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A MOVABLE STRING SIEVE – ANALYSIS OF SEED SCREENING

***Zdzisław Kaliniewicz*[1], *Jerzy Domański*[2]**

[1] Department of Heavy Duty Machines and Research Methodology, University of Warmia and Mazury, Poland

[2] Department of Mechanical Engineering and Machine Construction, University of Warmia and Mazury, Poland

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Abstract

The conditions of seed movement in a string sieve set into reciprocating motion have been formulated for cereal, vetch, pea, lupine and faba bean seeds. In the analyzed string sieve, seed movement was determined by a combination of the following parameters: angular velocity of the crank, crank radius, seed size, seed's coefficient of external friction, string diameter and angle of inclination of the separator screen. A string sieve for cleaning and sorting most farm-produced seeds was analyzed. The width of the separating groove was set at 1 mm at the beginning of the screen and 11 mm at the end of the screen, and the strings had the diameter of 4 mm. Our results indicate that seeds cannot be effectively graded in the modeled string sieve. The angular velocity of the crank exceeds the velocity which is applied to power conventional separator buckets, and it could damage the separator. A reduction in the angular velocity of the crank to the recommended level caused seeds to become jammed directly before the screening site. The above problem can be solved by propelling seeds into motion with the use of special sweeping brushes.

Symbols

a_s – horizontal longitudinal acceleration of the screen, $m \cdot s^{-2}$,
d – equivalent diameter of seeds, mm,
d_s – string diameter, mm,
g – gravitational acceleration, $m \cdot s^{-2}$,
G, G_y, G_z – gravity force and gravity force components, N,
F, F_y, F_z – inertia force and inertia force components, N,
m – seed weight, kg,
N_1, N_2 – the string's normal ground reaction forces, N,
r – crank radius, m,
s – width of the groove in a given screen location, mm,
T_1, T_2 – frictional force components, N,
T_s, W_s, L_s – thickness, width and length of a seed, mm,
v_s – horizontal longitudinal velocity of the screen, $m \cdot s^{-1}$,

* Corespondence: Zdzisław Kaliniewicz, Katedra Maszyn Roboczych i Metodologii Badań, Uniwersytet Warmińsko-Mazurski w Olsztynie, ul. Oczapowskiego 11/B112, 10-719 Olsztyn, phone: 48 89 523 39 34, e-mail: zdzislaw.kaliniewicz@uwm.edu.pl

x, SD – mean value and standard deviation of physical parameters characterizing different seed groups,
x_{min}, x_{max} – minimum and maximum value of a parameter,
α – angle of inclination of a string sieve, °,
μ_s – coefficient of static friction of seed on steel,
φ – included angle between a seed's gravity force component and a string's normal ground reaction force, °,
ω – angular velocity of the crank, s^{-1}.

Introduction

String sieves are applied in the process of cleaning and sorting seeds (GROCHOWICZ 1994, RAWA 1992, RAWA et al. 1990, WIERZBICKI et al. 1991). The separator bucket is the main operating element of a string sieve. Mesh screens are made of wire or metal sheet, and they feature openings of regular shape and size across the entire screen. A single mesh screen can be applied to separate seeds into two fractions only: seeds that are captured by the mesh and seeds that pass through the mesh. Several mesh screens are placed in the separator bucket to separate seeds into the desired number of fractions. A seed mixture is separated by choosing a set of screens with mesh openings that correspond to the dimensions (width and/or thickness) of graded seeds. In practice, different screens are used to separate various seed species or differently sized seeds of the same species (GROCHOWICZ 1994).

Some screening operations, in particular in the mining industry, involve groove or rod separators (DOMAGAŁA 1976, LEŚKIEWICZ et al. 1971, SKIRŁO et al. 1989, WITKOWICZ et al. 1974, 1977) where rods or wires are fixed perpendicularly to the longer sides of the screen frame. The resulting grooves have identical dimensions across the entire screen. When seeds are graded into several fractions, a set of mesh screens grouped in a large separator bucket may be required.

