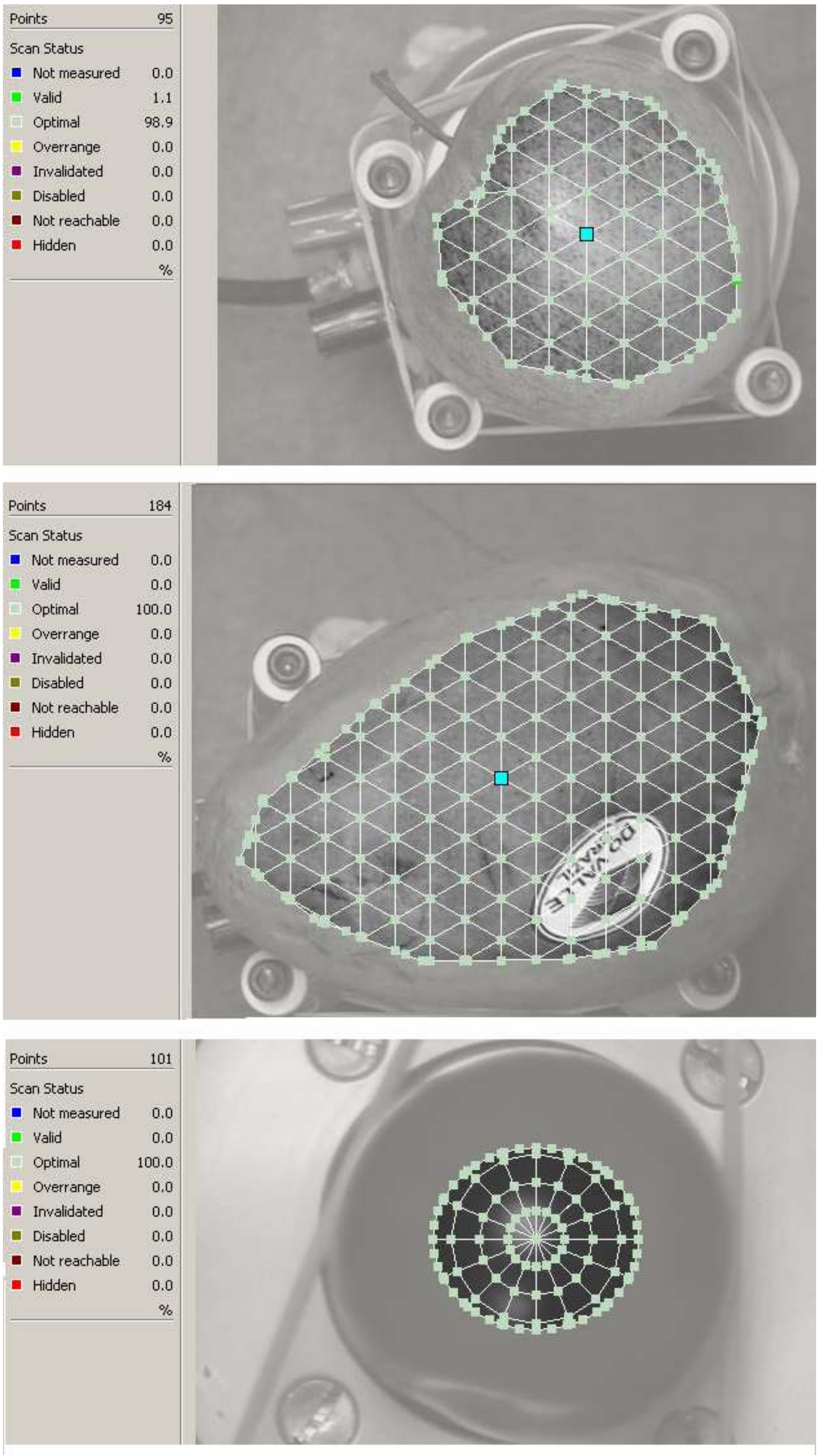

Figure 1 Typical grids of scanning points for the three fruits cultivars
(Gala apple, Rosa mango and Pachino cherry tomato)

