FLAX SEED SEPARATION WITH VIBRATING SCREENS

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A R T I C L E   I N F O

A B S T R A C T

The objective of the research consisted in comparing the operation efficiency of a separator provided with fixed screens mounted to the shoe and the one fitted with spring-mounted screens, determination of the impact of the basic kinematics parameters on the separation efficiency. Analysis was also carried out regarding the use of cylindrical spring-mounted screens and flat spring-mounted screens. The process of mass movement on the screen surface was examined also including the movement upward, downward and throwing up. The values characteristic for the separation process were output (capacity) of screens and the impurity separation degree. The analyzed kinematic parameters included: screen shoe vibration amplitude, screen vibration amplitude, screen inclination angle, screen vibration operation angle, own vibration frequency, kinematics limits coefficient. As a result, the mathematical models of separation were determined regarding the unit efficiency and the impurity separation degree. Next calculation based on these equations determined the value of the following parameters: A_p=1, 2, A=8 mm, K=2, 3, for which q_F=0.72 kg·s^{-1}·m^{-2}, E=0.87. The parameters of springs ensuring proper modulus may be determined with the monogram or formula (20). According to the conducted experiments q_F screen capacity depended on the straight-line basis on A_p spring stiffness, A screen shoe vibration amplitude and it increased as q_F and A_p values increased. The increase was less evident in case of ω and ε value increase. Whereas the non straight-line basis and significant increase followed as the values of α and K parameter increased. Impurity separation degree E increased initially and next decreased as increase followed of spring stiffness A_p, and along with screen hopper vibration amplitude increase. This increase was less evident in case of ω frequency and ε angle increase. Separation of impurities significantly decreased in case of α and K parameter increase.

Introduction

Cultivating and processing of flax in Poland follows mainly for two purposes related to production of fibre and seed. The whole processing has been mechanized, yet mechanization of these processes has not been satisfactory (Andrzejewska, 2006; Kruglenja, 2006; Kruglenja et al., 2011; Pawlak, 2010). Cultivating and processing of flax by sustainable and ecological farms has established the requirements with regard to limitation of negative impact on environment (Grabowska and Heller 2009; Heller, 2012; Janowska-Biernat, 2012). Threshing and separation of mass flax is one of such important processes. Many scientific and research works have been carried out in this regard aimed at production of good quality fibre and seed of high germination capacity. Therefore much emphasis has been placed on threshing and separation of the flax threshed mass (Kazarovec et al., 2004; Maksimov, 2004; Šaršunov et al., 2012; Kamiński et al., 2014a).

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The objective of the research was to compare the operation efficiency of a separator provided with fixed screens mounted to the shoe and the one with spring-mounted screens, determination of the impact of basic kinematics on theseparation efficiency. The analysis was also carried out with regard to the use of spring-mounted cylindrical screens and flat screens. The process of mass displacement on the screen surface including movement upward, downward, throwing up was examined also. The values characteristic for the separation process were output (capacity) of screens and the impurity separation degree.

Material and research methodology

To reduce energy consumption during flax seed separation with traditional equipment the efforts were made to design the seed-ball threshing machine that would provide initial and final seed separation. Consequently the separator was constructed purposed for initial separation of free seeds and in order to prevent damage caused by a threshing unit, as well as separated lightweight and fine impurities to improve output (capacity) of a separator (Šaršunov et al., 2010; Kamiński et al., 2014b). The Figure No. 1 includes the layout of the separator.

The process of flax seed separation is carried out according to the following. The mass of flax seed including impurities upon initial drying is placed inside the feeding shoe (1) and next is fed to the pneumatic duct (3), where air circulation ensures separation of light impurities. Next the mass is carried to the top screen shoe (2) which ensures separation of heavy impurities and single seeds. Whereas fine impurities after passing through the screen are placed on V-shaped chute that discharges them outside the machine. Bulk seeds after coming out from the screen are placed on the chute (7) and fed to the lower screen shoe (8). Poorly threshed seed-bags are fed from the top screen shoe (2) to the threshing unit (5) provided with two elastic rolls, and next are carried with the chute (6), to the respiration duct (4), where separation of light impurities generated during further threshing of seed-bags follows. Next seeds are fed to the lower screen shoe (8) where separation of impurities that are discharged from machine with II and IV duct follows.
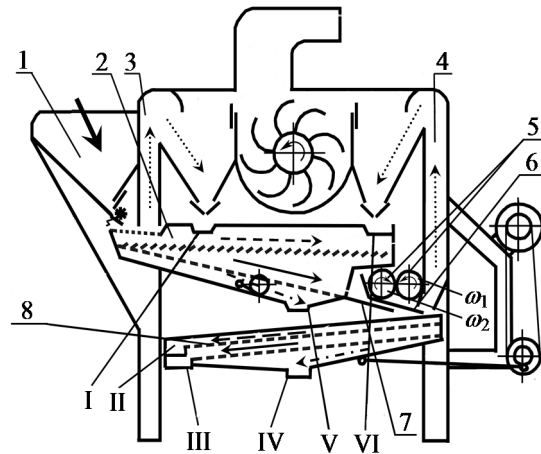
Figure 1. Process diagram of a flax seed separator: (1) feeding hopper, (2,8) screen shoe, (3,4) pneumatic ducts, (5) threshing device, (6,7) chutes, (I,VI) chute of light impurities, (II) chute of heavy impurities, (III) chute of flax seeds, (IV) and (V) chute of fine impurities, movement direction of: ⟶ *– mass,* ┈┈➤ *– light impurities,* ─ ─➤ *– seed-bags,* ⟶ *– bulk seeds,* ─ · ➤ *– fine impurities.*

