Method of forming technological parameters in the design of vibrating cone crushers

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Abstract. The paper deals with issues related to expanding the possibility of using a promising direction for improving vibrating cone crushers of secondary and fine crushing. The paper deals with two major issues that need to be solved at designing and creating vibrating cone crushers. First question: the value of the ratio of the crushing force in the standard design of a cone crusher of secondary or fine crushing. The second question is the frequency of forced oscillations of the additional vibration device. The choice of the ratio of the crushing force and the value of the driving force of the vibrator is based on the output of the rational frequency of forced oscillations of the unbalanced vibration device. For the first time in this paper for this type of machine the method of dividing the circular crushing chamber into separate sections is used. Each section is a zone of wave displacement of the compressive stress in the material from the action of the crushing force. The length of the section is considered in the range of the current action of the crushing force, in which the stress in the crushed material changes from zero to maximum and again to zero. This section of the action of the crushing force is an elementary section of the force effect of the crushing force on the material. The paper contains some new terms that are caused by the need to apply a more accurate description of the kinetics of the process. The paper forms new approaches to the process of calculating the parameters of vibrating cone crushers, so it can be considered in the “in order of discussion” format.

1. Introduction

Issues of the state and development of design solutions in the field of design and calculation of vibrating cone crushers are fully covered in [1-9]. These works show a number of technological advantages of using vibrating cone crushers of secondary and fine crushing. Basically, there are three types of vibrating cone crushers: cone crushers of the traditional, classical scheme with additional vibration of the internal movable cone, cone crushers of the traditional, classical scheme with additional vibration of the external stationary cone, cone crushers that use only vibration forces. This paper discusses theoretical and technical problems related to cone crushers of the first type.

In [1], information about the kinetics of the process in classical cone structures is presented, and the features of their design solutions are revealed. Classic design solutions have successfully solved production problems for many years. However, in modern conditions, there is a need for further development of design solutions. The publication contains a large and useful amount of information both for expanding research work in the field of improving crushing equipment, and for use in the
practical application of machines of this type. This paper is an attempt to consider some issues of the problem of calculation and design of vibration crushers, formulated on the basis of the material presented in [1].

2. Materials and methods

Grinding in cone crushers by its nature “lies” in the boundary area between a continuous and cyclic process. This process can be considered both continuous and cyclic [10].

Most often, starting from the classic textbook of M.Ya. Sapozhnikov [11] this process is considered as a continuous process of material output from the output hole of the crusher. At the same time, the process is considered as the output of material in one turn of the eccentric shaft, that is, in one cycle, taking into account the number of cycles per unit of time, for example, in 1 hour.

Based on this approach, it is possible to separate the elementary cycle of force action of crushing cones in the process of grinding material in a cone crusher of secondary or fine crushing, which in time consists of the following components:

\[ T_C = t_1 + t_2 + t_3 + t_4 + t_5 + t_6 + t_7 \]  

(1)

where \( t_1 \) – time of approach of the crushing cone surface to the grain (grains) of the material; \( t_2 \) – the time of the capture material crushing surfaces; \( t_3 \) – time during which fragments and crumbling of weak corners and sections of the lump material occur; \( t_4 \) – capture and increase of compression stress in grains (pieces) of the crushed material; \( t_5 \) – reaching the ultimate strength, or temporary compression resistance, of grains (pieces) of brittle crushed material; \( t_6 \) – formation of cracks and exposure of additional surface, destruction of grains (pieces) of the material and reduction of the size of the pieces; \( t_7 \) – withdrawal of the crushing cone from the crushed material.

The area of active interaction between the crushing cone and the material can in principle be considered as an elementary crushing chamber.