RESULTS AND DISCUSSION

One of the main requirements to try to set up an online inspection procedure for fruits is to define a frequency range in which a sufficient signal-to-noise ratio can be obtained, possibly for different fruits, so to automatise the quality discrimination. To measure the value of signal-to-noise ratio, often the variable "coherence" is used. In general, the concept of coherence is related to the stability, or predictability, of phase. Spatial coherence describes the correlation between the input (chirp) and output (fruit surface vibration) signals in the different grid points. Temporal coherence describes the correlation or predictable relationship between the two signals observed at different moments in time. Spatial and temporal coherence are related in turn with the width of interference patterns of Laser light and hence with the signal-to-noise ratio of the output signal, assuming that the signal fed has a signal-to-noise ratio approaching to infinity, which is about true for correctly focused Laser beams on surfaces that do not diffuse the reflected light.

In some vibrometry studies (e.g., [19]), a signal with coherence exceeding 0.9 is considered as a "valid" signal. Typical coherence diagrams over the 200-2000 Hz range are shown in Figure 2 for the three fruit cultivars considered. These diagrams suggest that the highest frequency at which a coherence value higher than 0.9 was obtained was 898 Hz for apples, 803 Hz for mangoes, and 1203 Hz for cherry tomatoes. In the latter case, the quasi-spherical shape of the fruits and the skin smoothness had a beneficial effect on the signal diffusion, potentially extending the possible range of application for the method.