The main disadvantage of spring-mounted screen shoe was poor efficiency of separation caused mainly by an ineffective movement of mass on the shoe flat surface with vibration direction similar to horizontal one, in particular in case of operation of round hole screens when particles passing through the screen should have be in vertical position.

In case of the above described separator, the shoe has been constructed (fig. 2) fitted with spring-mounted screens vibrating thanks to inertia, which enabled to improve separation efficiency due to additional vibration of a screen that provided for dynamic separation of mixture components and throwing up of seeds that facilitated entering of particles into screen slots (Kocuba and Kruglenja, 2004; Kruglenja et al., 2011). The basic components of flax threshed mass featured with absolute moisture content: seed- bags – 40-50%, single seeds – 15-27%, weeds 45-80%, targan – 25-65%.

The body of screen shoe vibration was driven with the cranked shaft. Inertia forces of shoe and spring stiffness forces resulted in additional vibration within vertical plane, and at the same time a shoe vibration angle increases, which results in dynamic separation of mixture components. Moreover the movement of particles followed because of throwing up at small values of screen shoe kinematics limits, which facilitates dynamic separation with round slotted screens.

Separation efficiency may be increased by mounting removable chutes (5) to the screen shoe, due to optimal use of lower screens that feed seed to the beginning of a screen, as well as improvement of screen shoe technical capacities. Additionally screens with slots of different type (rectangular and round shaped) require different kinematics parameters. In case of screen shoes being in operation at present it is difficult to provide, and usually operation follows for determined kinematics, which results in efficiency reduction. Inertial vibrating screens may be mounted inside the screen shoe independently from each other.

Adjustment of spring stiffness may ensure proper kinematics parameters for operation of each screen.
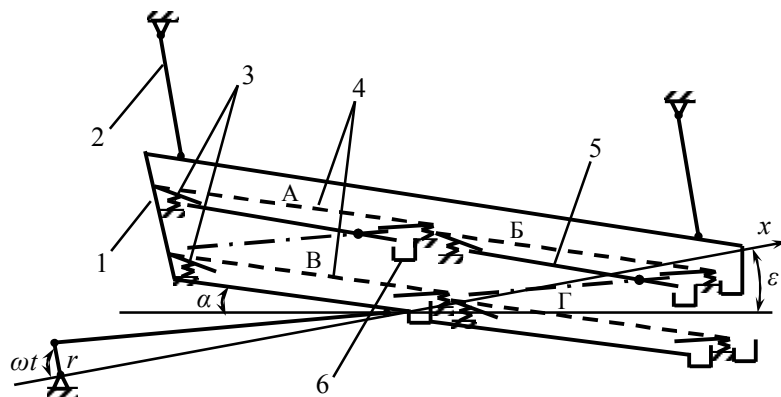

Figure 2. Diagram of a shoe with inertial vibrating screens: (1) screen shoe body, (2) suspending rods, (3) screen suspending springs, (4) screens, (5) screen shoe (return chutes), (6) separated fraction chute

Figure 3 specified schematic vibration of suggested screens (Kocuba and Kruglenja, 2004; Kruglenja et al., 2011). The screens were replaced with "m" mass mounted with spiral springs to the tilted casing. The screens were subjected to F_j inertia and $m \cdot g$ weight forces.

