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On preventing resonance condition in operation of rotary excavators

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Abstract. The article examines the causes of forced vibrations of the rotor. It was found that the increased tendency of rotary excavators to oscillate is caused by the frequency of scooping, which leads to self- oscillation. Основной причиной возбуждения нежелательных колебаний в роторных экскаваторах является формирование в процессе резания грунта сил отрицательного сопротивления. The frequencies of natural and forced rotor vibrations during the digging of different soils are determined depending on the speed of rotation of the working body and the depth of digging. The dynamic stability of the movement of the working body under the horizontal elastic pliability of the structure is investigated. The condition of occurrence of resonant phenomena during operation of a trench rotary excavator is determined.

1. Introduction

The development of construction industry that has taken place in our country in recent decades has naturally led to an increase in the volume of earthworks and, in particular, an increase in the length of the trenches necessary for laying communications. The most rational technical means of digging trenches, as is known, are specially designed for this purpose trench rotary excavators [1].

To reduce the construction time, the operation modes of such excavators (rotor speed n min^{-1} and linear speed of the whole machine S m/min are usually chosen so as to ensure the maximum possible excavation per unit time. However, this does not exclude the possibility of resonance occurring due to the convergence of the frequency of forced oscillations of the rotor during the digging of the soil with the frequency of natural oscillations of the rotor-boom system.

2. The main part

Consider the causes of forced vibrations of the rotor. The main ones are two: periodic changes in the digging force during the operation of the rotor buckets on the way from their entrance to the digging zone to their exit from it, and changes in the average value of this force when the rotor rotates due to its imbalance [2-5]. The second reason creates oscillations with a rotor speed equal to n and the first one with a frequency equal to the number z_p of its simultaneously working buckets. Figure 1 shows the change in digging force during operation of the rotor with one bucket (a), digging simultaneously with two buckets (b), digging with three buckets at once. From which it is seen that the amplitude of the oscillations of the force with the rotor z_p decreases, and the number of its peak values when the buckets

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pass the digging zone increases. At the same time, the indicated quantity is numerically really equal to z_p.

Let us find the approximate frequency of the forced oscillations of the rotor, taking into account the noted and taking into account that it, as a rule, grows with the increase of soil stiffness [6-9].