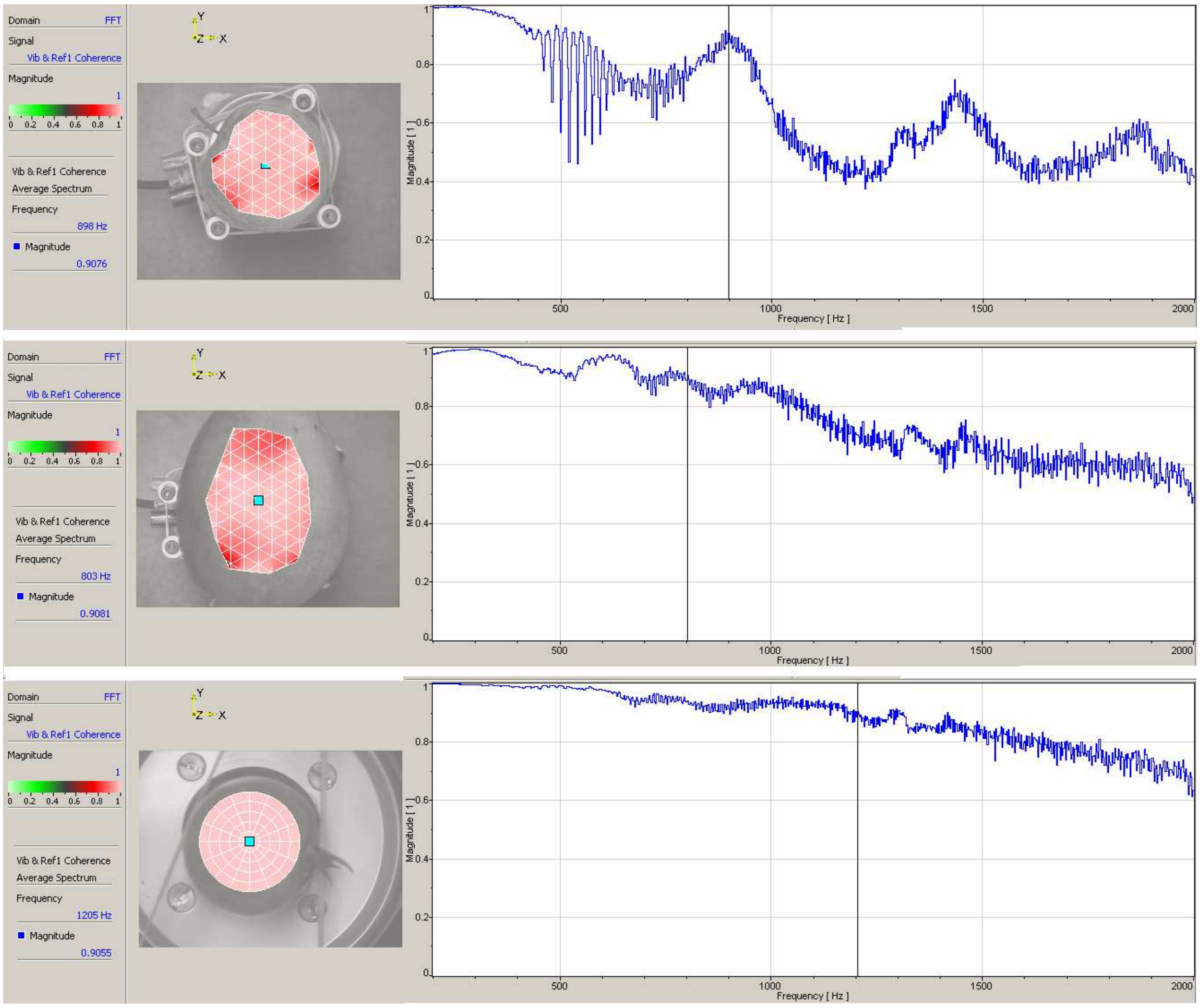

Figure 2 Typical coherence diagrams for the three fruit cultivars

Considering the average spectrum over the points scanned on the fruits, two effects can be singled out about the relation of first detected resonant mode with firmness. In particular, the firmer fruit can have a higher value of resonant frequency, as is the case with apples (Figure 3a), an effect which has been described already in [20]. However, for fruits, such as mangoes, where the thicker skin acts as a highly dampened membrane, it is more likely that the resonant mode detected on firmer fruits (around 550 Hz for hard H) mango disappears in the average spectrum for softer ones (medium M and soft S). A general consideration of the signal velocities obtained from the average spectrum (Figure 3b) suggests that the firmest mango has a less scattered output value, as well as the softest one, although the latter with absolute values of velocities about five to ten times lower. In contrast, the medium mango yields signal velocity values more oscillating with frequency, most probably as a result of a larger point-to-point scattering.

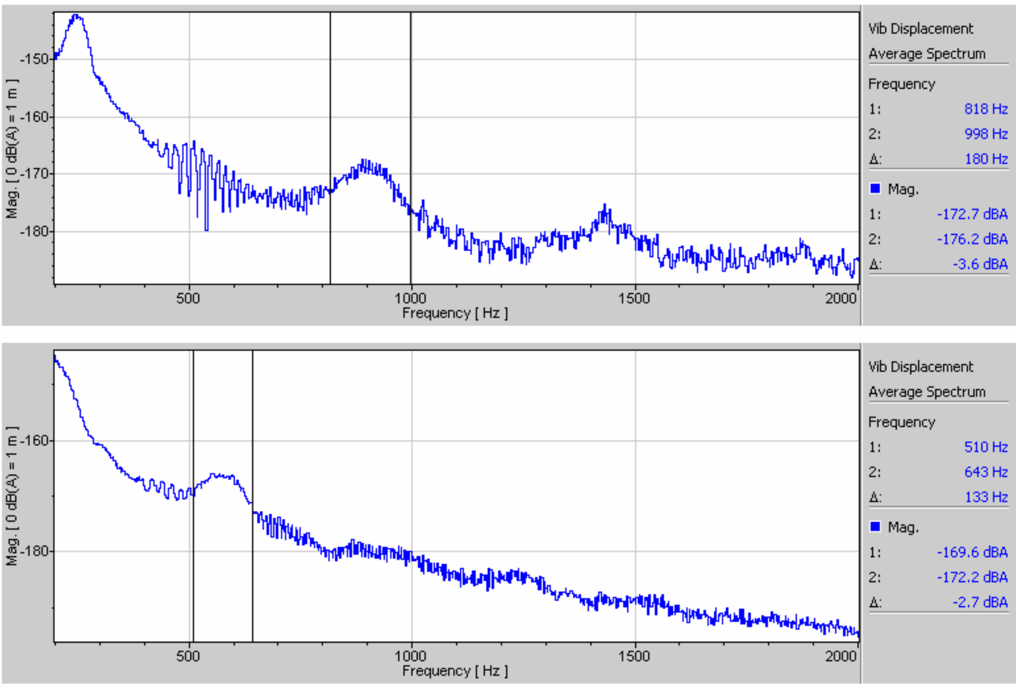

Figure 3a Average spectrum (200-2000 Hz) for a firm (above) and soft apple (below)

