Analytical study of oscillating horizontal vibrations of a road roller

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Abstract. Horizontal oscillating vibrations of a vibratory road roller are of secondary importance in comparison with vertical vibrations that compact soil and asphalt concrete. The consideration of horizontal vibrations is required for the improvement of the vibratory roller design aimed at reducing the overall accompanying vibration on the vibratory roller and on a human operator, as well as for the calculation of vibration exciter rolling bearings and rubber-metal shock absorbers. Two research tasks of vibratory drum horizontal vibrations on a solid non-deformable base have been solved in the article. The assumption has been made in the first task that there is sliding friction between the cylindrical roller and bearing surface; in the second research task of horizontal vibrations the cylindrical drum rolls over a solid bearing surface without slipping. The mode of horizontal oscillating vibrations differs in phase from the mode of vertical oscillating vibrations by the angle $\phi = 0.5\pi$. When creating vibratory rollers, manufacturing companies strive for increasing the operation efficiency of vibratory rollers at the expense of increasing the centrifugal exciting force while maintaining or reducing the total weight of the vibratory roller. As a result of which the oscillation mode appeared where negative effects of additional loading of rubber-metal shock absorbers were found, connecting the vibratory drum with the roller front frame and increasing the overall vibration of the vibratory roller. Dependences of horizontal travels, speed and acceleration of a vibratory drum have been determined during the road roller forward movement. During one turn of the vibration exciter rotation the forward movement of the drum becomes a non-uniform one, i.e. it takes an oscillating vibrating nature. Rules and recommendations have been developed for the study of sliding conditions, vibratory drum balancing over the bearing surface etc.

Key-words: vibratory drum, vibration exciter, principle of motion of center of mass, horizontal oscillations.

1. Introduction
At present, the production and development of vibratory rollers with smooth rollers are carried out by an enormous number of manufacturing companies that manufacture rollers of different types and sizes for the compaction of soils and materials. At present, vibratory rollers have not yet become a universal facility for the fulfillment of compaction operation, in the course of which it is necessary to use the system of vibratory rollers of different sizes because of the wide variety of properties and specifications of soils and materials. The theory of created structures and specifications of vibratory rollers lags behind the level of the technical development and cannot explain the physical processes of the vibratory drum interaction with the material to be compacted by the analytical method [1–7]. Advertising information relative to the usage of oscillating horizontal vibrations of vibratory rollers in special construction technologies has appeared in technical literature. The article presents the analytical research method of physical processes of oscillating horizontal vibration of the road roller vibratory drum.
2. Problem statement

The study of horizontal oscillating vibrations of a vibratory drum has been fulfilled by means of the laws of mechanics. The main kinematic characteristics of the vibrator drum are determined in the article by means of the principle of motion of center of mass of the mechanical system. The vibration exciter is a source of vertical and horizontal vibrations of the vibratory drum [8, 9, 10]. Amplitudes of horizontal movements, speed and acceleration of the vibratory drum represent the kinematic characteristics. At present time physical phenomena linking the characteristics of a vibratory roller with characteristics of compacted pavements (soil, asphalt, etc.) have not been sufficiently studied. The study of horizontal oscillations on non-deformable surface has been performed for a perfectly smooth surface and perfect drum rolling without slipping.

The real operating conditions of a vibratory drum are within the investigated range. The peculiarity of the study is characterized by a variable vertical reaction, variable friction forces and traction forces of the vibratory drum with bearing surface. Periodic takeoffs of the vibratory drum from the bearing surface represent an additional condition of the vibratory drum operating process. Physical phenomena of horizontal microsliding as well as rolling without slipping in separate phase segments of the operating cycle of the vibration exciter are implemented in each cycle of one rotation period of the vibratory drum.

Phase dependences of the drum normal reaction change taking into account its takeoff from the bearing surface, as well as the phase characteristics of the vibratory drum sliding relative to the bearings surface have been determined.

3. Theory

Figures 1 and 2 show the commencement of the horizontal exciting force formation process to the left from zero to maximum value in case the vibration exciter turns to the angle \( \varphi = 0.5\pi \).

Figures 3 and 4 show the commencement of the formation process and maximum value of the horizontal exciting force, directed to the right. For the kinematic problem solution, a special case of the principle of motion of center of mass of the mechanical system is used. For a drum on a smooth base there are no horizontal external forces, at the same time the excitatory inertial force is considered as an internal force, which is not shown in Figures 1-4.

The dual-mass mechanical system has the center of mass of the vibration exciter \( C_1 \), center of mass of the drum \( C_2 \) and general center of mass \( C \) of the system, which at the beginning of the process at \( t = 0 \) are on the \( z \) axis, at the same time \( \varphi = 0; y_c = 0 \) (Figure 1).

![Diagram of vibratory drum](image)

**Figure 1.** Vibratory drum on a smooth surface: horizontal coordinate of center of mass of the drum \( y_c = 0 \), angle \( \varphi = 0 \).
When the $C_2C_1$ crank of the vibration exciter turns on a smooth bearing surface to the angle $\phi = 0.5\pi$, center of mass of the roller maintains its position at the expense of the shift of centers of mass of the vibration exciter of the point $C_1$ to the left and drum of the point $C_2$ to the right.

