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Influence of sugar beet storage duration on root response to non-destructive impacts**

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A b s t r a c t. For the purpose of this paper, sugar beet roots were loaded by creating the impact of aluminium bars falling from different heights. The time history of the force at the contact between the sugar beet root and the bar was measured. The response of the sugar beet root to the impact was evaluated in terms of surface displacement. This displacement was measured using a laser vibrometer. The displacement was studied in the time and frequency domain during the postharvest period, up to 71 days after crop collection. The measured parameters describing the sugar beet response were significantly sensitive to the storage duration, namely in the frequency domain. Correlations between the storage duration and the main parameters of both the force and surface displacement were identified ($p < 0.05$).

K e y w o r d s: impact loading, vibration, response, storage, sugar beet root

INTRODUCTION

The quality parameters of sugar beets mainly include sugar content, soluble solids, moisture content and mechanical properties (Trzebinski, 1984; Vukov, 1977). In terms of the storability of sugar beet roots, storage temperature appears extremely important (Huijbregts, 2008; Kenter and Hoffmann, 2006; Olsson (2011), along with humidity (Andales *et al.*, 1980; van Swaaij and Huijbregts, 2010), frost damage (Kenter and Hoffmann, 2006) and treatment (Campbell and Klotz, 2006; Olsson, 2012).

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Mechanical properties are mostly measured using the Magness Taylor penetration test (Shmulevich *et al.*, 2003). However, this simple and rapid method is destructive and characterised with small accuracy, low measuring repeatability and dependence on the person carrying out the test; thus, it is not suitable for rapid and automated evaluation of sugar beets. Hence, rapid and non-destructive measurement methods can be valuable for assessing the quality and condition of sugar beets, both before and after the harvest. One of these methods, which uses hyperspectral scattering, was described by Pan *et al.* (2016). In this paper a brief review on non-destructive methods is also presented. Such methods have been developed for the evaluation of mechanical properties of fruit (Taniwaki *et al.*, 2009), eggs (Trnka *et al.*, 2016; Wang *et al.*, 2004) and some other raw agricultural (Kertész *et al.*, 2015; Kubík *et al.*, 2016) and food materials (Benedito *et al.*, 2004; Božiková and Hlaváč, 2016).

The present paper deals with a method based on the use of the mechanical impact. This procedure was developed by Delwiche *et al.* (1987). Some impact response parameters, such as maximum force, maximum deformation and impact duration, were shown to be closely related to firmness and, therefore, to ripeness during the postharvest period (Garcia *et al.*, 1988). Additional information on the product quality flows from the response function of the impacted product. This response can be released from the tested specimen during its impact loading or surface displacement, recorded using different methods.

In this paper a method of non-contact surface displacement measurement was used. A sugar beet root specimen was loaded by creating the impact of an aluminium bar during storage. The changes of both the impact force and surface displacement during sugar beet storage were evaluated. Correlations between the storage duration and the main parameters of force and surface displacements were identified.

MATERIAL AND METHODS

Sugar beets were collected from a field near Jiříkovice (the South Moravia region, Czech Republic) during the 2015 harvest season. The sugar beet roots samples were stored in a refrigerator at 4°C and 85% relative humidity. All beet samples were washed to remove adhered soil immediately prior to the experiment.

The response of sugar beet specimens to nondestructive impact was measured using an experimental setup, which was developed and built to evaluate the resonance signal, and to analyse the frequency domain for eggs (Kumbár *et al.*, 2015a; Trnka *et al.*, 2016). The experimental setup consisted of a bed made of polyurethane foam, a mechanical impulse excitation device (a bar falling on the beet root specimen from a definite height) and signal amplifiers. The personal computer and software were used to controll the experimental setup and analyse its results. The foam both simulates the soil in which the beet grows and protects the beet under investigation from damage during the impact experiments. More specificaly, the foam layer, which was only 5 mm thick, was glued on the inside of the cylindrical steel holder. Beet response measurements were carried out in such a short time that they did not show any supporting of the beet. The cylindrical striker sized 6 x 200 mm was guided by two thin strings. The friction of the striker was negligible during the drop. The experimental arrangement scheme is shown in Fig. 1.

The instrumentation of the bar by the strain gauges made it possible to record the (time) history of the force at the bar-beet specimen contact area. The beet specimen response was measured in terms of surface displacement. The measurement range of the semiconductor strain gauges, as well as the strain gauge control unit, had an upper bandwidth of 150 kHz. The cable was independently fixed to the upper part of the strings holder. The laser interferometer CLV 2000 (Polytec; Michigan, USA) was used. The signals were sampled at a rate of 200 000 samples per second for a period of 50 ms.

