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OPTIMIZATION OF PARAMETERS OF A VIBRATION SYSTEM FOR SORTING AND CALIBRATING DEEP FROZEN BERRY FRUITS

OPTIMIZACIJA PARAMETARA VIBRACIONOG SISTEMA ZA SORTIRANJE I KALIBRIRANJE DUBOKO ZAMRZNUTOG JAGODIČASTOG VOĆA

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ABSTRACT

Sorting and calibrating berry fruits is a costly process in terms of human labor and time needed for the efficient sorting based on quality and size. Sorting and calibrating is performed on previously cooled or frozen products, which prevents damaging the product during mechanical processing. The development of new solutions for sorting and calibrating should go in the direction of high capacity machines, with minimum engagement of human labor. This approach requires application of vibrating screen separators with predefined screen sizes, in order to meet the required size and quality. These systems should be capable to sort other fruits, besides raspberries, strawberries and blackberries. This paper shows the solutions for mechanical sorting and calibrating, with special attention to the optimization of working parameters. Exact designs were analyzed, an optimization of kinematic parameters was performed, an adequate model of a vibration system was shown, which makes the requested productivity possible, for the purpose of achieving an economically justified process for separation of deep frozen products.

Keywords: *Sorting, calibration, parameters, vibrating device, transport, cost efficient.*

REZIME

Sortiranje i kalibriranje jagodičastog voća ogleda se u visokim troškovima radne snage za izdvajanje oštećenih plodova i plodova po kvalitetu i veličini. Zahtevi koji se postavljaju pri sortiranju i kalibriranje jagodičastog voća se odnose i na tehnološke procese prethodnog hlađenja i zamrzavanje plodova čime se postiže mogućnost kvalitetnijeg izvršenja naknadnih mehaničkih operacija bez znatnih gubitaka. Razvoj rešenja za sortiranje i kalibriranje duboko zamrznutog voća treba tražiti u visoko proizvodnim sistemima sa minimalnim učešćem radne snage. Ovakav pristup zahteva primenu vibracionih sistema koji omogućavaju izdvajanje plodova na odgovarajućim sitima i sa odgovarajućim otvorima na sitima koja ostvaruju odvajanje plodova prema geometrijskim parametrima, odnosno prema propisanim klasama. Ovakvi vibracioni uređaji trebalo bi da obezbede i sortiranje i kalibriranje osim malina i jagode i kupine itd. U radu su data mašinska rešenja za sortiranje i kalibriranje sa posebnim osvrtom na optimizaciju parametara uređaja. Analizirana su i data rešenja ovih uređaja, izvršena optimizacija kinematskih parametara, dat adekvatan model vibracionog sistema koji omogućava traženu proizvodnost u cilju postizanja ekonomski opravdanijeg procesa izdvajanja duboko zamrznutih plodova po zadatim karakteristikama.

Ključne reči: *Sortiranje, kalibriranje, parametri, vibrator, transport, ekonomska opravdanost.*

INTRODUCTION

The final phase in the production of fruit refers to the preparation, i.e. selection of fruits for further use. This phase is important, regarding marketing, storing or further processing, because this is what makes the value of the product competitive. In Serbia, berries, primarily raspberries, are an important export product. In 2002, the production amount was 93982 t, while it dropped to 76991 t in 2007. Due to the export potential of raspberries, it is necessary to invest in this type of production in all its phases, from planting to operations performed after harvesting. This includes numerous operations, from the transportation of fruit, removal of impurities, sorting, calibration, to the final operations, which refer to further processing, if applicable (cutting, pureeing) or packaging of selected fruits according to size and quality. Most of these operations require great labor force, which extends the duration of these operations and thus affects the cost of the final product (*Marković et al, 2007*). The basic requirement for the creation of an economically justified fruit selection technology, aiming to reduce losses and achieve a higher level of quality, can be met by applying the machine-based systems in order to perform these operations with a higher share of automation. The sorting of berries like: strawberries, raspberries, blueberries and blackberries cannot be performed immediately after picking, because of the biological, physical and mechanical features of the fruits, which would lead to damaging, bruising, squeezing of some types of fruit, which again would result in creating a mass inappropriate for use for a certain period of time. Due to the aforesaid, especially raspberries require certain thermal processing before starting any mechanical treatment, which basically means cooling and freezing of fruit. Only with frozen fruit it is possible to start the sorting and calibration of berries. These operations, which are performed with vibrating sieves should enable the classifications of fruits in a number of fractions, keeping losses and damage to the fruits as low as possible.