Moreover movement characteristic was specified on the OXY fixed coordinate system and Oxy mobile coordinate system

Equations of screen vibration (fig. 3) may be defined on the Oxy mobile coordinate system as follows:

$$x = -r \cos \omega t (1 + A_q \cos^2(\alpha + \varepsilon) + A_p \sin^2(\alpha + \varepsilon)); \qquad (1)$$

$$y = -r \cos \omega t \sin(\alpha + \varepsilon) \cos(\alpha + \varepsilon)(A_p - A_q); \qquad (2)$$

or OXY fixed coordinate systems:

$$X = -r \cos(\alpha + \varepsilon) \cos \omega t (1 + A_q); \qquad (3)$$

$$Y = -r \sin(\alpha + \varepsilon) \cos \omega t (1 + A_p), \qquad (4)$$

where:

  r – connecting rod arm, (m)
  ω – crank arm angular speed, (rad·s^{-1})
  α – screen inclination angle, (°)
  ε – vibration direction angle, (°)

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$$A_p = \frac{\omega^2}{\left(2\pi p\right)^2 - \omega^2} \quad \text{and} \quad A_q = \frac{\omega^2}{\left(2\pi q\right)^2 - \omega^2}$$ – spring stiffness coefficient, taking into account the impact from own vibration of longitudinal springs (p) and diagonal ones (q).
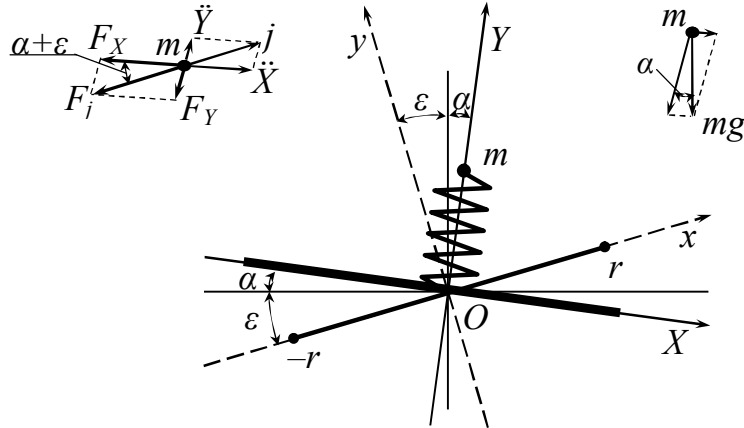
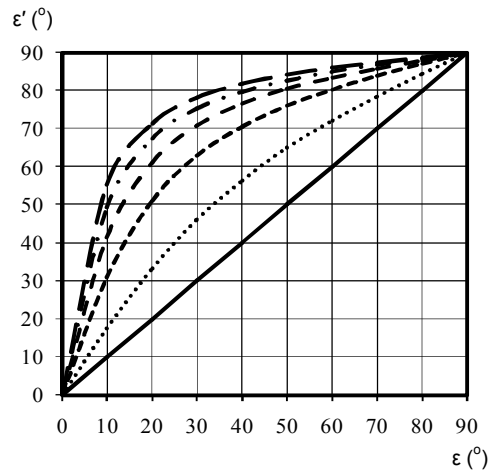Figure 3. Kinematics diagram of the inertial vibrating screen

Figure 4. *Relation of vibration direction angle (ε') of inertial screens to screen shoe vibration direction angle (ε) and the relationship of longitudinal (A_p) and diagonal (A_q) spring stiffness for the following cases:* ———— – $A_p = A_q$; ·········· – $A_p = 2A_q$; ————— – $A_p = 4A_q$ — — — – $A_p = 6A_q$; — · — · — $A_p = 8A_q$; —— —— – $A_p = 10A_q$

According to equations (1) and (2) screens harmonic vibration follow at frequency corresponding to screen shoe vibration frequency, but different amplitudes that depend on A_p and A_q.

These equations are true also after replacing cylindrical springs with flat ones, yet additional vibration will follow only in the plain perpendicular to screens surface (own vibration of flat springs were determined with stiffness modulus A_p and $A_q = 0$.

In case of spring absence (A_p and $A_q \rightarrow 0$) the equations of inertial screens movement take the form of screen shoe movement equations.

In case of $A_p = A_q$, screen vibration direction angle ε' was equal to ε screen shoe vibration direction. In case of $A_p > A_q$, screen vibration direction angle ε' was bigger than screen shoe vibration direction angle ε (fig. 4), what in practice improved operation quality of round slots.

Screen shoe operation limits for mass moved upwards (K_1) and downwards (K_2), as well as throwing up (K_o) may be defined with the following equations:

$$K_1 = \frac{\sin(\alpha + \varphi)}{\cos(\alpha + \varepsilon + \varphi) + \frac{1}{2}\left((A_q + A_p)\cos(\alpha + \varepsilon + \varphi) + (A_q - A_p)\cos(\alpha + \varepsilon - \varphi)\right)}; \quad (5)$$

$$K_2 = \frac{\sin(\varphi - \alpha)}{\cos(\alpha + \varepsilon - \varphi) + \frac{1}{2}\left((A_q + A_p)\cos(\alpha + \varepsilon - \varphi) + (A_q - A_p)\cos(\alpha + \varepsilon + \varphi)\right)}; \quad (6)$$

$$K_O = \frac{\cos\alpha}{(1 + A_p)\sin(\alpha + \varepsilon)}, \quad (7)$$

where:

φ – friction angle of separated mass against screen surface, ($^\circ$).