Descriptive parameters (radius r, height h and top v) shown in Fig. 2 are given in Table 1.

The drop heights of the bar were set as follows: 200, 400, 600 and 800 mm. No damage to the beet sample was observed after the impact of the bar falling from these heights.

All experiments were performed at room temperature (22°C).

All of the experimental data were analysed by means of variance analysis (ANOVA) and Duncan's test with $p<0.05$ using the MATLAB® statistics toolbox (MathWorks 274 Inc.; Massachusetts, USA).

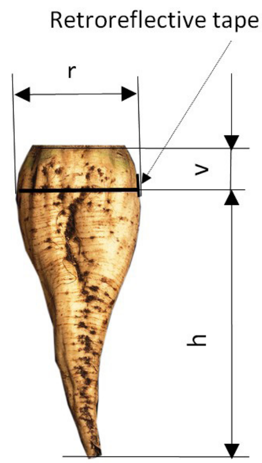

Fig. 2. Scheme of the beet specimen.

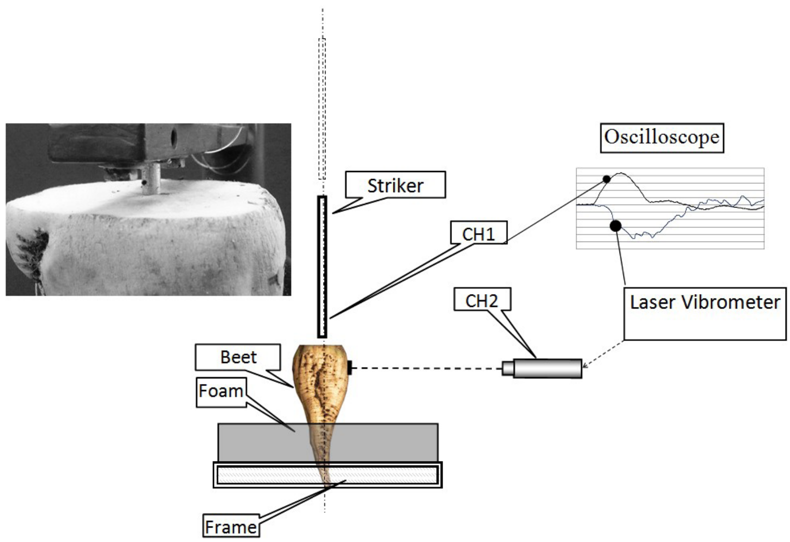

Fig. 1. Scheme of the impact loading of the beet specimen and photo of experimental detail.

Table 1. Parameters of the beet specimens used in the experiments ($N = 5$, results are shown as average ± standard deviation, index i denotes initial value)