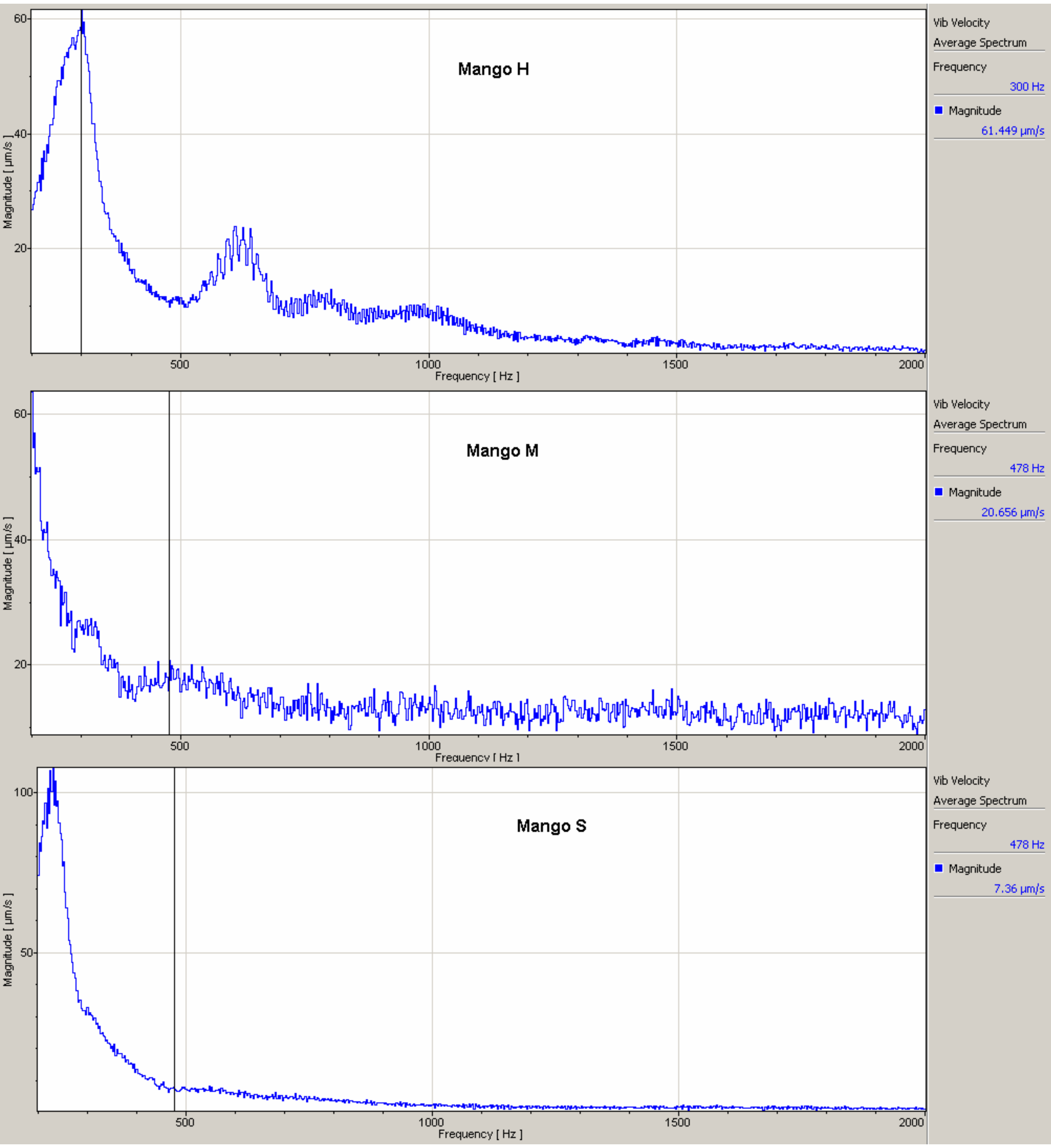

Figure 3b Average spectrum (200-2000 Hz) for a firm, medium and soft mango

This suggests, as a general consideration, that it should be possible to reduce the number of measurement points to a minimum and still obtain a good level of discrimination between "good" and "over-ripe" fruits. However, the possible refinement of the method to get a quantitative measurement of firmness would incur in further difficulties, as shown in the case of the *medium* (i.e., slightly over-ripe) mangoes.