In turn, the components \( t_1 + t_2 + t_3 + t_4 + t_5 \) within the cycle \( T_C \) represent the preparation time of the crushing conditions, \( t_{pcc} \), and can be represented by the expression

\[ t_{pcc} = t_1 + t_2 + t_3 + t_4 + t_5 \]  

(2)

The components of the grinding process that occur within the time \( t_1 \ldots t_5 \) can pass both sequentially and in parallel to each other. However, they meet all the conditions when the state of the ultimate compression stress has not been reached in the main material array yet [11]:

\[ p_{sp} = \sigma_{comp} = E_0 \cdot \varepsilon \leq \left[ \sigma_{comp} \right] \]  

(3)

where \( p_{sp} \) – specific pressure of the crushing cone on the material, N/m²; \( \sigma_{comp} \) – current value of the compression stress in the material, N/m²; \( E_0 \) – modulus of linear deformation of the material, N/m², table value [4]; \( \varepsilon \) – the relative linear deformation during compaction of the material; \( \left[ \sigma_{comp} \right] \) – temporary compression resistance of the source material, N/m².

At the time stage of destruction, grinding and crushing of pieces (grains) of the material, i.e. \( t_{gr} = t_6 \) the expression (3) takes the form:

\[ \sigma_{comp} = E_0 \cdot \varepsilon \geq \left[ \sigma_{comp} \right] \]  

(4)

Finally, at the stage when the mobile cone is removed from the elementary volume of grinding, the stress in the material decreases from \( \sigma_{comp_{max}} \) to 0. Denoting the time of the material unloading stage \( t_{un} = t_7 \), we get the time of the elementary grinding cycle in the crushing chamber of a cone crusher CST or CFT:

\[ T_C = t_{pcc} + t_{gr} + t_{un} \]  

(5)

In [1, p. 75], recommendations are given for “determining the crushing force in the mode of regular running-in of a movable cone over a stationary one” and it is shown that “the ratio between the forces developed by the cone and the unbalance determines the nature of the crusher operation:

\[ N = v_b \cdot F_b + v_c \cdot F_c, \]  

(6)
where $F_b$ and $F_n$ – forces developed by the cone and debalance, respectively; $\nu_b$ and $\nu_c$ – coefficients [1].

It should be noted that this expression allows creating a condition that is close to resonance. Resonance is not so much mechanical, but to the resonance of the process.

The frequency of forced vibrations generated by the unbalance also plays an important role in achieving a condition close to the resonance of the grinding process in a secondary or fine cone crusher.

If the speed of the crushing cone is 246 rpm (CST-1750), or 4.1 swings/s, then the time of one turn of the crushing cone is $T_{C1\ revolution} = 0.244$ s.

However, within the time of one turn, there may be several complete cycles described by the expression (1) or (5). Thus, if they know the time of one elementary cycle, $T_c$, within which the stress increases in the material from 0 to the maximum, grinding and reducing the stress again to 0, then they can determine how many elementary cycles of force action can be contained in one turn of the movable cone, i.e., within the time $T_{C1\ revolution} = 0.244$ s.

The question is important for the process: “What is the frequency and period, $T_c$, of one elementary loading in the limit of the running period, $T_{C1\ revolution} = 0.244$ s?”

We will conditionally set the number of such force actions, $n$, equal to four, namely:

$$n = \frac{T_{C1\ revolution}}{T_c} = 4.0$$ (7)

Then, the time of one elementary loading cycle will be: $T_c = \frac{0.244}{4} = 0.061$ s. At the same time, the beginning of each elementary cycle is shifted relative to the other by $90^\circ$. Moreover, the reference point of the period $T_{C1\ revolution}$ can be taken anywhere in the circle from $360^\circ$. The main condition remains that the period $T_{C1\ revolution}$ and the first elementary period $T_c$ started simultaneously from one common point, for example, p. b.