Nomenclature

a (m)	length of the connection rod
a_r (m/s^2)	relative acceleration of fruit
$\vec{F}_p^{in}$ (N)	transmissive inertial force
$\vec{F}_\mu$ (N)	sliding friction force
$\vec{F}_w$ (N)	aerodynamic resistance force
$\vec{N}$ (N)	joint reactive force
m (kg)	fruit mass
$\vec{g}$ (m/s^2)	gravity acceleration

ω (s^{-1})	radial velocity of the connection rod
$\vec{v}_p, \vec{v}_r, \vec{v}$ (m/s)	transversal, relative and absolute velocity of fruit
c_D (-)	dimensionless coefficient of aerodynamic resistance
k (kg/m)	resistance coefficient
ρ (kg/m^3)	air density
S (m^2)	reference circumstreamed fruit surface area
μ (-)	dimensionless sliding friction coefficient
φ (rad)	rotation angle of the connection rod (rad)
x, y (m)	coordinates of the fruit relative to the moving coordinate system
$\dot{x}, \dot{y}$ (m/s)	projections of the relative velocity of the fruit on the axes of the moving system
$\ddot{x}, \ddot{y}$ (m/s^2)	projections of the relative acceleration of the fruit on the axes of the moving system

MATERIAL AND METHOD

In the production of berry fruit, primarily raspberries, if numerous conditions, concerning the selection of varieties, fulfillment of agritechnical requirements, picking methods, the vicinity of freezing and processing facilities, the organized buying up, high quality roads and means of transportation, fast freezing, etc., are met, then high profitability can be achieved. In the last decades, frozen raspberries are on the market in the shape rolends, griz, fractions and blocks. Raspberries, of all the berries, most clearly show the need for using modern facilities for processing and fast freezing of fruit, and their effect on profitability. Timely, fast and quality preparation and freezing leads to a great percentage of rolend raspberries (single, whole fruit and more than 70%) which are the most appreciated, the best and most expensive on the market. The marketing-related and commercial quality of raspberry is determined according to the UNECE standard FFV-32 and applies to trading between members of the UN. The standard defines minimum requirements that all classes of raspberry have to meet. According to quality, raspberries are divided into three classes.

Extra class raspberries have to be of excellent quality, without deficits, except for small surface imperfections, that do not affect the quality and appearance in the package. Further, the raspberries must have a typical shape, ripeness and color, depending on the variety.

Raspberries of class I have to be of good quality, small deficits are allowed, provided they do not affect the overall impression related to the quality and appearance of product in the package. Small deficits in shape, size and ripeness (it must not be overripe) and color are allowed.

Class II includes raspberries the quality of which is not considered high grade, but meets minimum requirements, and they may be allowed, if the raspberries retain their basic characteristics, as are quality and appearance in the package, and no deficits in shape, size and color. Raspberries of this class must not have any big deficits, while a limited amount of overripe fruits is allowed.

The size is determined by the maximum diameter of the equivalent cross-section. The minimum diameter for grown raspberries of extra class is 15 mm, and 12 mm for class I. The is no corresponding diameter for grown raspberries of class II, nor is there one for wild raspberries.

Packages for the market have to comprise raspberries of the same origin, variety and quality. Extra class raspberries have to be of uniform ripeness, color and size, while for wild raspberries, this uniformity does not have to be that strict. The visible part of the packaging has to represent the whole content in a realistic way. The raspberries have to be packed into commercial packages with a net weight not greater than 500 g. All that can be provided only by the use of machine-based methods in technologically new facilities.