To try to evaluate this possibility, the vibration velocity point-by-point in the whole of the scanning grid considered has also been studied. In this case, the firmest and the softest apple have shown (Figure 4a) still considerable differences in signal velocities (from two to three times), consistent in most of the scanned points, although not as large as in the case of mangoes, at the two extreme frequencies, 200 and 2000 Hz. A similar study on mangoes at three frequencies, 220, 503 and 1413 Hz, the latter with signals of reduced coherence, show again that large differences in signal velocity (again 5-10 times from "hard" to "medium" and from "medium" to "soft" fruits) are still present in around 80% of the scanned points (Figure 4b). In contrast, on cherry tomatoes, the differences in signal velocities between “firm” and “over-ripe” fruits appear to be much lower and inconsistent below 1000 Hz (Figures 5a and 5b). A study above that frequency can possibly offer some results (differences in the order of 50-100%), although in that case a good compromise with the lower signal-to-noise ratio in this frequency range needs to be found.

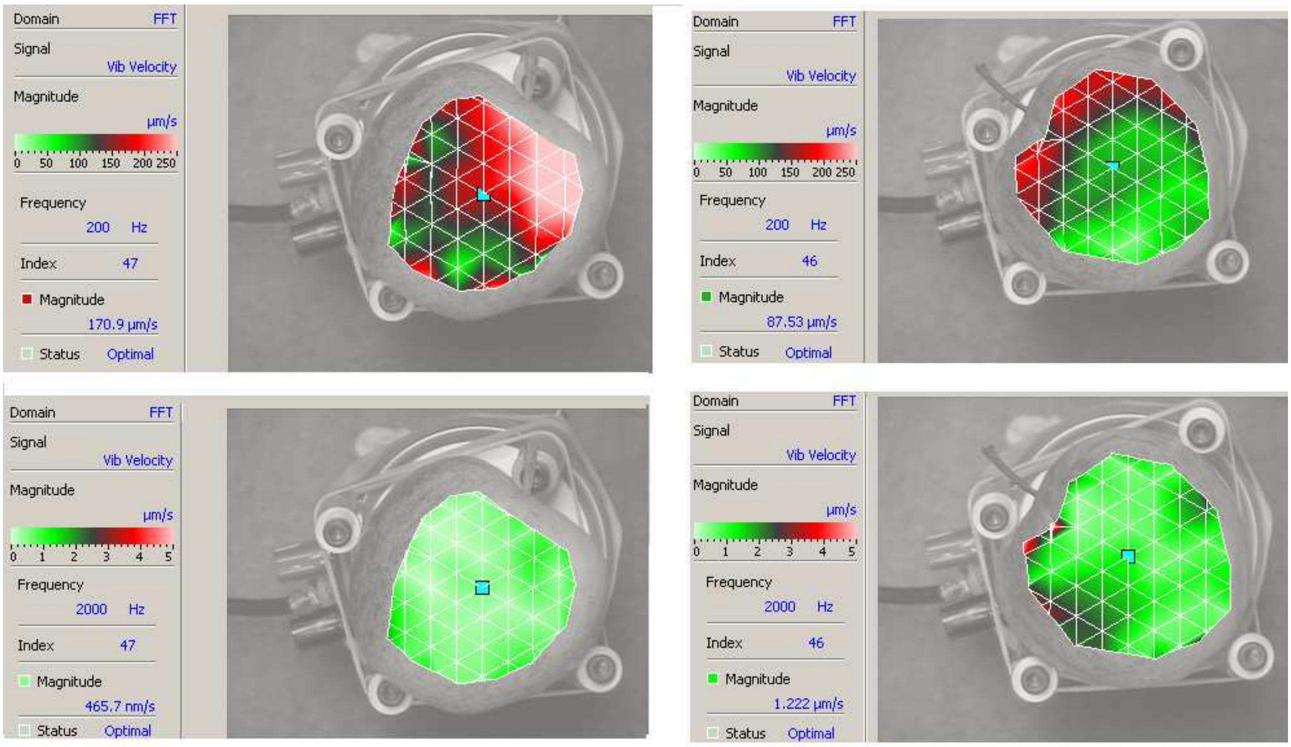

Figure 4a Point-by-point signal velocity for a firm (left) and soft (right) apple at 200 and 2000 Hz