Storage days	Specimen No.	Mass$_i$ (g)	Height (h_i)	Top (v_i) (mm)	Radius (r_i)	Mass (g)	Height (h)	Top (v) (mm)	Radius (r)
2	1	731.6±0.31	200±40	24.1±0.24	50.1±0.43	655.2±0.21	200±35	20.1±0.13	50.0±0.12
	2	556.3±0.24	175±26	37.0±0.14	45.8±0.35	491.9±0.20	175±20	20.0±0.21	45.4±0.19
	3	481.2±0.15	191±31	26.2±0.15	44.6±0.31	394.8±0.15	190±37	20.2±0.23	44.3±0.16
	5	658.2±0.25	154±25	22.0±0.16	50.0±0.21	543.0±0.26	154±38	12.3±0.10	49.3±0.35
	10	613.0±0.17	156±17	22.1±0.26	46.3±0.25	514.2±0.22	156±14	20.4±0.16	46.1±0.15
9	8	588.6±0.30	162±21	25.8±0.17	44.4±0.26	453.9±0.14	162±23	15.3±0.14	43.0±0.24
	13	570.9±0.21	160±12	21.7±0.11	44.9±0.27	449.0±0.29	155±18	20.2±0.28	43.0±0.46
	16	458.6±0.35	162±22	16.9±0.26	40.3±0.29	382.2±0.24	162±11	13.3±0.19	38.2±0.15
	27	638.2±0.36	180±36	22.1±0.12	46.5±0.39	523.3±0.37	170±28	14.9±0.15	45.2±0.30
	35	609.5±0.24	162±31	19.0±0.12	46.0±0.47	492.1±0.17	160±16	11.9±0.16	45.4±0.35
22	14	540.9±0.25	162±27	24.0±0.26	42.8±0.26	440.8±0.18	160±16	22.0±0.12	41.4±0.15
	15	710.9±0.40	178±29	25.1±0.27	48.4±0.22	592.7±0.38	178±24	24.0±0.20	47.0±0.34
	19	531.9±0.11	170±10	18.2±0.10	44.9±0.30	422.1±0.29	170±29	13.1±0.14	42.2±0.28
	28	464.2±0.22	171±21	20.8±0.22	39.8±0.31	412.3±0.23	170±20	15.0±0.15	39.0±0.27
	45	622.9±0.16	181±32	22.9±0.26	46.0±0.11	416.4±0.29	180±35	12.4±0.17	40.6±0.19
43	22	836.3±0.41	198±42	27.1±0.34	50.1±0.23	595.5±0.33	190±30	15.3±0.10	44.6±0.22
	30	517.3±0.36	180±21	20.2±0.14	40.3±0.38	295.7±0.15	170±10	10.0±0.19	35.8±0.13
	40	537.0±0.25	181±32	24.0±0.35	45.5±0.37	341.7±0.12	181±27	12.2±0.14	39.8±0.11
	43	696.1±0.17	200±33	30.9±0.36	50.1±0.56	393.0±0.24	200±26	15.3±0.22	42.5±0.22
	50	640.0±0.16	185±24	20.0±0.16	45.7±0.25	515.1±0.26	180±29	17.9±0.16	43.0±0.29
71	18	641.6±0.32	161±15	21.1±0.14	47.1±0.26	310.5±0.24	154±24	20.1±0.33	33.5±0.14
	21	411.0±0.25	204±54	18.9±0.15	38.2±0.15	186.1±0.17	195±35	15.2±0.13	29.1±0.10
	24	953.3±0.34	173±25	22.1±0.28	55.9±0.24	446.9±0.30	150±15	19.8±0.21	39.4±0.26
	46	441.0±0.36	140±40	20.0±0.11	42.5±0.30	197.9±0.18	135±16	19.7±0.28	29.9±0.10

Table 2. Solid content and sugar content in sugar beet roots during storage ($N = 10$, SD denotes standard deviation)

Storage day	Average solid content	SD	Average sugar content	SD
	(g 100 g^{-1})			
2	24.07	2.922	20.92	0.566
9	25.19	2.632	22.13	1.080
22	31.12	1.678	27.59	1.690
43	29.66	3.389	27.39	1.919

RESULTS AND DISCUSSION

Sugar beet root descriptive parameters were decreasing during storage. These decreases are shown in Table 1, with differences between the initial values and the values on the day of measurement. The most significant decrease is shown in sugar beet mass. After 9 days the average mass loss reached 19.63%, after 43 days 34.21%, and after 71 days 53.64% compared to the initial mass. Conversely, beet height did not vary so much. Similar results were presented by Kumbár *et al*. (2015b).

Other parameters such as solid content and sugar content in sugar beet roots are shown in Table 2. It is evident that the solid content and sugar content increased with storage time. A correlation between the solid and sugar content in the sugar beet root was also revealed ($p < 0.05$).

In Fig. 3 an example of the experimental records of both force and displacement is displayed. The maximum impact force increases with height h, *i.e*. with impact velocity. The rebound of the striker for 200 and 400 mm could be expected at longer times but it was not recorded in our experiment. The same phenomena were observed also on all storage days. A delay in the force is a consequence of some error in the time base which can sometimes be observed. The existence of two maximum values of the force is evidenced by the stress wave dispersion in the striker. This phenomenon is well known from the elastic wave propagation at the rod impact against another rod. This phenomenon is