RESULTS AND DISCUSSION

Technological and technical procedures for the production of frozen berry fruits

After their arrival, fresh berry fruits are temporarily stored in freezing chambers until the start of the processing itself. This period of time should be as short as possible, in order for the fruits not to lose their level of quality. In the freezing chambers, the fruits are cooled to a temperature of approx. 0°C, in order to preserve their quality. The construction of such freezing chambers requires large investments (except for twin-mode freezing chambers that can also be used for freezing fresh and storing frozen products), and that is a problem *(Blasco et al, 2003; Strateški tehnološki projekat BTR.5.03.0535.B, 2002-2005; Mayer and William, 1978)*.

The freezing speed has a great effect on the structure of frozen fruit, especially raspberries. As long as the raspberries are frozen, no differences in quality are visible, only when the raspberries are thawed, differences in quality and consistency become visible. These differences originate, among others, from changes caused by freezing below 0^oC, when ice crystals are formed. Crystals are mainly formed at temperatures between 0 and -4^oC, and in a smaller amount they can be formed all the way down to -20^oC. The amount of ice formed at a certain temperature, changes little with the change of the freezing speed, but the crystal size changes in an inversely proportional manner to the freezing speed. The greater the freezing speed, the greater the number of crystallization cores, an therefore, the smaller the crystals. Slow freezing generates a smaller number of bigger crystals, which, growing, damage the cell tissue. After thawing, cells with damaged tissue lose their original structure and juices. For the reasons mentioned, preservation by fast freezing is obligatory in the technical and technological procedures concerning freezing of berry fruits *(Godfrey, 2005; Marković et al, 2007; Marković et al, 2009)*.

Mathematical model of a vibration system

The mathematical model of a vibration system for sorting and calibrating deep frozen berries, is represented by a translatory movable screen **1,** which is put into motion by a system of parallel connection rods **2,** having the same length a, which is shown in figure 1.

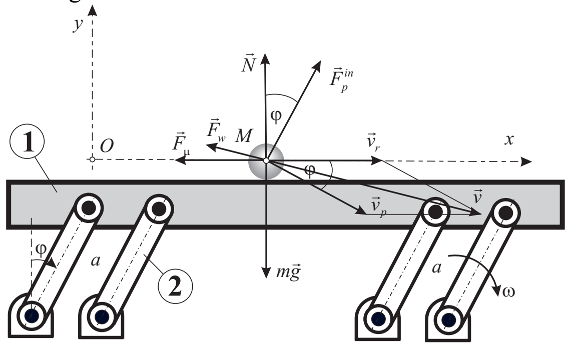

Fig. 1. Schematic description of the vibration system (Fried, 1979)

If we suppose that the radial velocity of the connecting rods is $\omega = const$, the differential equation describing the motion of isolated fruit M, having a mass of m, relative to the moving coordinate system xOy, rigidly attached to the vibrating screen, takes the following shape:

$$m\vec{a}_r = m\vec{g} + \vec{N} + \vec{F}_\mu + \vec{F}_w + \vec{F}_{pN}^{in}, \tag{1}$$

where $\vec{g}$ is the gravity acceleration, whereas $\vec{N}$ and $\vec{F}_\mu$ are the orthogonal components of the joint reactive force and the sliding friction force between screen and fruit, respectively. The aerodynamic resistance force is $\vec{F}_w$, and the transmissive inertial force is defined by the expression $\vec{F}_{pN}^{in} = ma\omega^2\left[\sin(\omega t)\vec{i} + \cos(\omega t)\vec{j}\right]$, where $\varphi = \omega t$ is the angle between the axis of the connection rods and the vertical line [7].