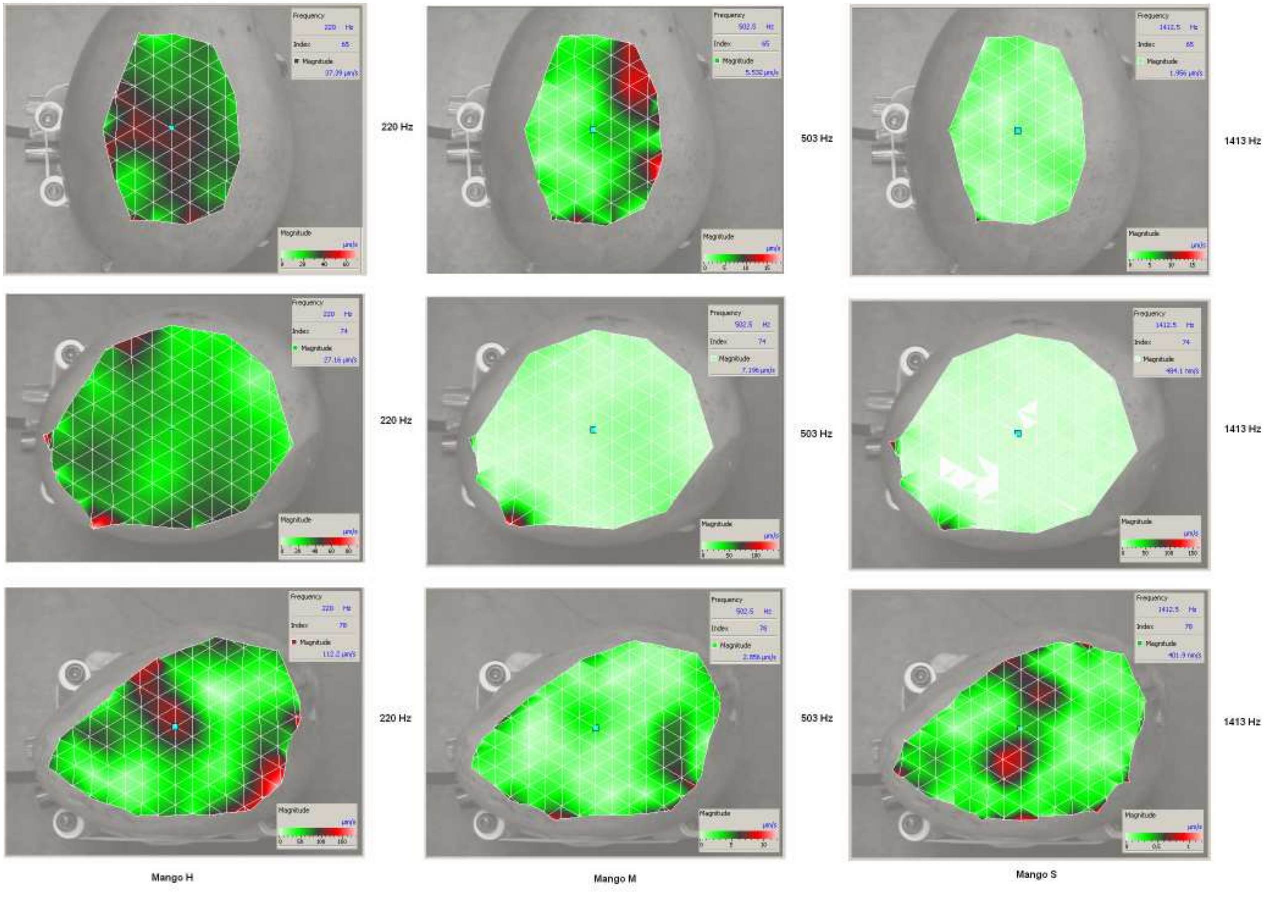

Figure 4b Point-by-point signal velocity for firm (left), medium (centre) and soft (right) mango at 220, 503 and 1413 Hz

