Bulgarian Journal of Agricultural Science, 13 (2007), 141-149
National Centre for Agrarian Sciences

Resistance of Operating Equipment and Agricultural Machinery during Progressive and Rotary Motion

B. BORISSOV
"Angel Kanchev" University of Rousse, BG-7007 Rousse, Bulgaria

Abstract

BORISSOV, B., 2007. Resistance of Operating Equipment and Agricultural Machinery during Progressive and Rotary Motion *Bulg. J. Agric. Sci.,* 13: 141-149

In the design and development of new operating equipment, machinery and apparatuses for agriculture, the main criterion for their evaluation is their resistance in a working environment, or, their specific energy consumption, respectively. Using the theory of similarity and dimensions we can apply as a general evaluation criterion the resistance R, defined through the equation $R = \Re \rho F v^2$, where $\Re$ is the similarity coefficient, ρ is the density of the environment, F is the characteristic section and v is the speed of movement of the specific equipment or machine, with a specific design in a specific environment. To define the resistance in progressive or rotary motion, the specific design features, the mode of impact and the environment parameters should be taken into consideration. In progressive motion the resistance depends mainly on the speed. It begins to increase considerably at speeds over 5 km.h$^{-1,}$ when the second gear is of extreme importance. With apparatuses using rotary motion it is important to note that the resistance also depends on the square speed. At idle stroke particularly, the excessively high speeds increase significantly the power needed. With fans the main criterion for minimum specific energy consumption can be determined by the specific relations between the power needed, the rotation frequency, the discharge and pressure head.

Key words: similarity, dimension, mass, length, time

Introduction

A considerable amount of energy is used for some essential operations like soil cultivation, harvesting, processing and transporting the agricultural production, etc. That is why it is very important to be well-acquainted with the operating equip-

E-mail: bborisov@ru.acad.bg

ment and machines, which perform these operations, particularly with regard to power and drive, with a view to the improvement of their quality indexes at minimum energy consumption. The improvement should be directed to developing new operating equipment and machinery, under new operating principles and considerably minimized resistance. It is mot enough for a given machine to be just "working" – its complex efficiency should be measured mainly by the energy consumption for performing a specific technological process, which depends predominantly on the resistance of motion of the operating equipment in a particular environment.

Materials and Methods

The agricultural machines work in various environments: soil (hard), water (fluid), air (gaseous) and other substances. Generally, the resistance of a body *R*, during progressive or rotary motion in a given environment depends on the type of environment and its density r, on the speed of motion *v*, on the area of the characteristic (average) body section *F* and its shape, and it can be expressed as an implicit function as follows:

$$R = \varphi\,(\rho, F, v) \qquad (1)$$

According to the dimension theory (Georgiev, 1978) the resistance *R* can be expressed as a power monomial of the type

$$R = \rho^{\alpha} F^{\beta} v^{\gamma} \qquad (2)$$

When you divide the right by the left part, you get the similarity criterion π_b for bodies, which can also be defined as the coefficient $\Re$, i.e.

$$\pi_b = \frac{R}{\rho^{\alpha} F^{\beta} v^{\gamma}} = \Re \qquad (3)$$

In order to obtain the values of the exponents α, β and γ, in such a way that the left and the right part have the same dimensions, according to *Fourier's* rule, it is necessary to equalize the respective symbols *R* to *N* $(kg.m.s^{-2})$, *ñ* to $kg.m^{-3}$, *F* to m^2 and v to $m.s^{-1}$ with their dimensions (Kurdov and Ìihov,1997), expressed through the mass *M*, length *L* and time *T* in the respective power of the equation (2), as follows

$$\left[MLT^{-2}\right] = \left[ML^{-3}\right]^{\alpha} \left[L^{2}\right]^{\beta} \left[LT^{-1}\right]^{\gamma} \qquad (4)$$

Expressing the exponents of the respective dimensions of the two parts of the equation (4) we get the following:

$$M \rightarrow \qquad 1 = \alpha$$

$$L \rightarrow \qquad 1 = -3\alpha + 2\beta + \gamma$$

$$T \rightarrow \qquad -2 = -\gamma$$

And after solving the set, the respective exponent values are determined, namely $\alpha = 1$, $\beta = 1$, and $\gamma = 2$.