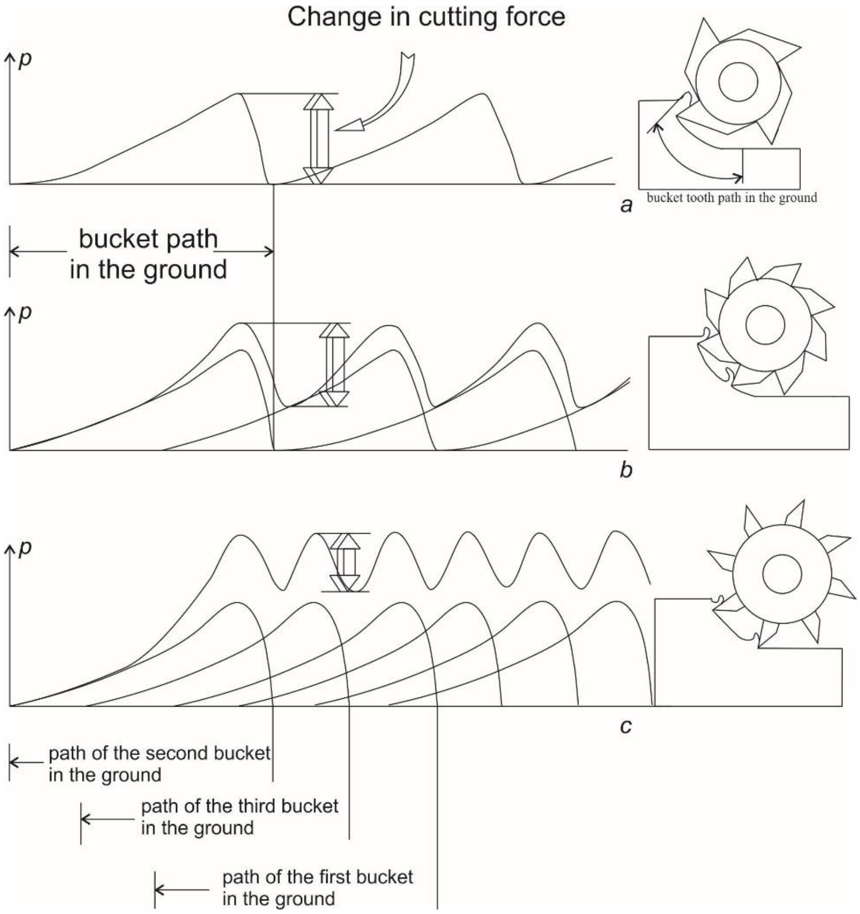

Figure 1. The influence of the number z_p of simultaneously working buckets on the cutting force *P*.

Let us use R. Hartley's theory of information. According to his theory, the amount of information *N* in a certain volume carrying it having *A* states is equal to the logarithm of *A*. If the objects are independent, then the amount of information in the aggregate of their states is the sum of the amounts of information corresponding to all these objects.

It follows that:

$$\log f_в = \log K + \log n + \log z_p, \tag{1}$$

where *K* is a certain indicator characterizing the rigidity of the soil. Potentiate (1) and get f_b in degrees:

$$f_b = \frac{1}{60} K \cdot n \cdot z_p. \tag{2}$$

There are different ways to determine K but it seems to be the easiest way, based on ideas about the analogy of soil stiffness to its shear resistance. The latter, according to the classical Coulomb formula, is

$$\tau = \sigma \cdot tg\varphi + C_0, \tag{3}$$

where σ is the stress in the soil under the action of external force, φ is the angle of internal friction of the soil, C_0 is the adhesion of the soil. The values of density γ, angle of internal friction φ and adhesion C_0 for clay soils of different consistencies are given in table 1 [8].

Table 1. Characteristics of different types of soils.

Consistency (ground conditions)	Clay			Loam			Sandy loam		
	γ, t / m³	φ, deg	C 0, kgf/cm²	γ, t/m³	φ, deg	C 0, kgf/cm²	γ, t/m³	φ, deg	C 0, kgf/cm²
Solid	2.15	22	1.0	2.15	25	0.6	2.05	28	0.20
Semi-solid	2.10	20	0.6	2.1	23	0.4	2.00	26	0.15
Refractory	2.05	18	0.4	2.0	21	0.25	1.95	24	0.10
Soft plastic	1.95	14	0.2	1.9	17	0.15	1.90	20	0.05
Tensile plastic	1.90	8	0.1	1.85	13	0.10	1.85	18	0.02
Flowing	1.80	6	0.05	1.8	10	0.05	1.80	14	0.0

With accuracy sufficient for engineering calculations, it is legitimate to assume that the destruction of the soil during digging begins when

$$\sigma \approx \sigma_{es} \approx \sigma_T \approx \sigma_P, \tag{4}$$

where σ_{es} is the elastic limit of the soil, σ_T is the yield strength, σ_P is the tensile strength. Those, then when

$$\tau = \tau_K = \sigma_T tg\varphi + C_0. \tag{5}$$

The larger τ_K, the stiffer the soil, which means that the indicator *K*, which characterizes the stiffness of the soil, can rightfully be considered a function of τ_K.

With an accuracy sufficient for engineering calculations, σ_T in this case, can be considered equal to the tensile strength σ_P [9]. The values of σ_P for different soils according to the VNIIstroydormash are given in table 2.

Table 2. Strength (conditional instantaneous resistance).