![Figure 1](image)

**Figure 1.** Scheme of elementary force actions of a moving cone on a material: I, II, III, IV – sequence of sections of elementary force action within a period, cycle, or one rolling of a moving cone; $d_l$ – minimum size of a piece of material; $d_f$ and $d_n$ – intermediate size of a piece of material; $d_{II}$ – the size of the piece entering the grinding zone; $D_{mc}$ – diameter of the movable cone $b$; $D_{fc}$ – diameter of the fixed cone; $e$ – eccentricity; $\sigma_{\text{max}}$ – amplitude of the maximum stress from the crushing force of the movable cone; $\sigma_0$ – minimum stress amplitude in the material; $O$ and $O_1$ – the center of a fixed and movable cone, respectively; $b$-$a$, $c$-$b$, $f$-$c$, $a$-$f$ – areas of elementary force impact of the crushing cone on the material; $\alpha=90^\circ$ – central angle of the elementary force impact area, $\omega$ – angular speed of running-in of a movable cone.
The rolling period of the mobile cone is $T_{\text{C1\_revolution}} = 0.244$ s. The value of the amount of crushing force graphically can be depicted as a traveling wave with some asymmetry on frequency [12, 13], caused by the difference in time flow process consisting of three phases: increased tension ($t_{\text{inc.\_ten.}}$), grinding ($t_{\text{gr.}}$) and the stress relief material ($t_{\text{st.\_rel.}}$): $t_{\text{inc.\_ten.}} > t_{\text{gr.}} \approx t_{\text{st.\_rel.}}$.

The nature of such oscillations, regardless of the magnitude of the crushing force itself, can be represented by the sum of two oscillatory processes with a shift in the initial phases, table 1.

**Table 1.** Initial parameters for obtaining the value of the crushing force within one elementary loading cycle.

| Parameter     | № of oscillatory process |
|---------------|--------------------------|
| Weight (kg)   | 1000                     | 125                     |
| Radius (cm)   | 1.5                      | 1.5                     |
| Init. phase (deg.) | 180                   | 270                     |
| Speed (rpm)   | 246                      | 492                     |
| Ri (m)        | 0.015                    | 0.015                   |
| $\phi_i$ (rad) | 3.14                    | 4.71                    |
| $\omega_i$ (1/s) | 25.76                  | 51.52                   |

Dividing the time of elementary exposure into 20 intervals by $dt = 0.012$ s. We obtain a change in the magnitude of the driving force of the first (F1) and second (F2) oscillations. The total calculated value of the driving force (Sum) forms the change in the crushing force in the area of elementary impact, table 2.

**Table 2.** Calculated values of the total driving force of two vibrators, displaying the form of the crushing force within the limits of the elementary force action.

| №   | $t$     | F1     | F2     | Sum  |
|-----|---------|--------|--------|------|
| 0   | 0.000   | -19.91 | 0.00   | -19.91 |
| 1   | 0.012   | -18.97 | 5.77   | -13.20 |
| 2   | 0.024   | -16.22 | 9.40   | -6.82  |
| 3   | 0.036   | -11.94 | 9.56   | -2.39  |
| 4   | 0.048   | -6.53  | 6.17   | -0.36  |
| 5   | 0.060   | -0.50  | 0.50   | 0.00   |
| 6   | 0.072   | 5.58   | -5.36  | 0.22   |
| 7   | 0.084   | 11.13  | -9.23  | 1.90   |
| 8   | 0.096   | 15.62  | -9.68  | 5.94   |
| 9   | 0.108   | 18.64  | -6.55  | 12.08  |
| 10  | 0.120   | 19.88  | -1.00  | 18.89  |
| 11  | 0.132   | 19.25  | 4.93   | 24.17  |
| 12  | 0.144   | 16.78  | 9.03   | 25.81  |
| 13  | 0.156   | 12.73  | 9.79   | 22.52  |
| 14  | 0.168   | 7.47   | 6.92   | 14.39  |
| 15  | 0.180   | 1.50   | 1.50   | 2.99   |
| 16  | 0.192   | -4.61  | -4.49  | -9.10  |
| 17  | 0.204   | -10.29 | -8.81  | -19.09 |
| 18  | 0.216   | -14.98 | -9.87  | -24.85 |
| 19  | 0.228   | -18.26 | -7.27  | -25.54 |
| 20  | 0.240   | -19.81 | -1.99  | -21.80 |

Max 25.81

Min -25.81
The graph of changes in the size of the crushing force is plotted relative to a certain average line. The crushing force is \(|Max| + |Min| = 51.62\, kN\).