The above problems are not encountered in the string sieve designed by KALINIEWICZ (2011, 2013a). In this solution, strings are stretched between two horizontal bars. This arrangement creates separating grooves between strings whose size changes gradually with distance from the beginning of the screen. Seeds are sorted into various size fractions by changing the position of collecting buckets under the screen. In view of the average size of farm-produced seeds, the width of the separating groove should be set at 1 mm at the beginning of the screen and 11 mm at the end of the screen. In sieves designed for grading cereal seeds, the width of the separating groove can be set at 1 mm and 5 mm, respectively (KALINIEWICZ 2013a). The results of a preliminary study (KALINIEWICZ 2013d) demonstrated that in separators with a fixed screen, the working surface should be set at an angle of 45° to propel seeds into motion and at 50° to ensure the continuity of the screening process. Such a large setting angle is not recommended, however, because the graded mixture contains plump seeds with a small coefficient of external friction which will travel at high speeds. The above deteriorates the quality of the separation process. The screen should be set at a small inclination angle and it move in reciprocating motion to ensure that seeds move along the screen.

The majority of seeds produced on agricultural farms are ellipsoid in shape. This group of seeds includes cereal seeds (wheat, rye, barley, oats and triticale), lupine and faba bean seeds, as well as spherical flattened seeds such as pea and vetch seeds. Since the average coefficient of sliding friction is higher that the average coefficient of rolling resistance (KALINIEWICZ 2013c), it is much more difficult to set ellipsoid seeds in motion, compared with spherical seeds. Thus, a string sieve whose operating parameters have been adapted to ellipsoid seeds can also be used to separate spherical seeds.

In this study, the movement of ellipsoid seeds on the working surface of a string sieve moving in reciprocating motion was described to support the selection of optimal operating parameters of a string sieve.

Theoretical analysis of the separation process

The analyzed string sieve was developed according to the concept proposed by KALINIEWICZ (2103a). In the original solution, the working surface is made of steel wires, rods or strings with circular cross-section. The conceptual diagram of the discussed device is presented in Figure 1. The separator bucket is supported by two rockers, and it is set into reciprocating motion by a crank system powered by an electric motor. Deflection amplitude and frequency are controlled by changing crank radius and rotational speed. The crank radius is much smaller than rocker length (1:100 ratio), therefore, it can be assumed that the sieve screen moves in linear motion. Due to a significant difference in the dimensions of the crank and the connecting rod (1:50 ratio), it can also be assumed that the motion is harmonic (GROCHOWICZ 1994). In extreme positions of the separator bucket, the differences in absolute acceleration do not exceed 4%.

The working surface of the string sieve was set at angle α relative to the horizontal plane (Fig. 1), which was smaller than the smallest coefficient of static friction of the analyzed seeds, to immobilize the seeds when the screen was not in motion. For the sake of simplicity, the following angles were disregarded: opening angle between strings in bottom rows, angle of inclination of bottom strings in the first row relative to top strings, and angle of inclination of bottom strings in the second row relative to top strings. The

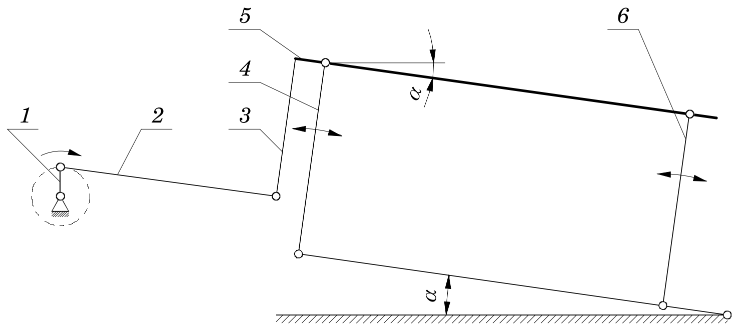

Fig. 1. Conceptual diagram of a string sieve: *1* – electric motor with a crank, *2* – connecting rod, *3* – frame of the screen bucket, *4* – front rocker, *5* – mesh screen, *6* – rear rocker, α – screen's angle of inclination relative to the horizontal plane