In case of equal longitudinal and diagonal spring stiffness ($A_p = A_q$) operations limits of screen shoe fitted with inertial vibrating screens K may be defined with the following formula:

$$K = \frac{K_{gr}}{(1 + A_p)} \quad (8)$$

where:

K_{gr} –kinematics limits for operation of used screen shoes (without springs).

Figure No. 5 determined the relationship regarding operation limits of inertial vibrating screens and vibration direction angle.

According to the Figure No. 5 for inertial vibrating screens fitted with cylindrical springs, the kinematics parameter of screen shoe was lower comparing to the traditional screen shoe $1+A_p$ times.

As drive power of the screen shoe depends on the kinematics limits, reduction thereof results in the reduction of power required for seed separation by 31.1-68.8%.
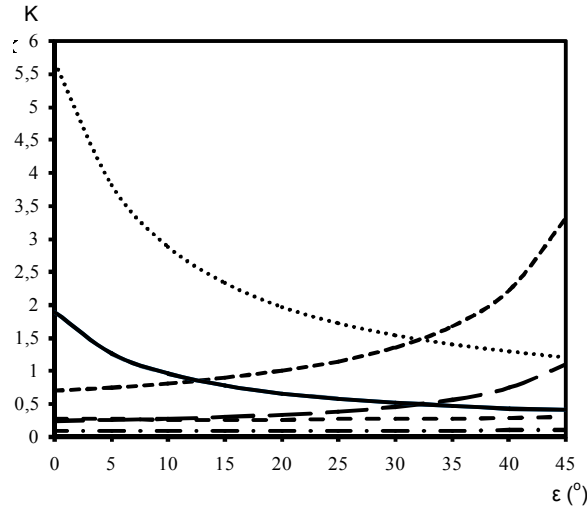
Figure 5. Diagram regarding relationship of inertial vibrating screen operation limits from ε vibration direction angle — — $- K_1$; $------ - K_{gr1}$; $- \cdot - \cdot - K_2$; $- - - - K_{gr2}$; ——— $- K_O$; $\cdots\cdots\cdots - K_{grO}$

Additionally the separated mass movement range increases including throwing up above the screen surface. Therefore at the vibration direction angle $\varepsilon = 0°$ in case of previous screens throwing up followed at the kinematics limits ratio of K=5.67, and in case of inertial vibrating screens at K=1.89, which ensures effective operation of round slotted screens at screen shoe kinematics decreases 3 times.

Analysis regarding conditions for material movement on (5), (6) and (7) screen indicated the following relationships for currently used inertial vibrating screens:

$$\frac{K_1}{K} = \frac{K_{gr1}}{K_{gr}}; \quad \frac{K_2}{K} = \frac{K_{gr2}}{K_{gr}}; \quad \frac{K_0}{K} = \frac{K_{gr0}}{K_{gr}}. \tag{9}$$

To determine the mass movement speed on the shoe a multiplier was applied in Letoszniew's formula (1963) that took into account a change of speed resulted from action of springs in (3) and (4) dependency.

$$v_1 = \omega r(1 + A_q)\cos(\alpha + \varepsilon)\left[(\sin\psi - \sin\psi_1) - (\psi - \psi_1)\frac{K_1}{K}\right]; \tag{10}$$

$$v_2 = \omega r(1 + A_q)\cos(\alpha + \varepsilon)\left[(\sin\theta - \sin\theta_1) + (\theta - \theta_1)\frac{K_2}{K}\right], \tag{11}$$

where:

v_1 and v_2 – speeds of mass upward and downward movement on screen surface, (m·s^{-1});

ψ and ψ_1 – current and initial moment of material upward movement on screen surface, (^{o});

θ and θ_1 – current and initial moment of material downward movement on screen surface, (^{o}).

Equation (9) and (10) may be also formulated as follows:

$$v_{1(2)} = \omega r(1 + A_q)\cos(\alpha + \varepsilon)\left[\sin(U_{1(2)} - \arccos Z_{1(2)}) + \sqrt{1 - Z_{1(2)}^2} - U_{1(2)}Z_{1(2)}\right] \quad (12)$$

where:

$$Z_1 = \frac{K_1}{K}, \ Z_2 = \frac{K_2}{K}, \ U_1 = \psi - \psi_1, \ U_2 = \theta - \theta_1$$

Maximum speed of mass movement on the screen will be obtained at $U = \arccos Z$, and (12) equation will be as follows:

$$v_{1(2)max} = 2\omega r(1 + A_q)\cos(\alpha + \varepsilon)\left[\sqrt{1 - Z_{1(2)}^2} - U_{1(2)}Z_{1(2)}\right] \quad (13)$$

