LASER DOPPLER FORCED VIBROLOGY OF SOFT AGRICULTURAL PRODUCTS

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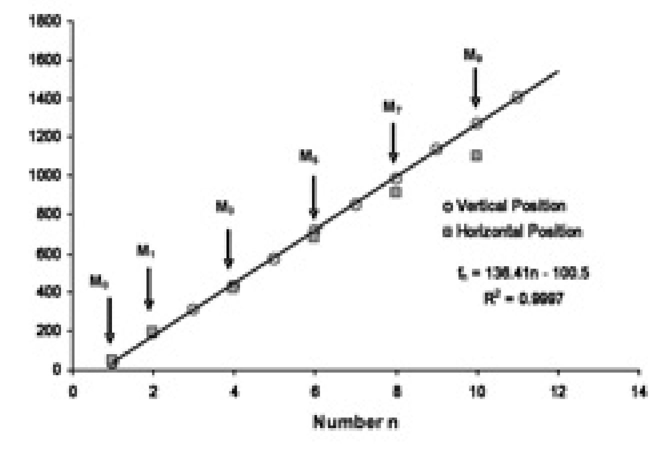
ABSTRACT:
We describe methodology of laser Doppler forced vibrology (LDFV) applied to texture assessment of soft agricultural products. The method is applied to a melon. The lowest frequency resonant peak (mode M_o) is used for corrections of the whole amplitude frequency plot expressed in relation to the forcing deformation level. The main differences between vibrology in vertical and horizontal laser positions are described. Missing and/or degeneration of some modes in the laser horizontal position are explained. Peak analysis of the results obtained reveals the parameters connected with information on internal damping, i.e. internal viscosity. Modulus of elasticity is calculated either from the peak frequency of the M_1 mode or by a new method from the M_o peak frequency. The modulus of elasticity of the latter method is nearly one order higher and is more variable than the former probably because the M_o mode is related to physical properties of the surface of the melon in contact with the vibrating table. Fine structure of the skin can lead to possible degenerated forms with more sub-peaks.

ZUSAMMENFASSUNG:
Wir beschreiben die Methodologie für herbeigeführte Doppler-Vibrologie, die zur Textur-Bewertung von weichen landwirtschaftlichen Produkten benutzt wird. Die Methodologie wurde für Wassermelone angewandt. Der Resonanzhöhepunkt mit der niedrigsten Frequenz (Modus M_o) wurde für die Korrektion der ganzen Abhängigkeit Amplitude-Frequenz bezogen zum Niveau der Deformationseinwirkung angewandt. Die Hauptunterschiede zwischen der Vibrologie mit vertikaler und horizontaler Lage des Lasers werden beschrieben. Die Degeneration mancher Modi bei den Experimenten mit horizontaler Laser-Lage wird beschrieben. Die Analyse der ermittelten Resonazhöhepunkte bringt Information über eine innere Dämpfung, das heißt über die innere Viskosität des Objekts. Das Elastizitätsmodul wurde sowohl aus der Frequenz von Modus M_1, als auch auf neue Weise aufgrund von Modus M_o errechnet. Im zweiten Falle war der Wert des Elastizitätsmoduls fast um eine Stelle höher und wesentlich variabler als im ersten Falle, weil sich Modus M_0 zu dem den Vibrationstisch kontaktierenden Oberflächenteil der Melone bezieht. Eine kompliziertere Struktur der Schale kann zu degenerierten Formen von Modus M_o mit höherer Anzahl der Teilhöhepunkte führen.

RÉSUMÉ:
Nous décrivons la méthodologie des vibrations excitées par le vibromètre dopplérien à laser utilisé pour évaluer la texture des produits agricoles moux. La méthodologie a été utilisée pour le pastèque. Le pic de résonance à amplitude la plus basse (mode M_o) a été utilisé pour corriger toute la dépendance amplitude-fréquence exprimée en relation au niveau de l´excitation de déformation. Les principales différences entre les vibrations à position verticale ou horizontale du laser ont été décrites. La dégénération de certains modes lors les expériences à position horizontale du laser a été expliquée. L´analyse des pics de resonance mesurés a offert l´information sur l´amortissement intérieur, c´est- à –dire de la viscosité intérieure de l´objet. Le module d´élasticité a été calculé de la fréquence et aussi en se servant du nouveau mode M_o. Dans le deuxième cas, la valeur du module d´élasticité a été supérieure presque d´un ordre et beacucoup plus variable que dans le premier cas parce que le mode M_o est en relation avec la partie supérieure du pastèque qui entre en contact avec la table vibrante. La stucture plus compliquée de l´écorce peut mener aux formes dégénérées du mode Mo au nombre plus élevé de pics séparés.