above angles did not exceed 1.5° (KALINIEWICZ 2013a). Assuming that the sieve is set into motion beginning from the position indicated in Fig. 1, horizontal longitudinal velocity and acceleration of the screen can be determined with the use of the below formulas:

$$v_s = r \cdot \omega \cdot \cos \omega t \tag{1}$$

$$a_s = -r \cdot \omega^2 \cdot \sin \omega t \tag{2}$$

It was assumed that seeds would be fed in a narrow stream to the initial section of the string sieve. The elastic strain of screen strings, the interactions between seeds and the influence of centripetal acceleration on seed motion were not taken into account for the sake of simplicity. This study analyzed only the sliding motion of seeds across the surface of a string sieve, therefore, the geometric model of the analyzed seeds was adopted in the form of a rotating ellipsoid (GASTON et al. 2002, GROCHOWICZ 1994, HEBDA, MICEK 2005, 2007, ŻABIŃSKI, SADOWSKA 2010). The major axis of the ellipsoid was seed length, and the minor axis was the average of seed thickness and width. The seeds had a circular cross-section whose equivalent diameter was determined based on the following equation:

$$d = \frac{T_s + W_s}{2} \tag{3}$$

In the first stage of the analysis, a seed was placed on the surface of a string sieve with its longitudinal axis parallel to the strings (Fig. 2), i.e. the seed was supported by two adjacent strings. The following forces acted upon the seed:

– gravity G,

– normal ground reaction force, as the resultant force exerted by strings N_1 and N_2,

– friction, as the resultant force exerted by T_1 and T_2,

– inertia F, in a direction opposite to acceleration, calculated from the following formula:

$$F = m \cdot r \cdot \omega^2 \cdot \sin\ \omega t \tag{4}$$

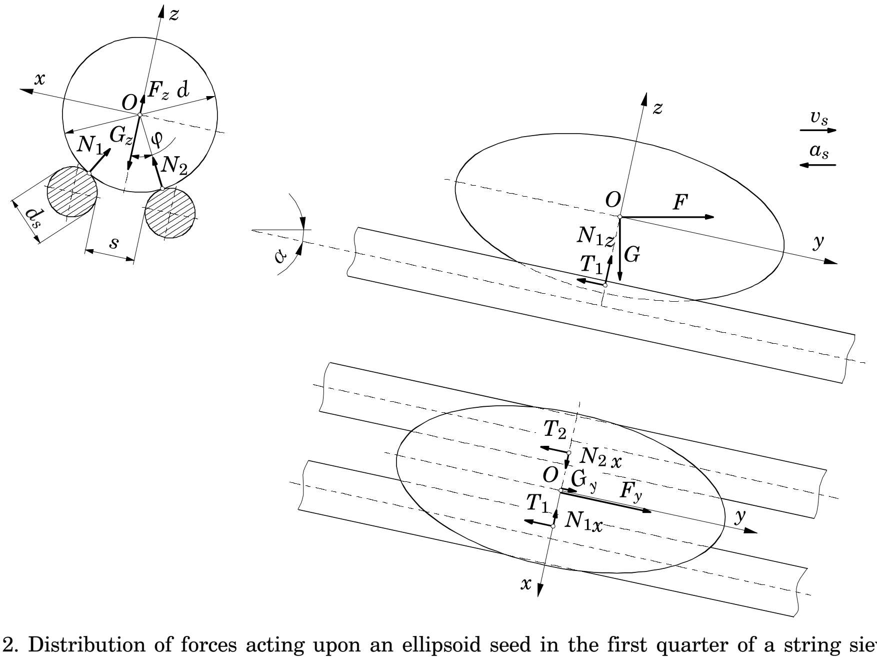

Fig. 2. Distribution of forces acting upon an ellipsoid seed in the first quarter of a string sieve's operating cycle