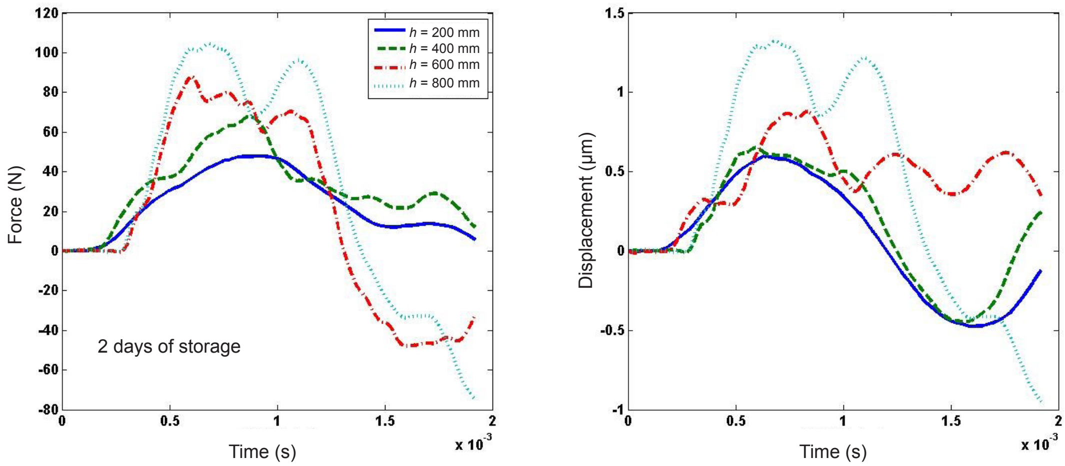

Fig. 3. Example of the experimental records of impact force and displacement.

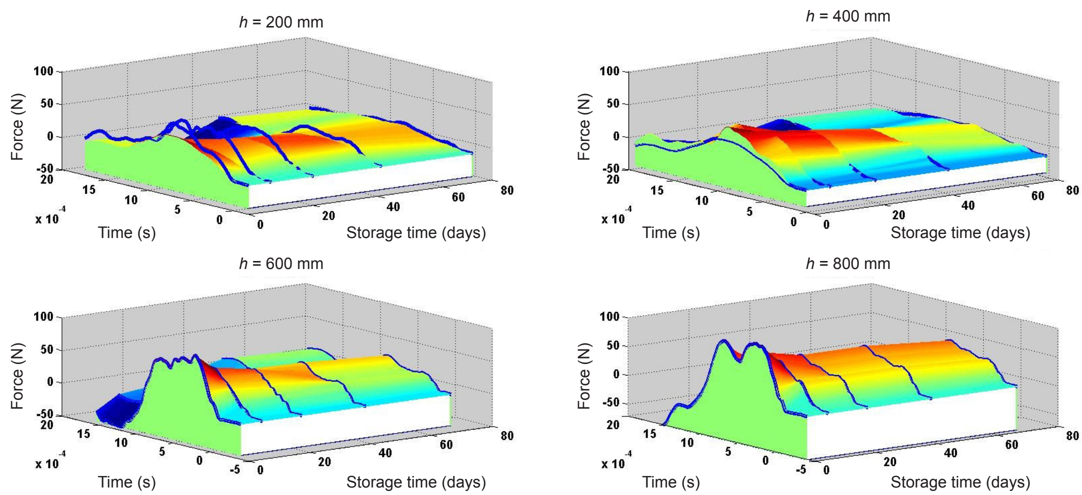

Fig. 4. Force-time history during beet storage.

observed mainly at higher impact velocities. This effect also depends on material rigidity which decreases with storage duration. This decrease leads to some changes in the force – time shape (Fig. 4).

The course of the force F – time t curves can be generally represented by maximum force F_m and by impulse I where:

$$I = \int F(t)\, dt. \qquad (1)$$

Changes to these parameters during beet storage are displayed in Fig. 5. Changes to the impulse, depending on the storage duration time, were analysed. It is evident that the maximum force increases with impact velocity and decreases with storage duration. The detailed explanation of the observed phenomena requires longer signal recording times. More experiments are also needed in order to identify the appropriate statistical method. The solution to these problems constitutes the subject-matter of our on-going research. The same is valid for force impulse (Nedomová, 2009).

The development of surface displacement during beet storage is shown in Fig. 6. The impact velocities correspond to the height of the striker h = 200 and 400 mm, and displacement p exhibits an oscillating character. The maximum values of displacement are shown in Fig. 7. It is evident that for the all values of h the maximum displacement decreases with the duration of beet storage.