The absolute velocity of the fruit is equal to the sum of the transmissive and relative velocity:

$$\vec{v} = \vec{v}_p + \vec{v}_r = a\omega[\cos(\omega t)\vec{i} - \sin(\omega t)\vec{j}] + \dot{x}\vec{i} + \dot{y}\vec{j}. \tag{2}$$

In equation (2), the projection of the relative fruit velocity onto axis x is designated as $\dot{x}$, while the projection onto y axis is annulled, i.e. $\dot{y} = 0$, provided that the fruit is not separated from the screen. The intensity of the aerodynamic resistance force is proportional to the squared absolute fruit velocity, i.e.

$$F_w = \frac{1}{2} c_D \rho v^2 S = kv^2, \tag{3}$$

where constant $k = 1/2\, \rho c_D S$, while ρ, c_D and S are the density of streaming air, resistance coefficient and the reference circumstreaming of the fruit surface area, respectively. The resistance force is collinear with the absolute fruit velocity $\vec{v}$ and in case of motion on the screen $(\dot{y} = 0)$ it is determined with the following equation, taking into account expressions (2) and (3):

$$\vec{F}_w = -kv\vec{v} = -k\sqrt{a^2\omega^2 + \dot{x}^2 + 2a\omega\dot{x}\cos(\omega t)}\left\{[\dot{x} + a\omega\cos(\omega t)]\vec{i} - a\omega\sin(\omega t)\vec{j}\right\}. \tag{4}$$

The sliding friction force works against the motion of fruit on the screen and can be be described by the following expression:

$$\vec{F}_\mu = -\mu N \frac{\vec{v}_r}{v_r} = -\mu N \,\mathrm{sgn}(\dot{x})\vec{i} \tag{5}$$

Based on equations (2)-(5), the system of vector equations (1) can be replaced with an equivalent system of scalar equations:

$$\begin{aligned} m\ddot{x} &= -k\sqrt{a^2\omega^2 + \dot{x}^2 + 2a\omega\dot{x}\cos(\omega t)}\,[\dot{x} + a\omega\cos(\omega t)] - \mu N \,\mathrm{sgn}(\dot{x}) + ma\omega^2\sin(\omega t), \\ m\ddot{y} &= N - mg + k\sqrt{a^2\omega^2 + \dot{x}^2 + 2a\omega\dot{x}\cos(\omega t)}\,a\omega\sin(\omega t) + ma\omega^2\cos(\omega t) = 0. \end{aligned} \tag{6}$$

The system of differential equations (6) is applicable only when there is no separation of the fruit from the screen. If during the relative motion of the fruit on the screen, the following condition is fulfilled:

$$N = mg - k\sqrt{a^2\omega^2 + \dot{x}^2 + 2a\omega\dot{x}\cos(\omega t)}\,a\omega\sin(\omega t) - ma\omega^2\cos(\omega t) \le 0, \tag{7}$$

the fruit will separate from the vibrating screen and will continue to move as a free material point in a resisting environment surrounded by the force of gravity. In this case, the system of differential equations (6) gets a new shape:

$$\begin{aligned} m\ddot{x} &= -k\sqrt{a^2\omega^2 + \dot{x}^2 + \dot{y}^2 + 2a\omega\dot{x}\cos(\omega t) - 2a\omega\dot{y}\sin(\omega t)}\,[\dot{x} + a\omega\cos(\omega t)] + \\ &\quad + ma\omega^2\sin(\omega t), \\ m\ddot{y} &= -mg - k\sqrt{a^2\omega^2 + \dot{x}^2 + \dot{y}^2 + 2a\omega\dot{x}\cos(\omega t) - 2a\omega\dot{y}\sin(\omega t)}\,[\dot{y} - a\omega\sin(\omega t)] + \\ &\quad + ma\omega^2\cos(\omega t). \end{aligned} \tag{8}$$

The differential equations, which describe the motion of fruit as a bound material point (6), or as a free material point (8), regarding their complexity and due to their distinct nonlinearity, can be solved using some numerical methods, the appropriate choice of which depends on the given boundary conditions, which has been elaborated in reference literature (*Butcher, 1987; Chapra and Chanale, 1988; Fried, 1979*) in detail.

In cases, where the force of aerodynamic resistance can be neglected, the differential equations (6) can be, after eliminating the resistance-related terms, written down in the following manner:

$$\begin{aligned} m\ddot{x} &= ma\omega^2\sin(\omega t) - \mu N \,\mathrm{sgn}(\dot{x}), \\ m\ddot{y} &= N - mg + ma\omega^2\cos(\omega t) = 0, \end{aligned} \tag{9}$$

and therefore the fruit cuts its bonds when the intensity of the orthogonal reactive force is annulled, i.e.

$$N = mg - ma\omega^2\cos(\omega t) \le 0. \tag{10}$$

How the velocity depends on acceleration of relative motion, and how fruit displacement depends on time, when there is no sliding friction force, is shown on the diagrams in figure 2.