Gravity force components can be expressed with the use of the below formulas:

$$G_y = m \cdot g \cdot \sin\alpha \tag{5}$$

$$G_z = m \cdot g \cdot \cos\alpha \tag{6}$$

The string's normal ground reaction force was determined based on the below formula:

$$N_1 = N_2 = \frac{G_z - F_z}{2\ \cos\varphi} = \frac{m \cdot g \cdot \cos\alpha - m \cdot r \cdot \omega^2 \cdot \sin\omega t \cdot \sin\alpha}{2\ \cos\varphi} \tag{7}$$

Frictional forces counteract the movement of seeds across strings, and in extreme cases, they can reach:

$$T_1 = \mu_s \cdot N_1 = \mu_s \cdot N_2 = T_2 \tag{8}$$

In the critical position of a seed (at the beginning of motion across the screen), frictional forces were projected to the y-axis to produce:

$$-2T_1 + G_y + F_y = 0 \tag{9}$$

Dependencies (8), (7) and (5) were substituted into equation (9), the inertia component was introduced and seed weight was reduced to produce:

$$\frac{\mu_s \cdot g \cdot \cos\alpha - \mu_s \cdot r \cdot \omega^2 \cdot \sin\omega t \cdot \sin\alpha}{\cos\varphi} = g \cdot \sin\alpha + r \cdot \omega^2 \cdot \sin\omega t \cdot \cos\alpha \tag{10}$$

Assuming that seeds should remain in motion at least upon the achievement of extreme delay (at $\omega t = 90^{o}$), equation (10) can be transformed to

$$\mu_s \cdot r \cdot \omega^2 \cdot \sin\alpha + r \cdot \omega^2 \cdot \cos\alpha \cdot \cos\varphi = \mu_s \cdot g \cdot \cos\alpha - \mathrm{g} \cdot \sin\alpha \cdot \cos\varphi \tag{11}$$

The above formula can be used to determine the angular velocity or the radius of the crank when the values of the remaining parameters are known. The remaining parameters condition the sliding motion of seeds across the surface of the string sieve, which is a prerequisite for separation. Formula (11) was used to determine the angular velocity of the crank:

$$\omega = \sqrt{\frac{g \cdot (\mu_s \cdot \cos\alpha - \sin\alpha \cdot \cos\varphi)}{r \cdot (\mu_s \cdot \sin\alpha + \cos\alpha \cdot \cos\varphi)}} \tag{12}$$

Angle φ is determined from a geometric function given by KALINIEWICZ (2013d):

$$\varphi = \arcsin\frac{s + d_s}{d + d_s} \tag{13}$$

Materials and methods

A comprehensive analysis of seed motion across the working surface of a string sieve requires the determination of the physical parameters of selected seed species, including dimensions (length, width, thickness) and the coefficient of external friction. The studied cereal species were wheat, rye, barley, oats and triticale, which were classified into a homogenous group of cereals. Other seed species (vetch, pea, lupine and faba bean) were analyzed as separate groups. One hundred and twenty seeds of each species were randomly selected for analysis. Oblong seeds which met the set criteria, in particular seeds whose motion was initiated by sliding (KALINIEWICZ 2013b, 2013c), were selected manually. The final sample sizes were as follows: cereals – 600 seeds, vetch – 60 seeds, pea – 46 seeds, lupine – 103 seeds, faba bean – 89 seeds. The length, width and thickness of seeds were determined under the MWM 2325 laboratory microscope, and the coefficient of external friction was determined with the use of a device described by KALINIEWICZ (2013b). The equivalent diameter of seeds was determined.

The results were processed statistically to determine differences between the mean values of geometric parameters and the correlations between equivalent diameters and coefficients of static friction (for a given group of seeds). The results were processed by one-way analysis of variance with a post-hoc test and correlation analysis (LUSZNIEWICZ, SŁABY 2008, RABIEJ 2012).

The analysis was carried out for a sieve with steel strings where the width of the separating groove was set at 1 mm at the beginning of the screen and 11 mm at the end of the screen (KALINIEWICZ 2013a).