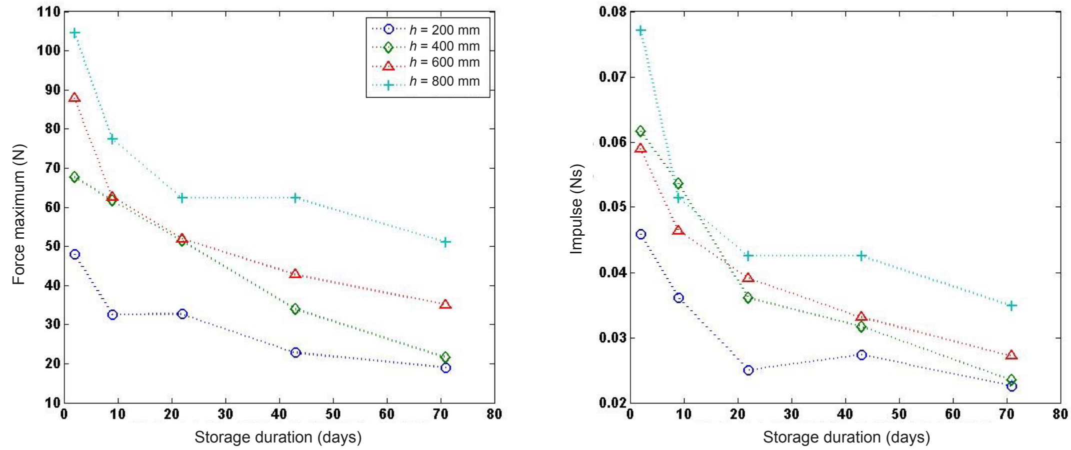

Fig. 5. Effect of the storage duration on the force maximum and on the impulse.

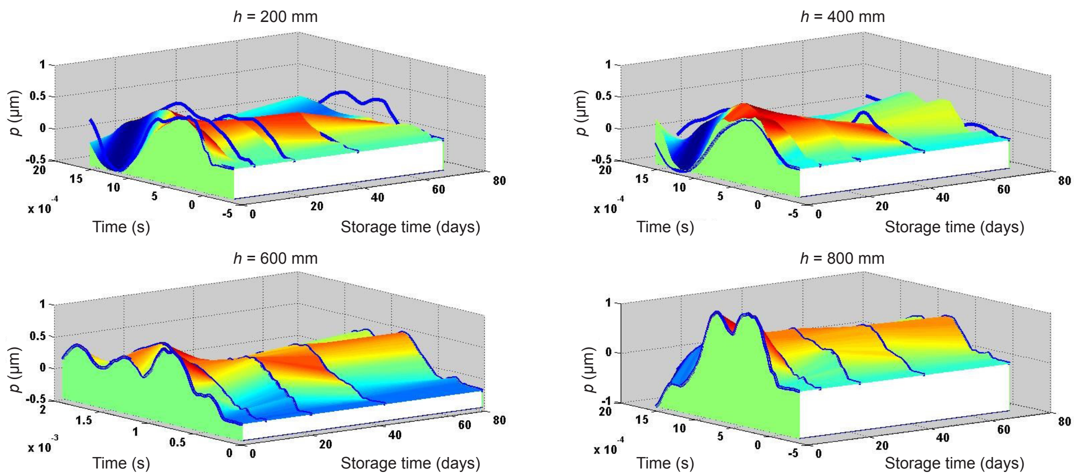

Fig. 6. Time histories of the beet surface displacement during its storage.

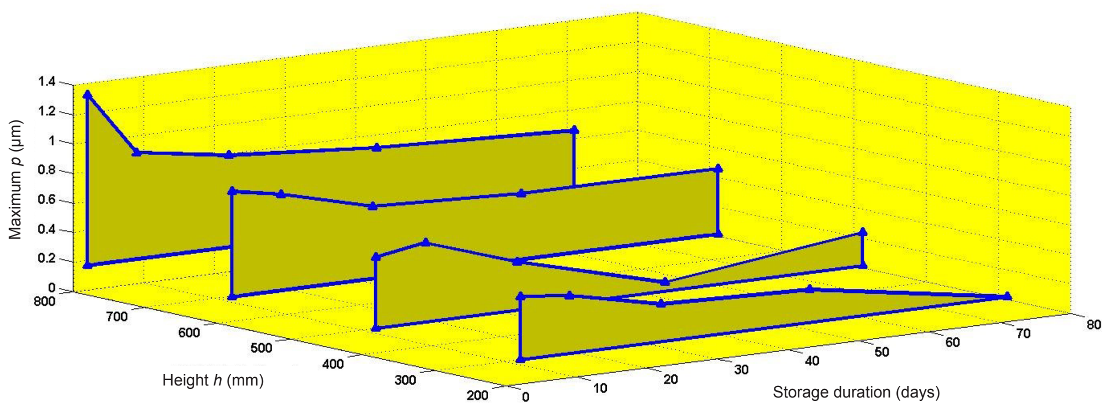

Fig. 7. Influence of the height h and the storage time on the maximum value of the displacement p.