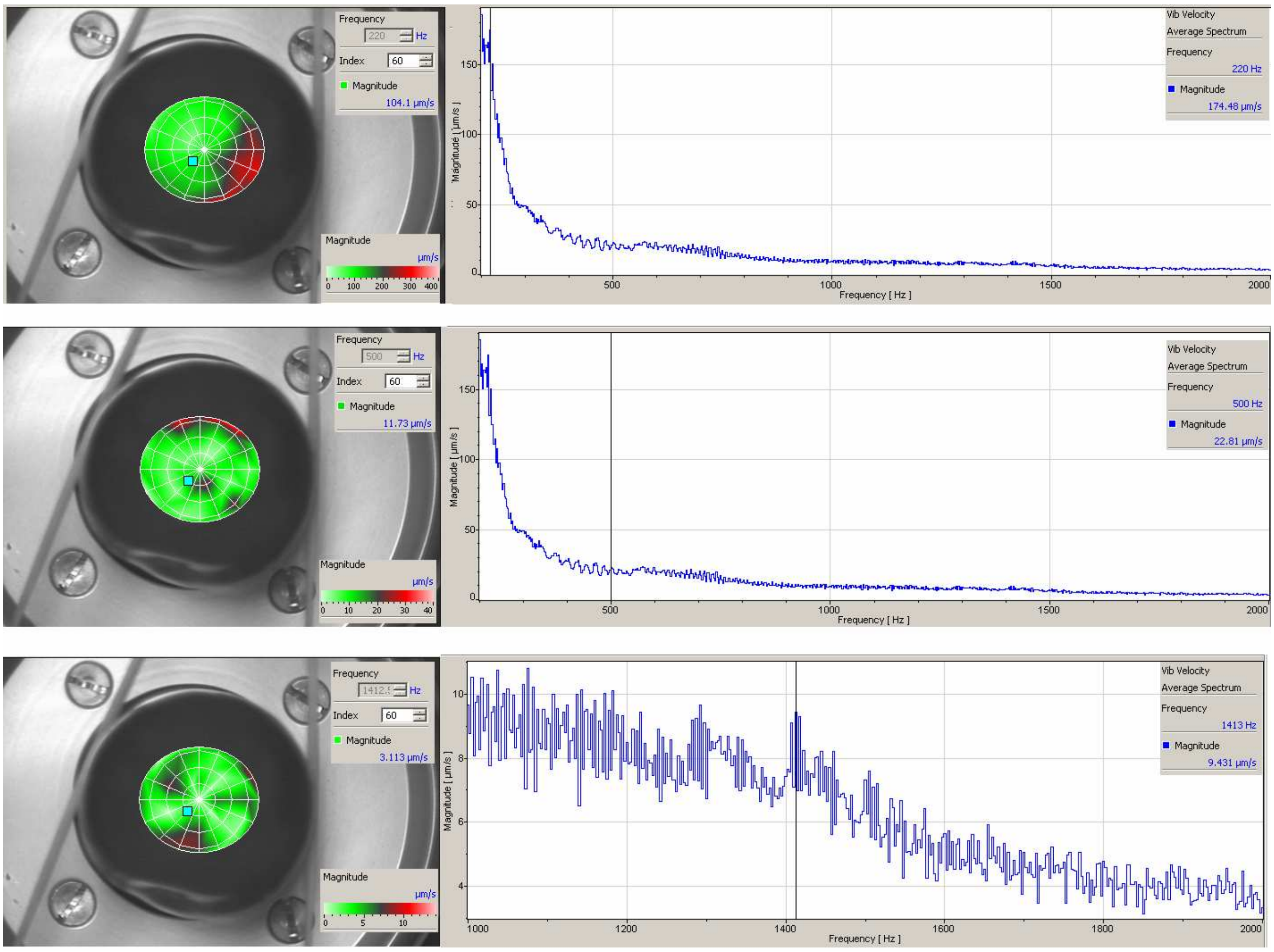

Figure 5a Point-by-point signal velocity and average spectrum for a firm cherry tomato at 220, 500 and 1413 Hz