Results and Discussion

Seed dimensions and the results of the comparison of the analyzed seed groups are presented in Table 1. In most cases, different results were reported for the examined seed groups (species). Significant differences were not observed only in a comparison of the length of pea seeds and lupine seeds and in a comparison of the coefficients of static friction of pea seeds and cereal seeds. A comparison with other authors' findings (ALTUNTAS, DEMIRTOLA 2007, COBORU 2012, LEMA et al. 2005, RYBIŃSKI et al. 2009, SADOWSKA, ŻABIŃSKI 2011, TASER et al. 2005, YALÇIN, ÖZARSLAN 2004, YALÇIN et al. 2007) indicates that vetch seeds were characterized by low plumpness, faba bean seeds – by medium plumpness, and lupine and pea seeds – by high plumpness. The analyzed seed groups were arranged in the following ascending order based on the average values of the equivalent diameter: cereals, vetch, lupine, pea and faba bean.

KALINIEWICZ (2013b, 2013c) demonstrated that physical dimensions (length, width, thickness), weight, volume, density and shape of seeds do not significantly affect their frictional properties. Similar results were reported during attempts to determine correlations between the seeds' equivalent

Table 1
The results of measurements and statistical calculations of selected physical properties of the analyzed seed groups

Seed group	Physical property	x_{min}	x_{max}	x	*SD*
Cereals	thickness, mm	1.75	3.41	2.67^e	0.30
	width, mm	1.83	4.40	3.23^e	0.49
	length, mm	5.40	13.70	8.24^b	1.51
	equivalent diameter, mm	1.79	3.81	2.95^e	0.37
	coefficient of static friction	0.23	0.33	0.34^a	0.06
Vetch	thickness, mm	2.60	3.64	3.16^d	0.28
	width, mm	3.42	4.70	4.15^d	0.29
	length, mm	3.63	5.14	4.45^d	0.34
	equivalent diameter, mm	3.13	4.11	3.66^d	0.25
	coefficient of static friction	0.23	0.43	0.30^b	0.04
Pea	thickness, mm	4.73	6.93	6.08^b	0.49
	width, mm	5.71	8.06	7.02^b	0.56
	length, mm	6.56	8.83	7.66^c	0.49
	equivalent diameter, mm	5.35	7.44	6.55^b	0.49
	coefficient of static friction	0.29	0.42	0.34^a	0.03
Lupine	thickness, mm	4.37	6.02	5.15^c	0.35
	width, mm	5.40	7.55	6.33^c	0.43
	length, mm	6.16	8.80	7.58^c	0.51
	equivalent diameter, mm	5.03	6.70	5.74^c	0.34
	coefficient of static friction	0.23	0.36	0.28^c	0.03
Faba bean	thickness, mm	5.55	8.91	7.39^a	0.71
	width, mm	6.55	10.20	8.63^a	0.84
	length, mm	7.38	13.00	10.34^a	1.13
	equivalent diameter, mm	6.05	9.54	8.01^a	0.75
	coefficient of static friction	0.19	0.36	0.22^d	0.03

a, b, c, d, e – values marked with the same letters in the superscript do not differ statistically

diameter and their coefficients of external friction. Significant correlations where the coefficient of correlation exceeded 0.4 were not observed, and the results of the cited studies are not discussed in this analysis. Every seed from a given group can be thus assigned a coefficient of sliding friction from the entire range of values determined for a given cereal species.

In the analyzed string sieve, string diameter was d_s= 4 mm (KALINIEWICZ 2013a). Formulas (12) and (13) contain a total of 6 variable parameters. For this reason, only exemplary minimum angular velocities of the crankshaft were presented as a function of one of the parameters, where the value of the remaining parameters was kept constant (Fig. 3). An analysis of changes in the examined parameters indicates that the minimum angular velocity of the crank which is required to set seeds into motion increases rapidly at the place where the width of the working groove becomes equal to the seeds' equivalent diameter, i.e. at the potential screening site. The above results from a rapid