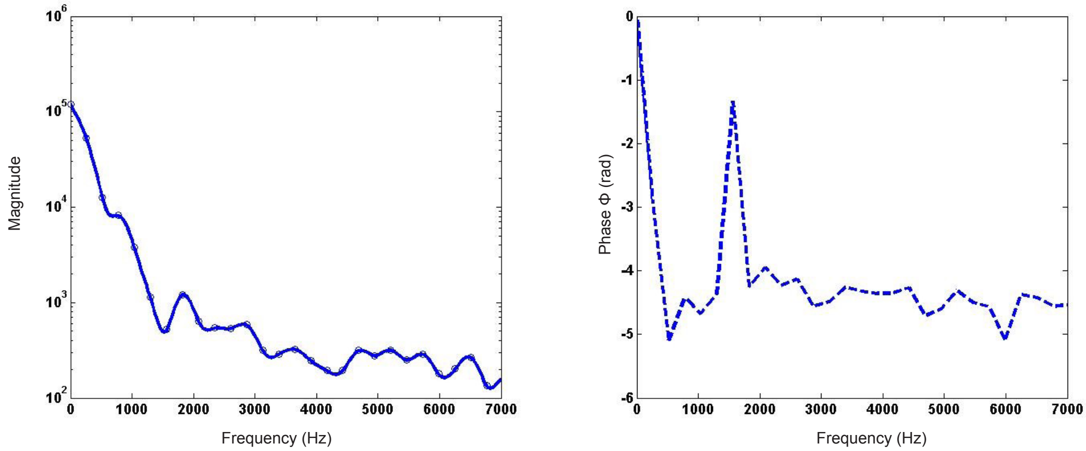

Fig. 8. Example of the spectral function magnitude and phase (2nd day of the beet storage, h = 200 mm).

The results suggest that the maximum values of both the impact force and displacement can be used for the estimation of storage duration and, thus, for the evaluation of the internal beet quality.

Beet response can also be described in the frequency domain. This procedure is based on the Fourier transform technique (Stein, 2003) for a review.

For a continuous function of one variable $f(t)$, the Fourier transform $F(\omega)$ can be defined as (Nedomová, 2009):

$$F(\omega) = \int_{-\infty}^{+\infty} f(t) e^{-i\omega t} dt, \tag{2}$$

and the inverse transform as:

$$f(t) = \int_{-\infty}^{+\infty} F(\omega) e^{i\omega t} d\omega, \tag{3}$$

where: F is the spectral function and ω is the angular frequency.

The same procedure can be used for the Fourier transform of an $x(k)$ series with N samples. This procedure is referred to as the discrete Fourier transform (DFT). A special kind of this transform is the fast Fourier transform (FFT). This procedure forms part of most software packages dealing with signal processing. The transform into the frequency domain will correspond to a complex valued function, *i.e.* exhibiting both magnitude and phase (Kumbár *et al.*, 2015a):

$$F(\omega) = \mathrm{Re}(F) + i\mathrm{IM}(F), \tag{4}$$

$$amplitude = \sqrt{\mathrm{Re}(F) + \mathrm{IM}(F)} F(\omega) = \mathrm{Re}(F) + i\mathrm{IM}(F), \tag{5}$$

$$phase = \arctan\left[\frac{\mathrm{Im}(F)}{\mathrm{Re}(F)}\right]. \tag{6}$$

In Fig. 8 an example of the frequency dependence of the amplitude and the phase of the spectral function (force) is shown. One can see that the amplitudes of the spectral function bellow *ca*. 2000 Hz are very small.

An example of the spectral function of the displacement is shown in Fig. 9. The amplitude of the spectral function exhibits a maximum value. This phenomenon was observed also for many other types of fruit (Delwiche *et al*., 1987; Sarig *et al*., 1985; Severa *et al*., 2012; Xu *et al*., 2015).

The corresponding frequency was denoted as the dominant frequency f_c. Abbott (1999) and Peleg (1999) showed that fruit firmness is highly correlated with stiffness coefficient IF:

$$IF = m f_c^2, \tag{7}$$

where m is the fruit mass.

The average stiffness values are displayed in Fig. 10. The values of stiffness significantly decreased with storage duration. The stiffness than appears independent of height h, *i.e.* of impact intensity. It seems that this quantity is very convenient for the evaluation of beet properties during storage. The proposed method seems to provide a promising tool to identify beet properties during storage.

CONCLUSIONS

1. The presented method is based on the analysis of changes in the history of the loading force and displacement during beet storage. The maximum value of this force was shown to decrease with the storage duration. Beet response to this impact was analysed both in the time and frequency domain.