A graphical representation of the change in the crushing force within the limits of an elementary force action is shown in Fig. 2.

![Graph of changes in the crushing force within the time of the elementary cycle of force action.]

**Figure 2.** Graph of changes in the crushing force within the time of the elementary cycle of force action.

The time of the elementary cycle of the power impact of \(T_c\) consists of two components. In the first section: points 20-21-1-13, the material compression stress increases from 0 to the maximum value \(\sigma_{comp} \leq \sigma_{comp}\). The duration of this section is 70% of the time \(T_c\).

At the second time interval, 13-20, which is 30% of the \(T_c\), the compression voltage is reset in the range from \(\sigma_{comp} \geq \sigma_{comp}\) to zero.

This model and the form of changing the crushing force characterize the classic design of a cone crusher without vibration. Within the angle 90°, the rotation of the movable cone, we have a fairly “large section” of time, which is characterized by a “slow” increase in voltage.

The ideas laid down in [1] allow taking advantage of this form and nature of the change in the crushing force. On the “stretched” section of the graph, they can embed additional force from the vibration mechanism.

Such a force effect can be created by a vibrating device with a multiple of the rotation frequency of the unbalanced mechanism in relation to the rotation frequency of the movable cone, table 3.

**Table 3.** Initial parameters for obtaining the value of the crushing force within one elementary loading cycle with a vibrating device.

| Parameter       | № of vibrator |
|-----------------|---------------|
|                 | 1  | 2  | 3  |
| Weight (kg)     | 1000 | 125 | 50 |
| Radius (cm)     | 1.5 | 1.5 | 1.5 |
| Init. phase (deg.) | 180 | 270 | 180 |
| Speed (rpm)     | 246 | 492 | 738 |
| Ri (m)          | 0.015 | 0.015 | 0.015 |
| \(\phi_i\) (rad) | 3.14 | 4.71 | 3.14 |
| \(\omega_i\) (1/s) | 25.76 | 51.52 | 77.28 |

The calculation of the crushing force taking into account the vibrator is shown in table 4. Here \(F_1\) and \(F_2\) represent the crushing force of the cone of the basic cone crusher: \(F_{cr} = F_1 + F_2 = 51.62\, kN\). The value of the driving force of the vibrator \(F_{vib}\) and \(F_{cr}\) form the total force.
Table 4. Calculation of the crushing force taking into account the vibrator.

| №  |  t   | F1   | F2   | F_vibr | Sum   |
|----|------|------|------|--------|-------|
| 0  | 0.000| -19.91| 0.00 | -8.96  | -28.87|
| 1  | 0.012| -18.97| 5.77 | -5.37  | -18.87|
| 2  | 0.024| -16.22| 9.40 | 2.51   | -4.31 |
| 3  | 0.036| -11.94| 9.56 | 8.39   | 6.00  |
| 4  | 0.048| -6.53 | 6.17 | 7.55   | 7.19  |
| 5  | 0.060| -0.50 | 0.50 | 0.67   | 0.67  |
| 6  | 0.072| 5.58  | -5.36| -6.74  | -6.52 |
| 7  | 0.084| 11.13 | -9.23| -8.76  | -6.86 |
| 8  | 0.096| 15.62 | -9.68| -3.77  | 2.17  |
| 9  | 0.108| 18.64 | -6.55| 4.24   | 16.32 |
| 10 | 0.120| 19.88 | -1.00| 8.86   | 27.74 |
| 11 | 0.132| 19.25 | 4.93 | 6.39   | 30.56 |
| 12 | 0.144| 16.78 | 9.03 | -1.19  | 24.62 |
| 13 | 0.156| 12.73 | 9.79 | -7.82  | 14.70 |
| 14 | 0.168| 7.47  | 6.92 | -8.19  | 6.20  |
| 15 | 0.180| 1.50  | 1.50 | -2.01  | 0.99  |
| 16 | 0.192| -4.61 | -4.49| 5.78   | -3.32 |
| 17 | 0.204| -10.29| -8.81| 8.94   | -10.15|
| 18 | 0.216| -14.98| -9.87| 4.95   | -19.90|
| 19 | 0.228| -18.26| -7.27| -3.00  | -28.54|
| 20 | 0.240| -19.81| -1.99| -8.55  | -30.35|
|    | Max  | 30.56 |      |        |       |
|    | Min  | -30.56|      |        |       |