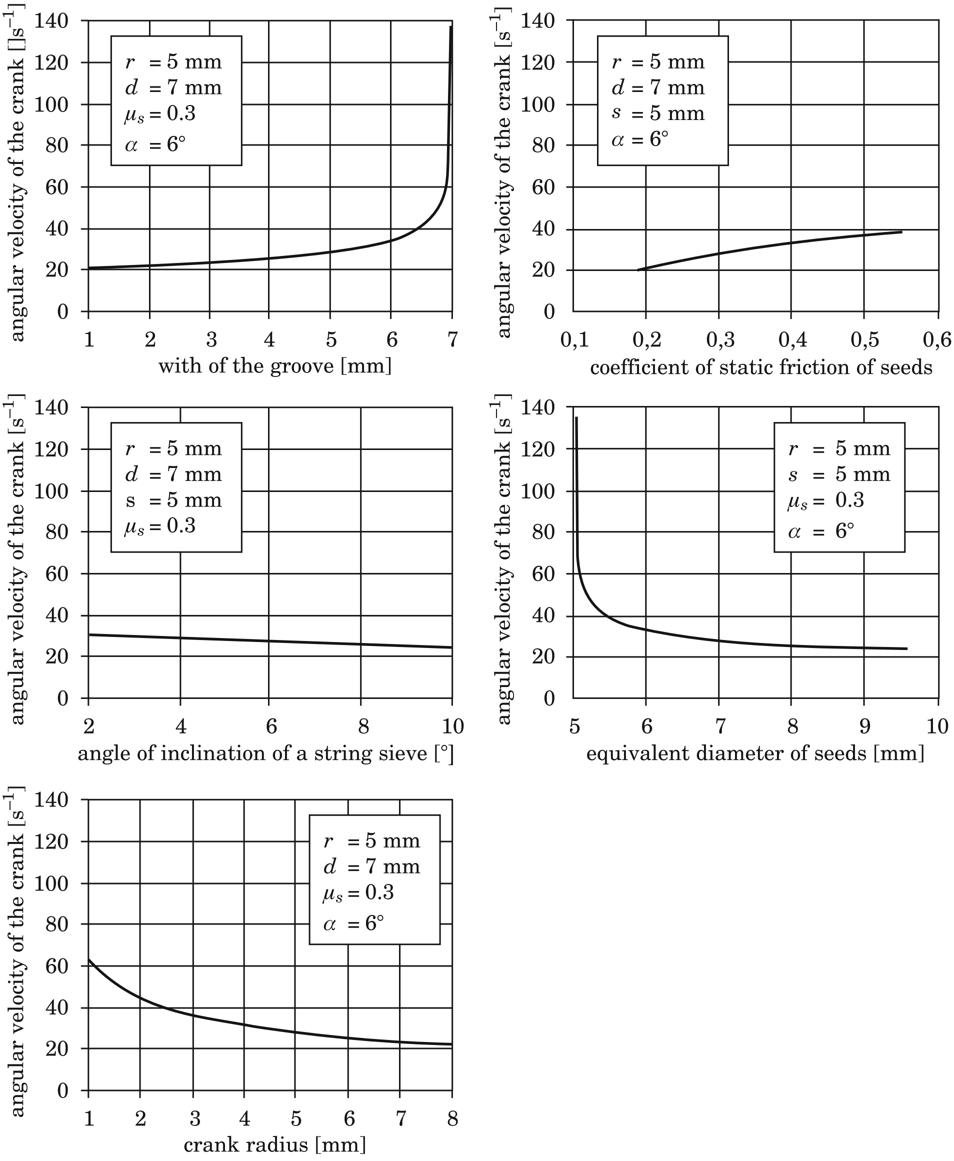

Fig. 3. The correlation between the minimum angular velocity of the crank in a string sieve, structural parameters and seed parameters

increase in normal ground reaction forces, which leads to the formation of powerful frictional forces that counteract seed motion across the screen. The crank radius significantly affects minimum angular velocity which is required to propel seeds into motion. Minimum angular velocity decreases with an increase in radius, and the higher the crank radius, the slower the decrease in angular velocity. According to published data (GROCHOWICZ 1994), the amplitude of bucket deflections should range from 5 to 12 mm, which implies that the crank should have the radius of 2.5 to 6 mm. To initiate the motion of seeds with a high coefficient of friction, the minimum angular velocity should be nearly twice that required for seeds with a low coefficient of friction. In the analyzed range of constant values, the sieve's angle of inclination does not significantly influence the minimum angular velocity of the crank. Minimum angular velocity decreases with an increase in the angle of inclination, and the noted change is nearly linear.