2. The spectral function of the displacement exhibits a dominant frequency as in the case of many other types of fruit. This frequency was used for the evaluation of beet stiffness.

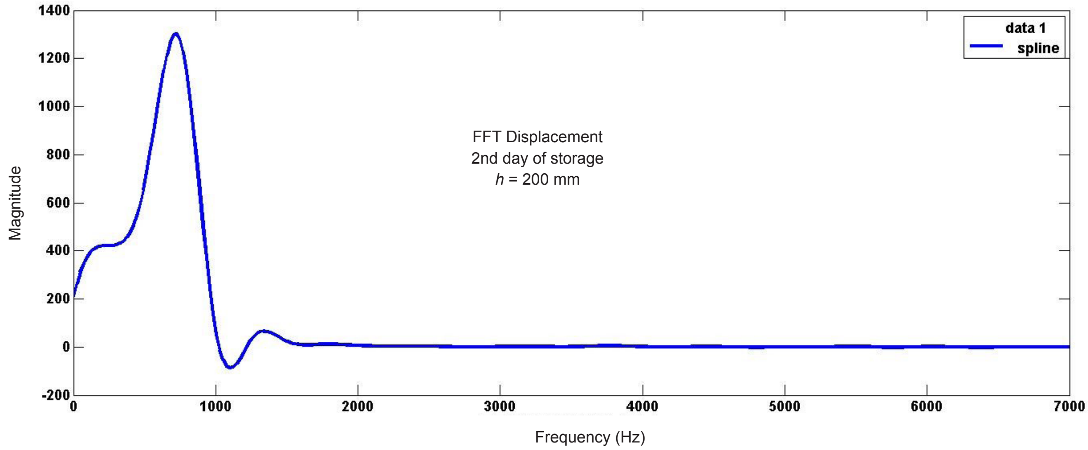

Fig. 9. Amplitude of the spectral function of the surface displacement.

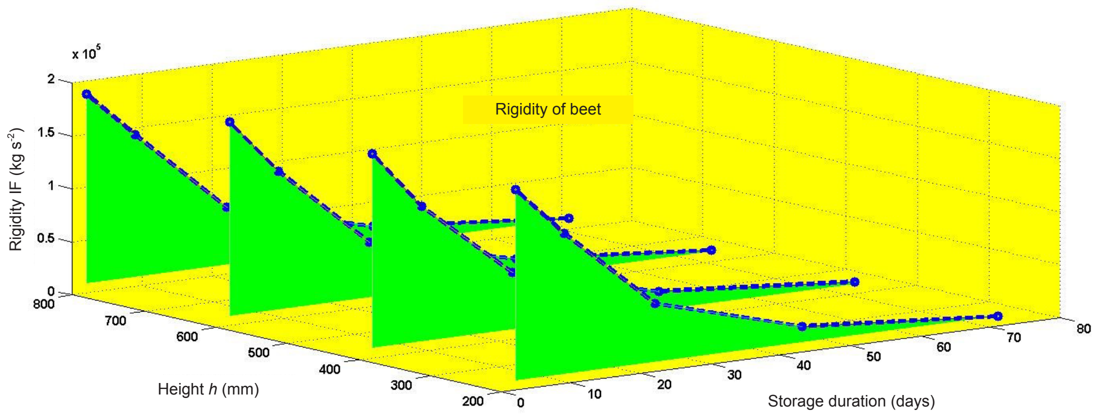

Fig. 10. Development stiffness of beet during its storage.

Conflict of interest: The authors do not declare conflict of interest.

REFERENCES

Abbott J.A., 1999. Quality measurement of fruits and vegetables. Postharvest Biology and Technology, 15(3), 207-225.

Andales S.C., Pettibone C.A., and Davis D.C., 1980. Influence of relative humidity and temperature on weight and sucrose losses of stored sugarbeets. Trans. ASAE, 23(2), 477-480.

Benedito J., Rey A., Garcia-Pascual P., Carcel J.A., and Perez-Muelas N., 2004. Non-destructive assessment of Manchego cheese texture. In: Emerging Technologies in Non Destructive Testing (Eds D.V. Hemelrijck, A. Anastasopoulos, N.E. Melanitis). Swets and Zeitlinger Publishers, Netherlands.

Božiková M. and Hlaváč P., 2016. Thermal properties of selected cheeses samples. J. Central Eur. Agric., 17(1), 63-74.

Campbell L.G. and Klotz K.L., 2006. Storage, in Sugar Beet (Eds A.P. Draycott). Blackwell Publ. Ltd, Oxford, UK.