Then the similarity (the coefficient $\Re$) criterion π_b from the equation (3) will be

$$\Re = \frac{R}{\rho\ F\ v^2} \qquad \text{or} \qquad R = \Re\ \rho\ F\ v^2 \qquad (5)$$

i.e., the well-known equation of *Newton* for the resistance of a body, moving in a defined environment with a specific speed is obtained. The significance and universality of this equation is great. Generally, it can be applied to the resistance of any body which can move, in any environment, as the similarity coefficient $\Re$ accounts for the shape of the body and its surface, and is the same for similar bodies. More specifically, when the resistance of a given body (operating equipment, machine) has been determined, its specific properties and those of the environment, namely the structure, the type of motion, the speed during the specific motion, etc., should be taken into consideration. It is well-known from practice that the speed v, is of primary importance, which is confirmed theoretically as well, since in the equation (5) it is raised to the second power.

Results and Discussion

Body resistance during progressive motion in the soil

Soil cultivation and more specifically ploughing, performed by different types of ploughs, and shows the biggest energy consumption.

It is known, by *Goryachkin*, that the traction resistance of the plough is the sum of friction and deformation resistance, expressed by *A,*

$$A = fG + kabn \tag{6}$$

and the speed resistance, expressed by *B,*

$$B = \varepsilon \ abn \tag{7}$$

where: $a.b = F$ is the section of the soil layer

f - the friction coefficient;

G - the force of plough weight;

k - the specific soil resistance;

ε - the speed resistance coefficient, depending on the shape of the plough surface and the soil properties;

n - the number of bodies.

Thus,

$$R = A + Bv^2 = A + \varepsilon F v^2 n \tag{8}$$

i.e., apart from the specific structure and the operation of the plough, expressed in the friction and soil deformation, the second member of the resistance has an analogous shape of resistance of a body, moving in a specific environment. Actually, if the resistance A is relatively permanent, then Bv^2 increases rapidly with the increase of the speed v. What's notable here is, that for speeds over 7 km. h^{-1} the ordinary ploughs deteriorate the ploughing quality, so for higher speeds it is advisable to use other structures of ploughing bodies, working with minimum energy consumption, i.e., working at optimum speed for the structure.

For practical approximate calculation for the most commonly used speeds up to 5 km.h^{-1}, for which the speed resistance does not exceed 5% of the complete traction resistance, the following equation is recommended

$$R = k_{pl} \ abn = k_{pl} \ Fn \tag{9}$$

where k_{pl} is the generalized coefficient for a specific plough, taking into account the specific properties of the structure, as well as the conditions of work. That's why this coefficient is not the same and should be determined for each specific case.

It is known that for the operating equipment performing progressive motion in the soil at relatively low speeds, the speed v does not have a significant impact. For cultivators, if the specific resistance q for a unit of width has been calculated, then the total traction resistance R_c depends on the total width B i.e.

$$R_c = q.B \tag{10}$$

It is an interesting case when, with the availability of data for the specific soil resistance k, the coefficient of speed resistance ε, the coefficient of friction f, the speed v, the plough weight G and its traction resistance R, referring to the operation of a specific plough, and provisionally taken as model, and marked by „M" $(k_M, \varepsilon_M, f_M, G_M, R_M)$, the traction resistance R_0 can be determined without any tests, for other conditions (soils), for which k_0, ε_0, $G_0 = G_M$ are known, respectively. According to the theory of similarity, applied to ploughs (Georgiev, 1978), the traction resistance for the same plough, but for the other working conditions, could be determined by the following equation

$$R_0 = R_M \lambda_c - f_M G_M (\lambda_c - 1) \tag{11}$$

where: $f_M G_M = f_0 G_0 = f_0 G_M$ (for one and the same plough);

λ_c - similarity coefficient, $\lambda_c = \dfrac{r_0}{r_M}$ (r - is the traction resistance for a unit section of the layer for an efficient performance of one plough body, namely: $r = \dfrac{R - fG}{ab} = k + \varepsilon\, v^2$,

$r_0 = k_0 + \varepsilon_0 v_0^2$ and

$r_M = k_M + \varepsilon_M v_M^2$) respectively. Generally, $v_0 = v_M$, i.e., the resistance R_0 is determined for one and the same speed.