Humidity, %	Strength (conditional instantaneous resistance), MPa, at σ_P tensile at different temperatures		
	- 1 ⁰ C	- 5 ⁰ C	- 10 ⁰ C
	σ_P	σ_P	σ_P
Sand			
5	0.12	0.4	0.59
10	0.32	0.66	0.93
15	0.44	1.01	1.34
18-20	0.62	1.34	1.66
Sandy loam			
5	0.2	0.31	0.49
10	0.62	0.92	1.06

17	0.77	1.52	2.23
	Loam		
20	0.87	1.92	2.09
30	1.23	2.16	2.23
41	1.15	2.26	2.4
70	0.94	1.6	2.06
	Clay		
20	0.55	1.14	2.01
30	0.84	1.55	2.11
48	1.4	2.16	2.5
70	1.17	1.4	2.05

Obviously, the soil of fluid consistency with very small σ_T, φ and C_0, practically does not have rigidity and K can be used for it equal to 1. Putting $\tau_K = \tau_{\min}$ for it, we got $1 = \frac{\tau_K}{\tau_{\min}}$, and for soils of a firmer consistency - $K = \frac{\tau_K}{\tau_{\min}}$. Using the data given in [8], we find $\tau_{\min} = 0.03$ MPa.

As a result, we will have a formula with which you can find K for any soil:

$$K = 33,3(\sigma_T tg\phi + C_0). \tag{6}$$

Substituting (6) into (2), we can calculate $f_{\text{в}}$ for excavators digging trenches in any soil. But for this, it is necessary to determine what is included in (2) z_P.

Let's turn to figure 2. It shows that $\frac{R-t}{R} = \cos\alpha$ or $\alpha = \arccos\frac{R-t}{R}$, where R is the radius of the rotor, t is the depth of the digging trench. With the number of rotor buckets, z this entails

$$z_P = \frac{za}{2\pi} = \frac{z}{2\pi}\arccos\frac{R-t}{R}, \tag{7}$$

and

$$f_b = 33,3n(\sigma_T tg\varphi + C_0)\frac{z}{2\pi}\arccos\frac{R-t}{R}. \tag{8}$$

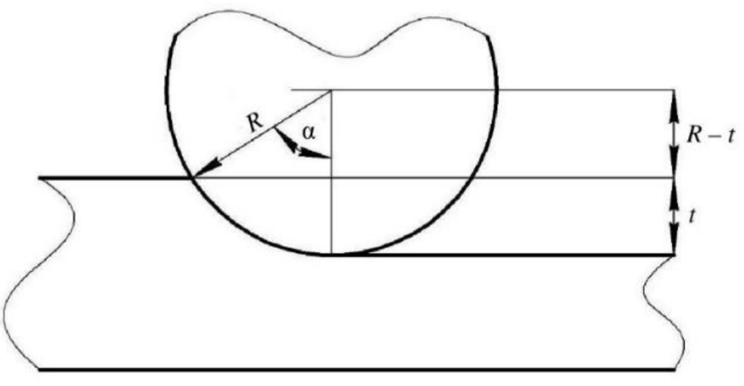

Figure 2. The scheme for calculating the number z_P taking into account the digging depth *t*.

Formula (10) allows us to calculate the frequency of forced oscillations of the rotor at extremely small speeds *S* of the movement of the excavator. It makes it possible to control the value f_b by changing the speed of rotation of the rotor *n* and the digging depth *t*. However, it is well known from practice that at sufficiently high speeds *S*, the frequency of forced oscillations of the rotor can also be controlled by changing the speed of linear movement of the excavator [10-13].

The linear movement of the excavator (figure 3), as it were, “stretches” the zone of interaction of the rotor with the soil, increasing it by a certain amount of *U*. The angle of interaction γ of the rotor buckets with the soil with such an interpretation of the process in question can be considered "containing" some conditional number of simultaneously working buckets, depending on both on the depth of the digging trench *t* and on the speed of the excavator *S*.