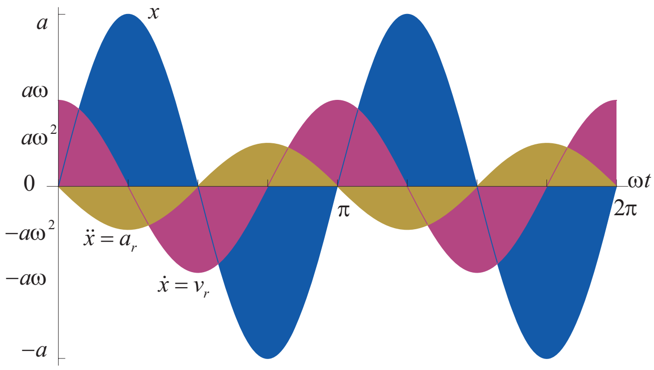

Fig. 2. Relative displacement, velocity and fruit acceleration

The model shown above gives the possibility for a qualitative and quantitative analysis of dynamical behavior of frozen berry fruits on the vibrating screen of a sorting and calibrating device and at the same time it gives recommendations for the optimization of kinematic parameters of the vibration system.

Vibrating calibrators and transport devices use a vibration motor with a cam (figure 3b) or an electromagnet (figure 3d) as a drive unit.

Vibrating calibrators, transport devices with a cam, were designed for applications in the food industry. Important features of vibrating calibrators and transport devices of this type, are (*Key Technology, 2009*):

- Variable position of the cam weights, which provides the possibility to change the amplitude of the vibrating hull, and perform optimum calibration of the frozen product,
- Changing the rpm rate of the electromotor (through frequency regulation) of the drive unit with a cam, changes the number of oscillations per unit of time and thereby the optimum calibration of a frozen product can be achieved.

Vibrating calibrators and transport devices with a magnetic drive unit provide frequency and amplitude control for vibrating screens, using special electronic control devices.

Vibrating calibrators and transport devices are designed so as to provide a maximum frequency of 16 Hz and a maximum amplitude of 9 mm. Depending on the condition and variety of frozen fruit, frequency and amplitude are defined experimentally, in order to secure the optimum calibration of the frozen product (*Marković et al, 2007*).

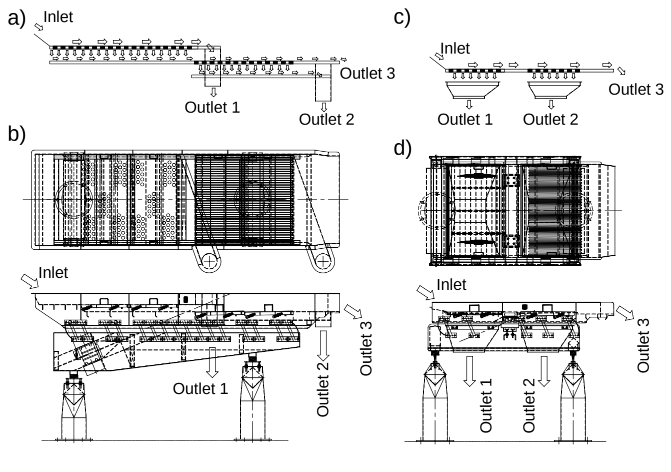

Fig. 3. Examples of vibratory drives, transport devices, calibration schemes

Figure 3a shows a scheme for calibrating frozen berry fruits, where first the biggest parts are sorted out (a number of fruits that are frozen as a whole-as a block), and then the calibration of smaller fruits is performed going up to fruits of bigger size. This method of calibration of frozen fruit, where first the big chunks and blocks, are sorted out, reduces the labor force needed for its extraction and provides more optimal calibration of the residual mass of frozen berry fruits.