Figure 6 presents diagram regarding relationship between the maximum speed of mass movement and kinematics at $\omega = 10$ rad·s^{-1}, $r = 6$ mm, $\alpha = 10°$, $\varepsilon = 0°$ and $A_q = 2$.
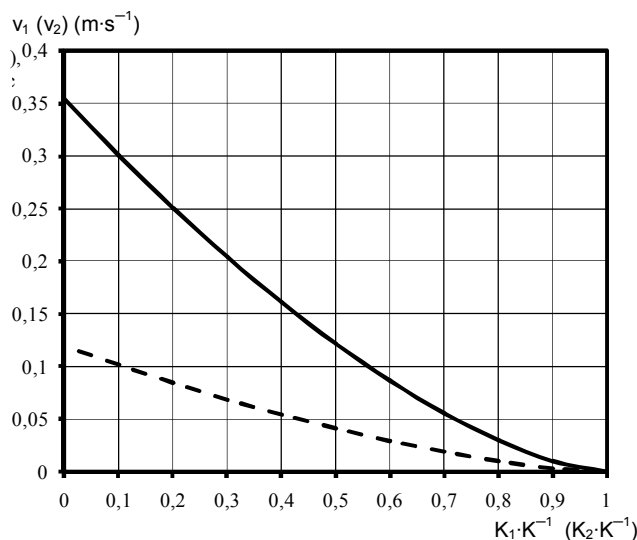

Figure 6. The relationship between the mass movement speed $v_1(v_2)$ and kinematics $K_1 \cdot K^{-1}$ ($K_2 \cdot K^{-1}$) ——— *– inertial vibrating screens;* — — — *– current non vibrating screens*

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According to Figure no. 6 the use of inertial vibrating screen resulted in $1+A_p$ times speed increase of separated mass movement on screen's surface, which improved efficiency. Additionally it enabled reduction of frequency and amplitude of screen shoe vibration, what also decreased demand for screen shoe drive power and counterweight mass required to maintain balance.

An average speed of mass movement upon screen surface may be calculated from the following formula:

$$v_{śr} = \frac{\xi_d - \xi_g}{2\pi}\omega \tag{14}$$

Where: ξ_d and ξ_g – particle movement upward and downward on screen surface, (m).
Value of movement is calculated using the following equation:

$$\xi_{1(2)} = r(1+A_q)\cos(\alpha+\varepsilon)[Z_{1(2)} - \cos\left(U_{1(2)} - \arccos Z_{1(2)}\right) + $$
$$+ U_{1(2)}\sqrt{1-Z_{1(2)}^2} - \frac{1}{2}U_{1(2)}^2 Z_{1(2)}]. \tag{15}$$

Mass movement speed above the limit value results in reduced fine fraction shifting efficiency, due to passing of particle next to the slot or particle reflected against the edge.

Limit values of mass upward and downward movement on screen surface may be defined with the following equations:

$$v_{gr1} = (B\cos\alpha - r_M)\sqrt{\frac{g}{2(r_M + B\sin\alpha)}} \tag{16}$$

$$v_{gr2} = (B\cos\alpha - r_M)\sqrt{\frac{g}{2(r_M - B\sin\alpha)}} \tag{17}$$

where:
B – screen slot width, (m)
r_M – particle radius (seed), (m).

On the basis of particle speed movement (12), (13), (16) and (17), as well as its path (15) it was possible to determine separation degree of mass passing through screen slots.

The mathematical models for flax mass separation with inertial vibrating screens have been determined with the traditional methodology, including separating single-coefficient experiments, 2^3 total coefficient experiment and three-level program of second row Boks-Bienkin's for three coefficients.

Results

As a result of physical and chemical properties examination of flax mass, the technological diagram was prepared for flax seed separation with separating plant fitted with inertial vibrating screens, actuating separation with blown air stream at speed of 3.5-4.0 m·s⁻¹, separation of coarse impurities from mass with screen of rectangular slot 1.2-1.5 mm wide and

separation of fraction passing through screens with round slots of 2.2mm diameter, with rectangular slots 1.1 mm wide and round slots of 1.8 mm diameter.

Figure No. 7 presents the results from laboratory tests of proposed vibrating screens. The objective function was unit efficiency of screen q_F (kg·s⁻¹·m⁻²) and impurity separation degree (from passing fraction) E. The variability intervals of coefficients and their limits were defined on basis of conducted theoretical discussion and a′priori information.