During progressive motion of machines (units, tractors, self-propelled machines, etc.) the traction resistance is not significantly influenced by the speed v, either, for the most commonly used speeds. The main influence comes from the mass (weight), and then the necessary power P will depend on the speed v as well, i.e.

$$P = \frac{f\,G\,v}{\eta_{tr}\ \eta_{sl}} \tag{12}$$

where: f - is the coefficient of rolling resistance ($f = 0.13$ when moving along a stubble field and $f = 0.08$ - when moving along hard surface roads);

G - the weight of the machine or unit;

η_{tr} - the mechanical efficiency coefficient of the transmission, $\eta_{tr} \approx 0.8$;

η_{sl} - the coefficient of slipping,

$\eta_{sl} = 0.97 \div 1$.

Consequently, the resistance of operating equipment during progressive motion in the soil, and the motion of machines over the soil do not depend on the speed much, but only within the limit of their practical application at this stage of their mass utilization in agriculture.

During progressive motion of operating equipment and machines in heavily humid soil, with changing properties of the environment, the resistance is a complex equation, but it does not depend on the speed v sufficiently, either.

Body resistance during rotary motion

Most of the operating equipment in the agricultural machinery performs rotary motion at specified speeds. Typical representatives of this equipment are rotary cultivators, threshing and cutting machines, specialized fans and extractors, etc. They work in different conditions, but what they have in common is the fact that the power needed * is in strong correlation with the speed.

If the power needed to drive the working organs of the rotary cultivator is expressed as P in *kW*, the diameter as D in *m*, the angle speed as ω in s^{-1}, the soil density as ρ in $kg.m^{-3}$, the productivity as $Q = Bhv_n\rho$ in $kg.s^{-1}$ or in $t.h^{-1}$, then from the similarity theory (Georgiev, 1984), applied to cultivators, the main criterion for the power for cultivators π_{cf} can be obtained

$$\pi_{cf} = \frac{P}{D^2\omega^2 Q} = \frac{P}{D^2\omega^2 Bhv\rho} \qquad (13)$$

from where the specific consumption for a unit of productivity ($kWh.t^{-1}$) will be

$$\frac{P}{Q} = C_1 D^2\omega^2 = C'_1 v^2 \qquad (14)$$

And for a unit of operating width

$$\frac{P}{B} = C_1 D^2\omega^2 hv\rho \qquad (15)$$

Generally, the power needed for a specific cultivator can be determined as follows

$$P = C_1 D^2\omega^2 Bhv\rho \qquad (16)$$

where $C_1 = \pi_{cf}$ is the similarity criterion and is the generalizing coefficient, characteristic for the specific properties of a given type of cultivators and the working conditions.

That's why this coefficient is not the same for all cultivators and should be determined separately for each case.

According to the drum theory (Georgiev and Stanev, 1989), if in the clearance of the threshing machine there is a constant influx of mass Δm for time Δt of blow, it obtains speed v. Thus the motion it gets will be equal to the impulse of the blow force F_1 i.e. (for speed of mass $v_1 = 0$).

$$F_1\Delta t = \Delta m(v - v_1) = \Delta m v \qquad (17)$$

$$F_1 = \frac{\Delta m}{\Delta t} v = m_t v \qquad (18)$$

where $\frac{\Delta m}{\Delta t} = m_t$ is the quantity of mass

* In this case it is more acceptable to use power, while the evaluation of energy needed is done by the specific energy consumption $kWh.t^{-1}$.

for a unit of time (second mass).

If $m_t = Q$ is the productivity of the threshing machine in kg.s[-1], then the power needed P_{sp} for the appropriate speed of the mass v will be

$$P_{sp} = F_1 v = Qv^2 \qquad (19)$$

The power for overcoming the resistances from friction is proportional to the power for threshing P_{tr}, i.e.

$$P_f = f' P_{tr} \qquad (20)$$

where f' is the wear-out coefficient, $f' = 0.7 \div 0.8$

Then, since the threshing power P_{tr} is used to convey the speed to the mass from P_{sp} and power P_f is used to overcome the resistance originating from the movement of the mass, then

$$P_{tr} = P_{sp} + P_f \qquad (21)$$

Consequently $P_{tr} = P_{sp} + f' P_{tr}$, then

$$P_{tr} = \frac{P_{sp}}{1 - f'} = \frac{Qv^2}{1 - f'} \qquad (22)$$

Since every threshing machine has its specific structure, this equation could be valid for every threshing drum with a specified coefficient (Georgiev and Stanev, 1989) $k_d \approx 0.8 \div 1.2$, i.e.

$$P_{tr} = k_d \frac{Qv^2}{(1 - f)} \qquad (23)$$

To determine the total power needed for a specific threshing machine, we must add to P_{tr} the idle stroke power P_i, dependent mainly on the periphery drum speed v and the coefficients A and B, obtained through the formula

$$P_i = Av + Bv^3 \qquad (24)$$

The threshing speed has been technologically determined for the different crops. Its increase or decrease leads to breaking of the grains or not completing the threshing process, respectively.