KEY WORDS: vibration, fruits, vegetable, Laser-Doppler vibrometer, resonance peak, amplitude-frequency plot, mode



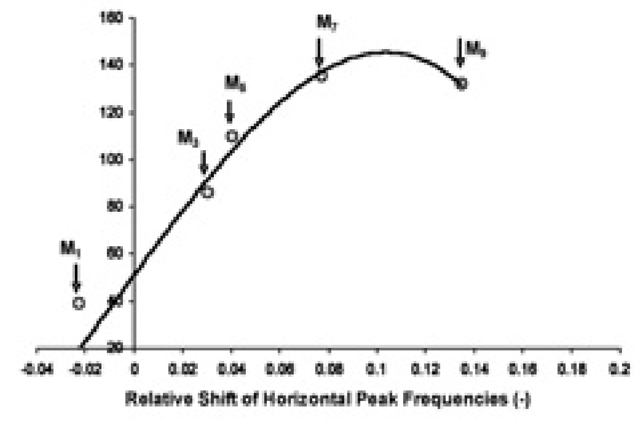


Figure 7 (left): Peak frequency plotted against number n (number of periods of the standing waves on the circumference of the meridian circle of the tested melon). The arrows determine position of the modes.

Figure 8: Peak width W (vertical position) plotted against ratio of relative shift of horizontal peak frequencies (RS = (VF – HF)/VF, where VF and HF are vertical and horizontal peak frequencies, re.

stood also as the increasing role of the product (melon) viscosity. The observed deviation of peak frequencies (between horizontal and vertical positions) as an indication of the product viscosity was previously found theoretically (Akimoto 2005, unpublished).

The corrected M_o peak frequency was 35.73 Hz for vertical and 49.23 Hz for horizontal laser positions. Both values are different from the ones previously used for the measurement corrections: 38.15 Hz for vertical and 51.88 Hz for horizontal laser positions. The differences are not too big (less than 5% in the both cases).

5 ELASTIC PROPERTIES OF TESTED MELON

Putting the results obtained for M_1 mode into Eq. 1 we obtained the following comparable values of modulus of elasticity of 3.32 MPa for vertical position and 3.47 MPa for horizontal position (melon's mass and its diameter are given in text to Figure 2, ν was approximated by 0.3). The obtained values are nearly identical with relative difference of only 4.5 %, corresponding to a set of measurement on melons 3.59 ± 0.62 MPa ($n = 10$). Modulus of elasticity can be also calculated from mode M_o as information on the product elasticity in the contact point.

Supposing the melon contacts with a tough flat table (steel table of vibration generator) in terms of homogeneous elastic sphere of radius r, the static contact force F between melon and the table can be described in terms of Hertz's contact theory [14]:

$$F = \frac{4}{3}\frac{E}{1-\nu^2}\sqrt{r}x^{3/2} = mg \tag{8}$$

where E is elastic modulus of the sphere, m its mass, ν its Poisson ratio, and x the surface perpendicular deformation. The derivative dF/dx can be calculated from the first part of Eq. 8 and the second part can be used for exclusion of deformation x. Putting the calculated dF/dx into Eq. 4a the resulting equation for contact modulus of elasticity E_c is obtained:

$$E_c = \frac{m}{\sqrt{3gd}}\omega_o^3\left(1-\nu^2\right) \tag{9}$$

where g is gravitational acceleration and d sphere diameter .

The M_o peaks obtained for our melon gave the following values of E_c = 9.98 MPa (vertical position) and 26.1 MPa (horizontal position). This difference cannot be explained by the above mentioned shifts of the M_o peak during data corrections that was less than 5% in both positions and then E_c error can be enlarged only about 16 %. The observed difference in E_c rather expresses differences in the surface properties of the tested melon that gave in repeated measurement 18.4 5± 6.4 MPa ($n = 10$) . It is clear that interpretation of the M_o data as well as the process of the correction should be made with the highest care.

6 CONCLUSIONS

The peak M_o gives important information about the corrections that is necessary for the AFP of the forced vibrology. It also contains information about surface properties of the product in contact with the table of vibration generator. These properties can vary and could be expressed by elastic modulus of the contact surface of the tested product. Splitting of the M_o peak can be caused by structural variations in the skin contact.

For corrections of the obtained AFP as well as for peak analysis, the amplitudes have to be expressed in the natural relative form. Test with laser in horizontal position gives reduced infor-

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mation on the tested product: the modes with odd *n* (number of nodes on the meridian connected poles: the vibrator contact and the analysed place with laser in vertical position) are either missing or reduced. Other modes are shifted in comparison to the laser vertical position to their lower values.

In vertical position, each mode peak is shifted with a constant increment of frequency (~ 136 Hz in our case). The peak heights as well as the peak widths can be expressed as a power function of the peak frequency. Peak width as well as peak height correlate with relative shift of the horizontal peak frequencies. Both of them correlate with shift of the peak frequencies representing at least some part of information about damping (viscosity) level corresponding to the individual modes.

The AFPs afford information about the modulus of elasticity of the tested products. The mode M_1 gives some kind of holistic modulus of elasticity of the tested product. Approximately the same values were obtained in both laser positions. The M_0 gives the local surface modulus of elasticity that could be different in different places of the tested product.

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