Figure 3c shows a scheme of calibration of frozen berry fruit used in the classic calibration system, where frozen fruits are sorted going from smaller to bigger ones. In this case, it is necessary to sort out blocks of fruits manually.

A fraction from outlet 3 is directly directed to optical sorting by color, and fractions from outlets 1 and 2 are put together and afterwards let through a color sorting device, in order to get a frozen product of high quality.

For the experimental testing of screens and various light inlets for sorting out of the best fruits, rolends, the screens shown in figure 4 were used.

A screen without perforation (a) is used when the vibrating calibrator serves as a simple vibrating transport device. Screen with perforation (b, c) is used for removing parts of soil and small frozen fruit parts which are not suitable for commercial use. Screen (d) is used for sorting out smaller fruits and fruit parts of smaller size (a=4; 6; 7 mm) *(Marković, 2008)*.

Screens (e) are designed and experimentally tested, and their perforations are of variable size (a-2 mm at the starting point of the perforation, and at the end point of the perforation, a=8; 10; 12; 14; 15 mm). These have shown the best performance and prevented jamming of frozen fruit on the screens, which makes the cleaning of screens unnecessary.

Figure 5. shows a system for fast securing of the screen onto the vibrating hull of the vibratory calibrator and transportation device. The screen and the locking mechanism are designed so that depending on the technological requirements, the screens can be replaced in a simple and quick manner, without using tools.

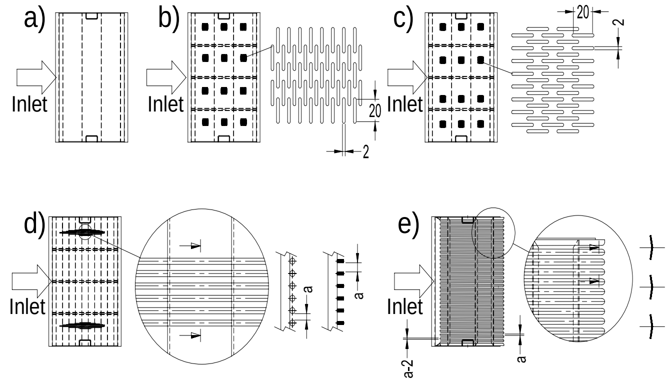

Fig. 4. Example of calibrating screens for sorting frozen berry fruits
a – screen without perforation, b – screen with perforation, orthogonal to product flow, c – screen with perforation, parallel with product flow, d – Screen with "open" perforations in the direction of product flow, e – Screen with variable "open" perforations in the direction of product flow (Marković et al, 2007)

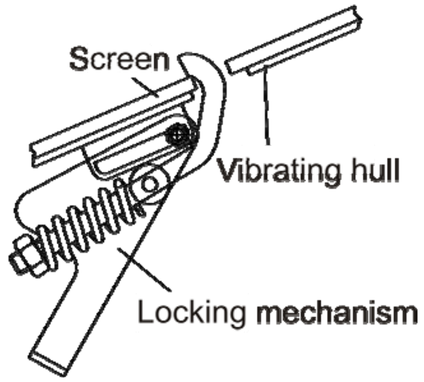

Fig. 5. Mechanism for perforated screen locking

CONCLUSION

Based on the results of the analyses performed, the considerations and the parameter optimization, we can conclude that the machine-based frozen fruit selection process on vibrating screens has an advantage over the method of visual inspection of the fruit on classical transport devices, using human labor force, because working time is reduced, as is the needed human labor force, and also because quality and uniform fractions (classes) of fruit are achieved, which leads to the reduction of the total cost for the operations mentioned. The mathematical model shown here enables further optimization of kinematic parameters (amplitude and frequency), in order to achieve greater universality and greater productivity. Another reason is the optimization of geometrical parameters of the screen, primarily the opening of the screen, which enables the use of vibration systems for sorting and calibration of fruits of different varieties and sizes. The future direction in the development of these systems should go towards a more intensive use of automation, which means using automatic control and work process regulation and developing systems with integrated optical color sorting devices.

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