The power needed for the threshing drum is directly connected with its inertia moment J_d. It should be sufficient, corresponding to the specific productivity of the threshing machine.

Then

$$P_{tr} = J_d \frac{d\omega}{dt} \omega = k_d \frac{Q\,v^2}{1 - f'} \qquad (25)$$

where: J_d is the threshing drum inertia moment;

$\frac{d\omega}{dt} = \varepsilon$ - the angular acceleration.

Thus the inertia moment of the rotary drum will be

$$J_d = k_d \frac{Q\,v^2}{(1 - f')\omega \frac{d\omega}{dt}} \qquad (26)$$

for which, if the drum is connected to the drive of other rotors as well (beaters and other rotary components), the adjusted inertia moment should be used in operation. Each productivity (or that in a given range) requires a specified inertia moment, and we shouldn't use different productivity values for one and the same drum, for example 3 *kg.s*$^{-1}$ and 15 *kg.s*$^{-1}$. What has a significant importance in this case is the drum diameter, which ca be changed within a given range, bearing in mind the fact that it is not only J_d that increases with the increase of diameter, but also the sieving surface of the underdrum (Georgiev, 1984; Georgiev and Stanev, 1989).

For the fodder cutting machines, the power needed can be determined after (Georgiev et al., 1991) from the following equation

$$P = k\ A_c\ Q \tag{27}$$

where: Q is the productivity of the cutter in kg.s^{-1} or t.h^{-1};

k - the coefficient for the structure and the principle of cutting of a given machine;

A_c - the work needed for cutting, *kJ.kg*$^{-1}$, which can be determined after *Melnikov* through the following equation

$$A_c = c(\lambda - 1) \tag{28}$$

where: c is the coefficient characteristic for the specific types of fodder, *kJ.kg*$^{-1}$, as $c = 0.9 \div 1.2$ for straw;

$c = 1.8 \div 2.2$ for hay;

$c = 1.4 \div 1.8$ for grass fodders (Georgiev et al.,1991);

λ - the level of cutting, $\lambda = \frac{L}{l}$ (*L* and l, the respective average lengths of stems before and after cutting).

In this case, like for all rotors in resistance environment, the similarity criterion π_r is applied

$$\pi_r = \frac{P}{QD^2\omega^2} = k_0 \tag{29}$$

$$P = k_0\ Q\ D^2\omega^2 = k'_0\,Q\ v^2 \tag{30}$$

The equation (30) shows that the power needed and the specific energy consumption depend on the periphery speed, which should be technologically sufficient and optimal, that is, the ratio $q = \frac{P}{Q}$ in *kWh.t*$^{-1}$ should be minimal. The idle stroke power, which can be significant when some speeds have been unnecessarily high, is not taken into account, because $P_{i.}$ increases with the third power of the speed v due to the fanning effect, similarly to the threshing drums, according to (24). That's why every cutting machine has to be tested at optimal speed.

Every machine for cutting fodder is characterized with its specific energy consumption q. Since it is the same for a given type of machine, it is convenient to use it for determining the power needed for other conditions of work (another productivity, other types of fodder or different humidity for the same type, which is normal in practice), (Georgiev et al., 1991).

Thus for another productivity

$$P_0 = \frac{P_м}{Q_м} Q_0 \tag{31}$$

For one and the same productivity for the "model" with "M" and the "sample" with "O" $Q_м = Q_0 = Q$, but for a different cutting length, changed from $l_м$ to l_0 (this is applied in practice for different categories of animals), the power needed for the operation of the machine it the conditions accepted as "sample", could be obtained using the equation

$$P_0 = P_м \frac{l_м}{l_0} \qquad (32)$$

And in the general case, the power needed should be determined according to the formula

$$P_0 = Q_0 \left(\frac{P_м}{Q_м} \right) \frac{l_м}{l_0} \qquad (33)$$

For different humidity W_0 (within the range of possible work in practice), by analogy, P_0 will be

$$P_0 = Q_0 \left(\frac{P_м}{Q_м} \right) \frac{100 - W_м}{100 - W_0} \qquad (34)$$

The machines which consume a relatively big amount of power are the fans. Hey are widely applied in agricultural machinery and individually as well. A possible criterion for their usage should be the specific energy consumption in comparison to other appropriate solutions.