In table 4, in addition to the crushing force, $F_{cr}$ we have the vibration force $F_{vibr}$. Together they form an analog of the expression (6):

$$N = F_{cr} + F_{vibr}$$ (8)

where $F_{cr}$ – crushing force generated by the mobile cone of the crusher on the material, kN; $F_{vibr}$ – the driving force of the vibrating device. In our case,

$$N = |30.56| + |-30.56| = 61.12$$

3. Results and discussion
The graph of changes in the total crushing force is shown in Fig. 3.

Figure 3. Graph of changes in the crushing force within the time of the elementary cycle of force action using a vibration mechanism at $\omega_d = 3 \cdot \omega_e = 738$ rpm.
The increase in the crushing force by the value of the driving force of the vibrator can be 
(0.4...0.5)· \( F_{cr} \) [1]. In this case, the total crushing force is increased by 18.4%.

In addition, during the crushing process, additional force pulses are formed within each elementary force action, which can favorably affect the efficiency of grinding.

The value of the additional vibration force must be determined by calculation. So, when using the frequency ratio: \( \omega_{cr} = 3 \cdot \omega_c = 738 \text{ rpm} \), where \( \omega_{cr} \) and \( \omega_c \) – the angular velocity of rotation of the debalance of the vibrator and the movable cone, respectively, has two pulses within each elementary cycle of force action. Additional impulses of the crushing force are observed in p. 4-5 and p. 12.

If the rotation frequency of the unbalanced mechanism is increased, the picture of the force effect will take a different form. When \( \omega_d = 4 \cdot \omega_c = 984 \text{ rpm} \) the total crushing force increases to 74.8 kN, which is 44.5% of the original. The graph of changes in the total driving force, at the same time, records an increase in the number of additional pulses, Fig. 4.

![Characteristic points of time of the elementary cycle of force action, \( T_c \)](image)

**Figure 4.** Graph of changes in the crushing force within the time of the elementary cycle of force action using a vibration mechanism at \( \omega_d = 4 \cdot \omega_c = 984 \text{ rpm} \).

The use of additional vibration impact on the crushed material is a reasonable means of increasing the speed of the grinding process in cone crushers of secondary and fine crushing significantly. A special feature of this effect is an attempt to create conditions for the process to approach the resonant effect [14,15,16,17,18]. When the effect is close to resonant, the speed of the process can increase not only by several times, but also by orders of magnitude. Attempts to solve such problems are given in [19]. However, solving such problems will require not only additional theoretical research and design development, but also financial support.

4. **Summary**
The use of a vibrating mechanism in the design of secondary and fine cone crushers can significantly increase the speed of the material crushing process in them. The purpose of using vibration mechanisms in the design of cone crushers is to create conditions close to the resonance of the process. An important condition for achieving the required conditions is the choice of a rational ratio between the size of the crushing force of the movable cone and the size of the driving force of the vibrating device. The paper presents the results of theoretical research in the development of methods for designing and calculating rational parameters of certain types of vibrating cone crushers.

5. **References**
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