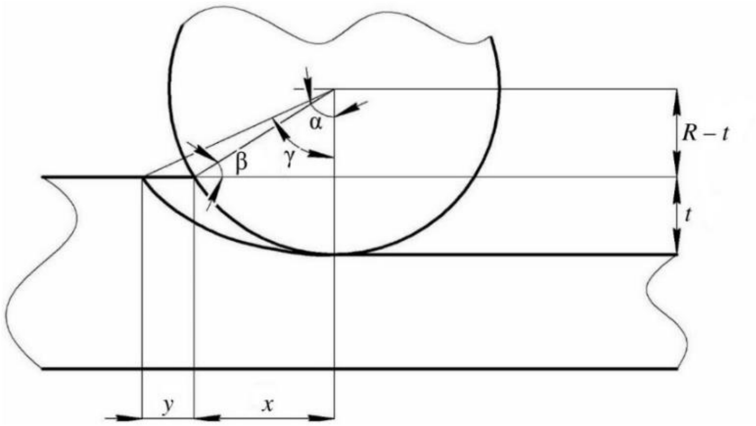

Figure 3. The scheme for calculating the number taking into account the digging depth and giving.

By analogy with figure 2 we have $\frac{X}{R} = \cos\beta$ or $\beta = \frac{\pi}{2} - \arccos\frac{R-t}{R}$. Therefore

$$X = R\cos(\frac{\pi}{2} - \arccos\frac{R-t}{R}), \tag{9}$$

and because

$$\frac{X+Y}{R-t} = tg\gamma, \tag{10}$$

then from (9) and (10), it follows

$$\gamma = arctg\frac{R\cos(\frac{\pi}{2} - \arccos\frac{R-t}{R}) + Y}{R-t}. \tag{11}$$

Set *Y* equal to $\frac{S}{n}$ - the value of the linear movement of the excavator per rotation of the rotor. Then some conditional-calculated z_P can be defined as

$$z_P = \frac{z\gamma}{2\pi} = \frac{z}{2\pi} arctg\frac{R\cos(\frac{\pi}{2} - \arccos\frac{R-t}{R}) + \frac{S}{n}}{R-t}. \tag{12}$$

Substituting (12) in (2), we obtain

$$f_b = 33,3(\sigma_T tg\varphi + C_0)\frac{nz}{2\pi} arctg \frac{R\cos(\frac{\pi}{2} - \arccos\frac{R-t}{R}) + \frac{S}{n}}{R-t}. \quad (13)$$

Formula (13) can be used for an approximate calculation of the frequency of forced vibrations, and its control by changing *t*, *n*, *S* and when digging different soils. However, for a purposeful, rather than a chaotic change in these parameters, you need to know the frequency of natural oscillations f_c of the system "rotor-boom". Unlike the frequency f_b, it can be determined quite simply.

It is known that the frequency of natural vibrations of any mechanical system can be expressed in hertz as $f_c = \frac{1}{2\pi}\sqrt{\frac{g}{m}}$, where *g* is the rigidity of the system, *m* is the mass. The mass of the "rotor-boom" system is $m = m_p + m_c$, where m_p and m_c, respectively, are the mass of elements of this system.

The stiffness of the *g* system is connected by the stiffnesses of the g_p rotor and g_c boom as $\frac{1}{g} = \frac{1}{g_p} + \frac{1}{g_c}$, from $g = \frac{g_p \cdot g_c}{g_p + g_c}$. Thus, in the case under consideration

$$f_c = \frac{1}{2\pi}\sqrt{\frac{g_p + g_c}{(g_p + g_c)(m_p + m_c)}}.$$

3. Conclusion

The frequency calculations f_c and f_b allow to check if resonant phenomena will occur during operation of the trench rotary excavator.

It is believed that the frequency f_b should differ from f_c 20-25%. Given, however, the approximate nature of the calculations, it is advisable to increase this difference to 30-35%. If this condition is not met, then for fixed *t* it is necessary to correct *n* and *S* so that f_b is changed to the desired value.

However, with a relatively small f_b, it is more correct to assume that not the frequencies f_b and f_c themselves should differ by 30-35%, but their ratio $\frac{f_c}{f_b}$ from a certain integer.

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