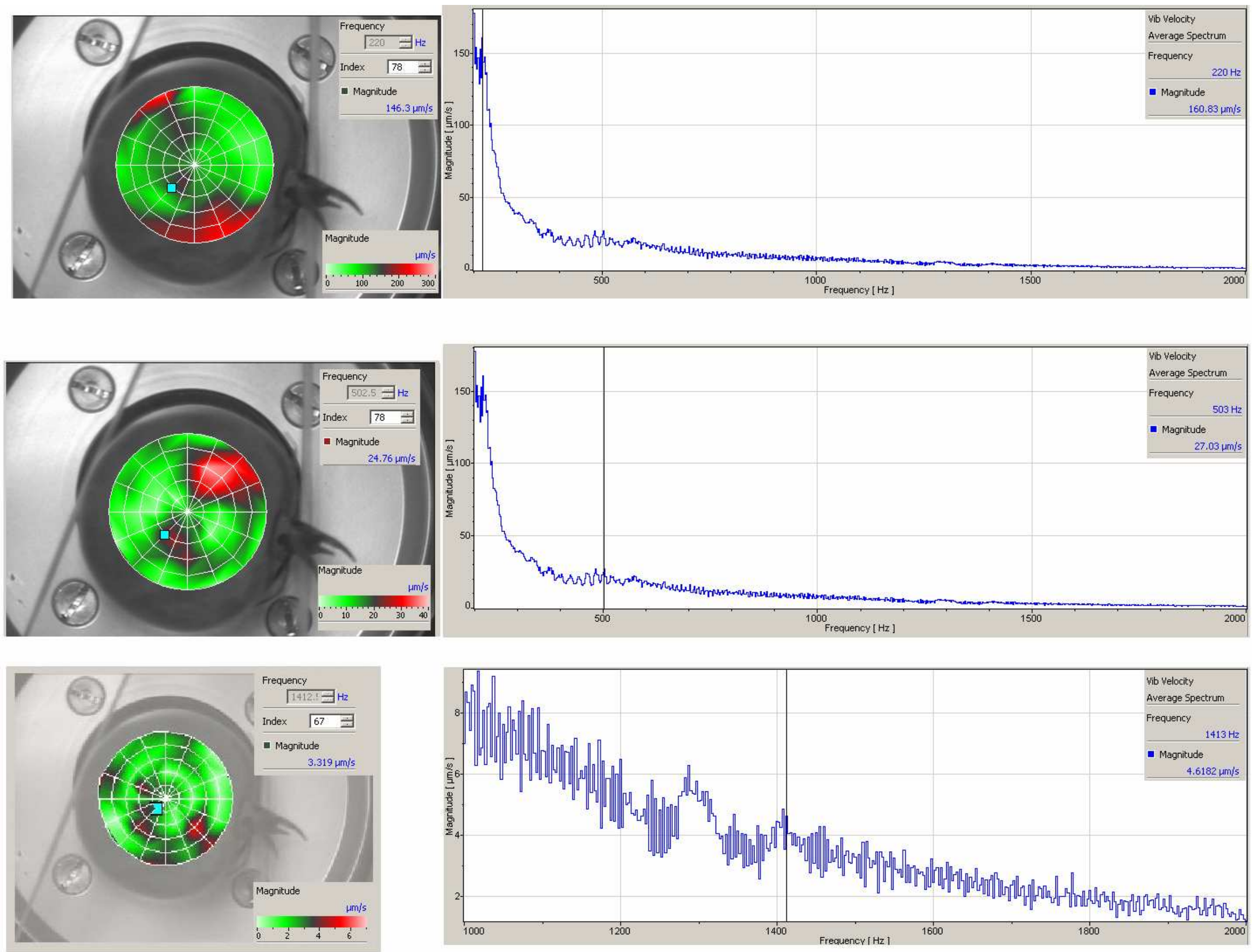

Figure 5b Point-by-point signal velocity and average spectrum for a soft cherry tomato at 220, 500 and 1413 Hz

CONCLUSIONS

The envisaged application of scanning Laser vibrometry as a non-contact technique for the quality discrimination of fruits proved promising. The excitation of fruits with chirps of sound reasonably close to “white noise” from 200 to 2000 Hz yielded an optimal signal-to-noise ratio on the fruits below 800-900 Hz, and consistent results on most points even above these frequencies.

Very good discrimination between “firm” and “soft” fruits was obtained throughout on mangoes, also because of the dampening properties of their thick skin, whilst on apples and cherry tomatoes more caution has to be taken in selecting measurement points and frequency ranges.

In general, this work may constitute a good basis for the application of this method on distribution lines for a number of food products.

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