In the final stage of seed movement, i.e. when seeds reach the location where they pass through the screen, the required crank angular velocity increases rapidly. The equation (12) noted in the potential screening sites are presented in Fig. 4. Within the set range of values of the sieve's inclination angle and crank radius, the angular velocity of the crank can be estimated in the range of 83 to 530 s^{-1}. The above velocities significantly exceed the recommended values. According to GROCHOWICZ (1994), the angular velocity of a crank in a string sieve should range from 30 to 63 s^{-1}. Higher velocities can damage the separator bucket. Even the highest angular velocity values given in literature will not guarantee continuous seed motion, therefore the structure

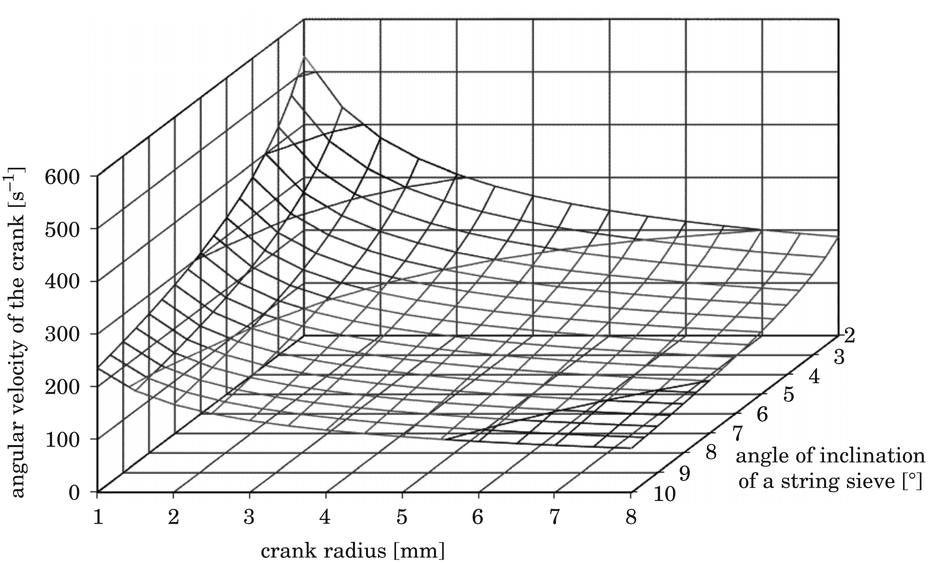

Fig. 4. Diagram illustrating changes in the minimum angular velocity of the crank which enables seeds to pass through the screen, subject to the crank radius and the angle of inclination of the sieve screen

of the string sieve should be modified accordingly. This can be achieved by motion with the use of sweeping brushes, elements that strike the screen or cause it to vibrate, or by equipping the sieve with divergent strings.

Conclusions

The following parameters affect seed movement across the working surface of a string sieve when the separator bucket is set into reciprocating motion: angular velocity of the crank, crank radius, angle of inclination of the separator screen, string diameter, seed size and the seeds' coefficient of external friction. If cereal, vetch, pea, lupine and faba bean seeds are to pass through the screen, the frequency of screen movement has to be significantly higher than that recommended for separator buckets. Thus, the string sieve modeled in this study cannot be used for cleaning and grading of the analyzed seed mixtures because seeds will be jammed between strings even when sieve parameters are set at maximum values within the recommended range. The above problem can be solved by choosing a different transmission system to power the separator bucket, using special brushes to sweep layers of seeds or by equipping the sieve with divergent strings.

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