As a result of experiments, the rational intervals regarding coefficient changes were determined for flax threshed mass separation:

Spring stiffness modulus A_p – 0.8-1.6; connecting rod angular speed ω – 30-60 rad.·s⁻¹; vibration amplitude A – 8-15 mm; vibration direction angle ε – 30-45°; screen inclination angle α – 9-12°; kinematics limits coefficient for screen shoe K – 2.0-3.0.

The conducted experiments related to shifting determined that the factors that had most significant impact on optimization of flax threshed mass separation process were: spring stiffness modulus, vibration amplitude and kinematics limits ratio of screen shoe (Kruglenja et al., 2011; Zagajewski and Dreszer, 2008).

Further research defined mathematical models for flax threshed mass separation with inertial vibrating screens taking into account the basic coefficients:
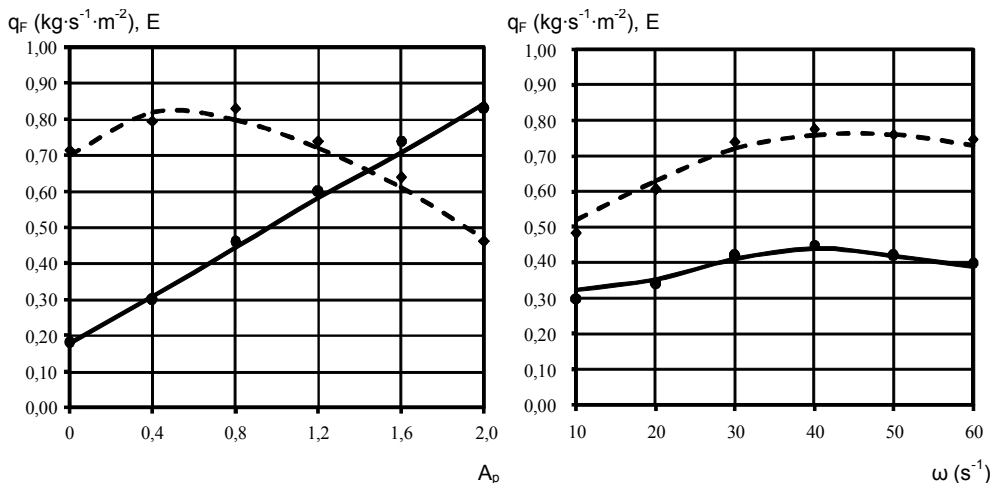
– regarding unit output (capacity)

$$q_F = 0,51 + 0,06 \cdot A_p + 0,03 \cdot A + 0,08 \cdot K + 0,01 \cdot A_p \cdot A +$$
$$+ 0,01 \cdot A_p \cdot K + 0,01 \cdot A \cdot K + 0,01 \cdot A_p^2 - 0,02 \cdot A^2 + 0,01 \cdot K^2; \tag{18}$$

– regarding impurity separation degree

$$E = 0,67 - 0,05 \cdot A_p - 0,04 \cdot A - 0,06 \cdot K + 0,01 \cdot A^2 - 0,01 \cdot K^2. \tag{19}$$

To solve the problem, electronic calculation technology and Microsoft Excel software were used that provided the rational values of the following parameters:

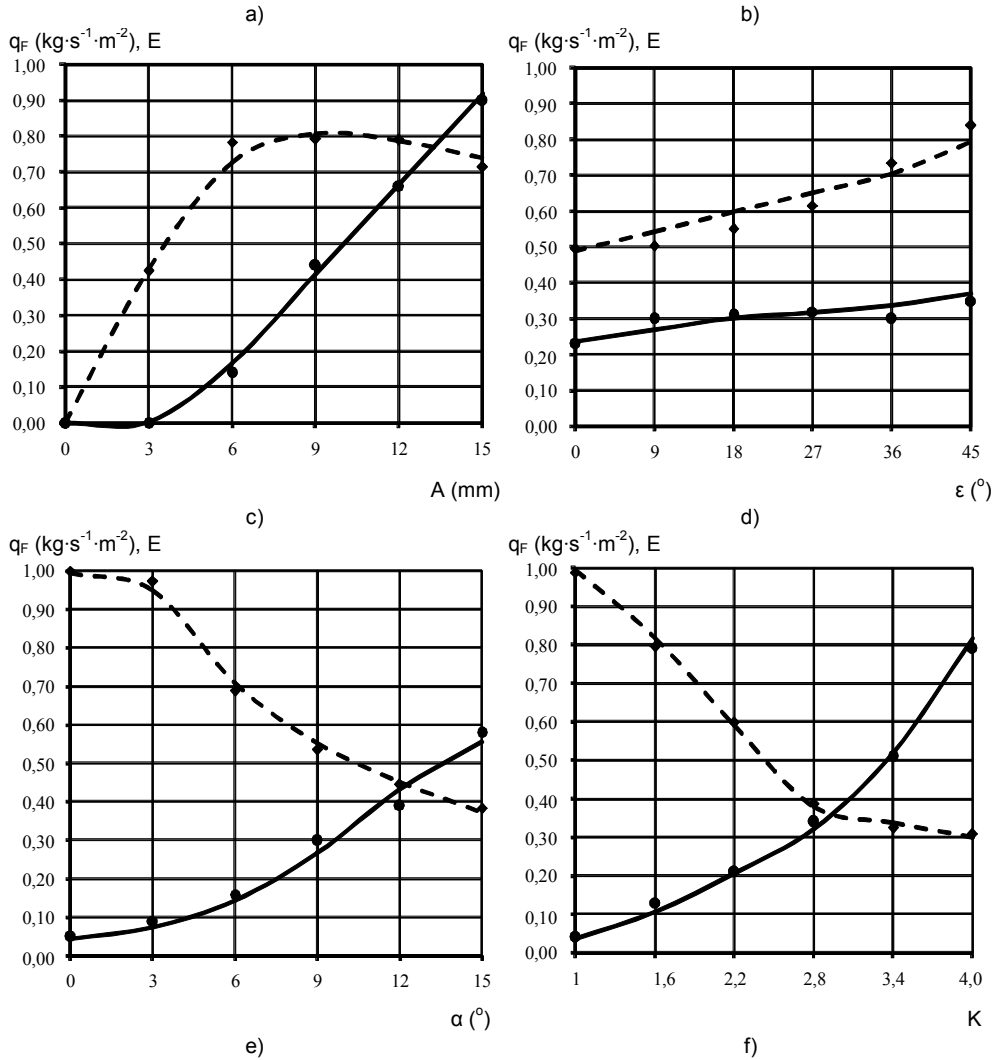A_p = 1.2, A = 8 mm, K = 2.3. At q_F = 0.72 kg·s⁻¹·m⁻², E = 0.87

Figure 7. Diagrams regarding the relationship of q_F single screen output (capacity) and E impurity separation degree with A_p (a) spring stiffness modulus, ω (b) frequency, A (c) amplitude, ε (d) direction angle of screen shoe vibration, α (e) screen inclination angle and kinematics coefficient of screen shoe operation limits K (f), ——— – q_F (kg·s^{-1}·m^{-2}); — — — E;

The performance tests of a designed threshing plant – a separator fitted with inertial screens were conducted in 2003-2005 at Seed Centre in Gorecko.

To determine rational structure parameters of inertial screens it was suggested to use the monogram included in Figure No. 8, determined on the basis of theoretical research and experiments.
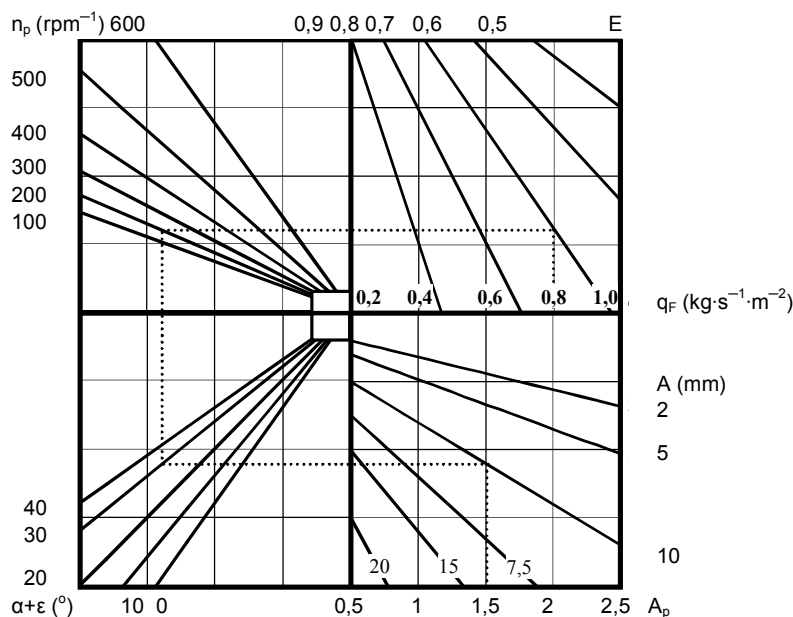

Figure 8. Monogram for determination of flax separation spring-mounted screens parameters: q_F – single screen output, (kg·s^{-1}·m^{-2}); E – impurity separation degree, n_p – screen shoe vibration frequency, (min^{-1}); α – screen inclination angle, (°); ε – screen vibration direction angle, (°); A – screen shoe vibration amplitude, mm; A_p – spring stiffness modulus

Spring stiffness modulus may be determined on the basis of single screen output and impurity separation degree, and upon choice of connecting rod rotation frequency, screen inclination angle, direction angle and screen shoe vibration amplitude. Depending on the output data also other parameters used in the monogram may be specified.