Delwiche M.J., McDonald T., and Bowers S.V., 1987. Determination of peach firmness by analysis of impact forces. Trans. ASABE, 30(1), 249-254.

Garcıa C., Ruiz-Altisent M., and Chen P., 1988. Impact parameters related to bruising in selected fruit. Proc. Int. Meeting American Society of Agricultural Engineers, Paper No. 88-6027, June 26-29, Rapid City, South Dakota, USA.

Huijbregts A.W.M., 2008. Sugar beet storage – An overview of Dutch research. Int. Sugar J., 110(1318), 618-624.

Kenter C. and Hoffman C., 2006. Qualitätsveränderungen bei der Lagerung frostgeschädigter Zuckerrüben in Abhängigkeit von Temperatur und Sorte. Zuckerindustrie, 131(2), 85-91.

Kertész Á., Hlaváčová Z., Vozáry E., and Staroňová L., 2015. Relationship between moisture content and electrical impedance of carrot slices during drying. Int. Agrophys., 29(1), 61-66.

Kubík L., Adamovský F., and Kažimírová V., 2016. Evaluation of mechanical parameters of pellets. Acta Universitatis Agriculturae Et Silviculturae Mendelianae Brunensis, 64(5), 1593-1601.

Kumbár V., Trnka J., Nedomová Š., and Buchar J., 2015a. On the influence of storage duration on rheological properties of liquid egg products and response of eggs to impact loading - Japanese quail eggs. J. Food Eng., 166, 86-94.

Kumbár V., Votava J., and Nedomová Š., 2015b. Influence of storage time, initial mass and circumference on weight and size disposals of sugar beet. Listy Cukrovarnicke a Reparske,131(11), 334-337.

Nedomová Š., 2009. Response of the potato tubers to impact loading. Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis, 57(4), 63-72.

Olsson A., 2011. Sustanaible harvest and storage of sugar beets – more beet and more sugar to the factory – variety and storage 2010-2011. NBR Report 611-2010-2011, 34pp.

Olsson R., 2012. Quality of beet storage depends on you, soil, and variety (in Swedish). Betodlaren, 3, 46-52.

Pan L., Lu R., Zhu Q., Tu K., and Cen H., 2016. Predict compositions and mechanical properties of sugar beet using hyperspectral scattering. Food Bioprocess Technol., 9(7), 1177-1186.

Peleg K., 1999. Development of a commercial fruit firmness sorter. J. Agric. Eng. Res., 72, 231-238.

Sarig Y., Little R.W., and Segerlind L.J., 1985. Comparative solutions for a punch problem of an elastic sphere encapsulated in an elastic shell. Int. J. Impact Eng., 3(2), 93-105.

Severa L., Nedomová Š., Buchar J., Trnka J., and Dvořáková P., 2012. Impact test as a tool for evaluation of peach firmness. Acta Horticulturae, 962, 577-584.

Shmulevich I., Galili N., and Howarth M.S., 2003. Nondestructive dynamic testing of apples for firmness evaluation. Postharvest Biol. Technol., 29(3), 287-299.

Stein E.M. and Shakarchi R., 2003. Fourier Analysis: An Introduction. World Book Publishing Company, Princeton University Press, New Jersey, USA.

Taniwaki M., Hanada T., Tohro M., and Sakurai N., 2009. Nondestructive determination of the optimum eating ripeness of pears and their texture measurements using acoustical vibration techniques. Postharvest Biol. Technol., 51(3), 305-310.

Trnka J., Nedomová Š., Kumbár V., Šustr M., and Buchar J., 2016. A new approach to analyze the dynamic strength of eggs. J. Biological Physics, 42(4), 525-537.

Trzebinski J., 1984. Processing quality of sugar beets. Gazeta cukrownicza, 11, 240-242.

van Swaaij N. and Huijbregts T., 2010. Long-term storability of different sugarbeet genotypes – Results of a joint IIRB study. Sugar Industry, 135(11), 661-667.

Vukov K., 1977. Physics and Chemistry of sugar beet in sugar manufacture. Akademia Kiado, Budapest, Hungary.

Wang J., Jiang R.S., and Yu Y., 2004. Relationship between dynamic resonance frequency and egg physical properties. Food Res. Int., 37(1), 45-50.

Xu H., Wu J., Wang Z., Gao Y., Wang Z., and Zhao Z., 2015. Characteristics of the dynamic spectral response of Korla pear. Modern Food Sci. Technol., 31(3), 71-76.