If D_2 is the diameter of the working wheel of the fan, Q - the discharge rate, H - the pressure, P - the power needed, n – the rotation frequency, ρ - the air density, then we can write down the functional dependence between the values in a general implicit equation

$$\varphi(D_2, n, \rho, Q, H, P) = 0 \qquad (35)$$

According to the similarity theory (Georgiev, 1984) we can write down the criterion equation

$$\varphi(\pi_1, \pi_2, \pi_3) = 0 \qquad (36)$$

where: $\pi_1 = \frac{Q}{D_2^3 n}$ - discharge criterion,

$\pi_2 = \frac{H}{D_2^2 n^2 \rho}$ - pressure criterion,

$\pi_2 = \frac{P}{D_2^5 n^3 \rho}$ - power criterion.

Depending on what we want to determine, these criteria can be used in the process. Thus when the diameters ($D_c = 1$) and densities ($\rho_c = 1$) are the same, we obtain:

$$Q_0 = Q_м \frac{n_0}{n_м};$$

$$H_0 = H_м \left(\frac{n_0}{n_м} \right)^2; \qquad (37)$$

$$P_0 = P_м \left(\frac{n_0}{n_м} \right)^3$$

For the same rotation frequency (n_c = *1*), the pressure H_0 and power P_0 can be determined by their diameters, by the equation

$$H_0 = H_м \left(\frac{D_{20}}{D_{2м}} \right)^2 ; P_0 = P_м \left(\frac{D_{20}}{D_{2м}} \right)^5 \quad (38)$$

It can be seen from these criteria that the increase of the rotation frequency, and especially of the diameter, leads to a significant increase of pressure, and, particularly of energy consumption. This means that every fan of appropriate structure, should work in such a mode, as to ensure the technological process (grain cleaning, transport, drying, etc.) at minimum technological (optimal) speed. Using the fans (for example in transporting different materials) should be accepted after evaluation of the power, in comparison with other appropriate means.

Conclusion

Designing specific machines or equipment for agriculture, we should take into account the following main criterion when evaluating them: the possibility for providing minimum resistance, or, more specifically, minimum specific energy consumption.

As a summary type of resistance we can offer the equation $R = \Re \rho F v^2$, as in (5). Applying it to the specific cases, for progressive and rotary motion, we should consider the specific features of the structure, the type of impact and the environment.

Thus, for the machines with progressive motion, the resistance starts growing sufficiently by v^2 when the speed is over 5 km.h^{-1}. Even at lower speeds its influence is considerable. The power needed grows by the first power of speed ($P = R\ v$).

For the machinery with rotary motion the power needed depends on the mass processed (the productivity) and the speed square. When the speed is unnecessarily high, the idle stroke power grows considerably.

When designing fans for specific purposes, or choosing well-known structures, changing the mode, etc., we should bear in mind the specific dependences between P, n, H, Q etc. The main criterion here too should be providing a mode with minimum energy consumption.

References

Georgiev, Iv.,1978. Foundations of similarity and modeling of agricultural machinery. *Zemizdad*, Sofia, 247 pp. (Bg).

Georgiev, Iv.,1984. Designing of agricultural machinery. *Rousse University*, 287 pp. (Bg).

Georgiev, Iv. and St. Stanev, 1989. Harvesting machinery. *Zemizdad,* Sofia,123 pp. (Bg).

Georgiev, Iv., K. Vassilev, I. Dochev, B. Borissov, P. Terziev, M. Vassileva, S. Mitev and A. Tachev, 1991. Technologies and sets of machines for harvesting rough fodder. *Rousse University*, 194 pp. (Bg).

Kurdov, Z. and M. Mihov, 1997. Values and units under BDS-ISO applied in agricultural machinery research. *Agricultural machinery,* **1**: 42-48 (Bg).

Received October, 12, 2006; accepted, February, 16, 2007.