Thus for single screen output $q_F = 0.8$ kg·s^{-1}·m^{-2}, impurity separation degree E=0.7, screen shoe vibration frequency $n_p = 200$ rpm^{-1}, the sum of screen inclination angle and vibration direction angle α+ε=30° and screen shoe vibration amplitude A=10 mm, the required spring stiffness modulus was $A_p = 1.5$.

Spring parameters that provided the required modulus, may be determined according to the monogram or following formula:

$$A_p = \frac{\omega^2}{\dfrac{\pi^2 G d_B^4}{2 n_B m D_\Pi^3} - \omega^2} \qquad (20)$$

where:

ω – connecting rod angular speed, (s^{-1})

G – nature deformation modulus, (MPa)

d_B – spiral spring wire section diameter, (m)

n_B – cylindrical spring coil number;

m – screen mass, (kg)

D_Π – cylindrical spring diameter, (m).

Comparing to the previous ones, the inertial vibrating screens allowed to increase seed separation degree by 6-8%, reduce cracking and damages of seed surface by 9-12%, as well as increase machine output by 10-25% (Kruglenja et al., 2011).

Conclusions

1. Comparing the results of theoretical discussion and experiments conducted with the use of the separator fitted with fixed screens mounted to the shoe and spring-mounted screens, for proper kinematics parameters the spring-mounted screens featured with improved output (capacity), precise fine and coarse impurity separation, as well as the reduced demand for screen shoe drive power.

2. Basic physical values that had impact on the separation process, namely, single screen output and impurity separation degree were: the screen shoe vibration degree, screen inclination degree and vibration direction, vibration amplitude and spring stiffness modulus. The rational values of these parameters may be specified using the mathematical formulas and the prepared monogram.

3. The screen capacity, namely q_F was on the straight-line basis dependent on A_p screen stiffness, A screen shoe vibration amplitude and increased along with the increase of q_F and A_p values. The increase was less evident in case of ω and ε value increase. Whereas a significant non-linear increase was evident in case of α and K parameters increase.

4. The impurity separation degree, namely E initially increased and then decreased as A_p spring stiffness increased, along with the increase of the screen shoe vibration amplitude. The increase was less evident in case of ω frequency and ε angle increase and decreased as a result of α and K parameter value increase.

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CZYSZCZALNIA DO NASION LNU Z DRGAJĄCYMI SITAMI

Streszczenie. Celem badań było porównanie efektywności pracy czyszczalni z sitami mocowanymi w koszu sitowym na stałe z mocowanymi sprężyście, ustalenie wpływu podstawowych parametrów kinematycznych na wydajność procesu czyszczenia. Analizowano przypadki stosowania mocowania sit na sprężynach cylindrycznych i płaskich. Badano proces przemieszczania się materiału czyszczonego po powierzchni sit z włączaniem etapów ruchu do góry, do dołu, podrzucania. Wielkościami charakteryzującymi proces czyszczenia były wydajność (przepustowość) sit i stopień oddzielania domieszek. Analizowanymi parametrami kinematycznymi były: amplituda drgań kosza sitowego, amplituda drgań własnych sit, kąt pochylenia sit, kąt kierunkowy drgań sit, częstotliwość drgań własnych, wskaźnik reżimu kinematycznego. W rezultacie otrzymano matematyczne modele procesu separacji dla jednostkowej wydajności i stopnia oddzielania domieszek. Z równań tych obliczono najlepsze wartości parametrów: A_p=1,2, A=8 mm, K=2,3, dla których q_F=0,72 kg·s^{-1}·m^{-2}, E=0,87. Parametry sprężyn, zapewniające wymagany współczynnik sprężystości, można określić za pomocą monogramu lub formuły matematycznej (20). Z przeprowadzonych eksperymentów wynika, że przepustowość sit q_F zależy liniowo od sztywności sprężyn A_p, amplitudy drgań kosza sitowego A i rośnie wraz z wartościami q_F i A_p. Mniej wyraźnie wzrasta również ze wzrostem wartości ω i ε. Natomiast nieliniowo i znacznie wzrasta ze wzrostem parametrów α i K. Stopień oddzielania domieszek E początkowo wzrasta a następnie maleje ze wzrostem sztywności sprężyn A_p, oraz ze wzrostem amplitudy drgań kosza sitowego. Mniej wyraźnie wzrasta ze wzrostem częstotliwości ω i kąta ε. Oddzielanie domieszek wyraźnie maleje ze wzrostem wartości parametrów α i K.

Słowa kluczowe: uprawa lnu, omłot, nasiona lnu, czyszczalnia, separator