For the determination of the amplitude of horizontal travels of the cylindrical drum, let us write the equation of the coordinate of center of mass $y_c$ (Figure 2)

$$y_c = \sum \frac{m_k y_{ck}}{m_k} = \frac{m_1 y_{c1} + m_2 y_{c2}}{m_1 + m_2} = 0. \tag{1}$$

In equation (1) we express the coordinate $y_{c1}$ through the coordinate $y_{c2}$ (see Figure 2)

$$y_{c1} = y_{c2} - r_c, \tag{2}$$

where $y_{c1}$ – horizontal coordinate of the center of mass $C_1$ of the vibration exciter; $y_{c2}$ – horizontal coordinate of the center of mass $C_2$ of the drum; $r_c$ – vibration exciter eccentricity, $C_1C_2 = r_c$.

**Figure 2.** Vibratory drum on a smooth surface: horizontal coordinate of center of mass of the drum $y_{c2\text{max}}$, angle $\phi=0.5\pi$.

**Figure 3.** Vibratory drum on a smooth surface: horizontal coordinate of center of mass of the drum $y_c = 0$, angle $\phi=\pi$.

The numerator of expression (1) is equal to zero.

By means of expression (2) let’s present it in the following form

$$-m_1 r_c + m_1 y_{c2} + m_2 y_{c2} = 0.$$
Figure 4. Vibratory drum on a smooth surface: horizontal coordinate of center of mass of the drum $y_{c2\text{max}}$, angle $\phi=3\pi/4$.

The horizontal shift of the center of mass of the drum (Figure 2) is determined by the formula

$$y_{c2} = \frac{m_1}{m_1 + m_2} r_c .$$

In the general case for any time moment $t$ the horizontal travel of the drum on a smooth base is determined by the formula

$$y_{c2} = \frac{m_1}{m_1 + m_2} r_c \sin \omega t ,$$

where $\omega$ – rotation frequency of the vibration exciter.

Equation (4) allows to write the equation of speed and acceleration of horizontal travels of the center of mass of the drum

$$\dot{y}_{c2} = \frac{m_1}{m_1 + m_2} r_c \omega \cos \omega t .$$

$$\ddot{y}_{c2} = -\frac{m_1}{m_1 + m_2} r_c \omega^2 \sin \omega t .$$

In equation (6) we can distinguish the expression of the exciting horizontal force amplitude

$$P_d = m_1 r_c \omega^2 .$$

The considered operating mode of the vibratory roller when moving on a smooth surface can be identified in some approximation with the asphalt concrete compaction at a high temperature (see Figures 1–4).

4. Results discussion

Table 1 shows the kinematic characteristics of the vibratory drum horizontal vibrations.

Analytical aspects of the theory of the vibratory drum horizontal vibrations are considered. The study results of the horizontal vibrations in the form of movement amplitudes, speed amplitudes and amplitudes of acceleration of center of mass of the drum moving on a smooth surface are very significant (see Table 1).
In technical literature this phenomenon was called as the vibratory roller oscillatory vibrations. At the same time, the article’s authors didn’t succeed to find in the technical literature a scientific justification of the vibratory roller oscillating mode of operation.

Table 1. Kinematic characteristics of the vibratory drum horizontal vibrations when moving on a smooth surface.

| Manufacturer, band   | Weight of vibration exciter, \( m_1 \), kg | Weight of vibratory drum, \( m_2 \), kg | Eccentricity of vibration exciter, \( r_c \), m | Angular speed of vibration exciter rotation, \( \omega \), rad/s | Amplitude of horizontal travels of center of mass of drum, \( A(y_c) \), m | Amplitude of horizontal velocities of center of mass of drum, \( \dot{A}(\dot{y}_c) \), m/s | Amplitude of horizontal accelerations of center of mass of drum, \( \ddot{A}(\ddot{y}_c) \), m/s² |
|----------------------|-------------------------------------------|----------------------------------------|-----------------------------------------------|-------------------------------------------------|------------------------------------------|---------------------------------------------|-----------------------------------------------|
| Sakai SW65H-1        | 15.496                                    | 3600                                   | 0.04693                                       | 307.88                                          | 0.000198                                 | 0.06096                                     | 19.0866                                       |
| Sakai SV900TV        | 95.09                                     | 7850                                   | 0.08314                                       | 175.93                                          | 0.00172                                  | 0.175059                                    | 30.798                                        |
| Raskat RV-15DT       | 105.83                                    | 6500                                   | 0.07985                                       | 188.50                                          | 0.00128                                  | 0.241                                       | 45.457                                        |
| Amkodor 6712B        | 79.356                                    | 5200                                   | 0.0724                                        | 201.06                                          | 0.00110                                  | 0.218                                       | 43.994                                        |

The process of the vibratory drum horizontal vibrations differs in phase from the process of vertical vibrations by the value \( \varphi = 0.5\pi \). That’s why the process of the vibratory drum horizontal oscillation may be considered as independent of the process of vertical oscillations. During some part of the period of one rotation turn of the vibration exciter, vibratory drum moves without slipping, in the other part of the period of one rotation of the vibration exciter the drum is in a balancing position above the bearing surface and, finally, in another part of the period, the drum slips relative to the support surface of the soil or material.

Let us determine the horizontal reaction \( R_y \) acting on the bearing surface and bearing.

The mechanical system (Figure 5) is affected by the gravitational force of the vibration exciter \( m_1g \) and the roller \( m_2g \).

Figure 5. Analytical model of the vibratory drum horizontal vibrations given the case of rolling on non-deformable surface without slipping: \( P_d \) – radial exciting force; \( U \) – drum forward motion speed.
The principle of motion of center of mass in the projection on the y-axis possesses the form of the basic equation of the Newtonian dynamics, where the d’Alembert inertia force $P_d$

$$m\ddot{y}_c = R_y,$$  

(8)

where $m$ – mass of the mechanical system; $\ddot{y}_c$ – projection on the y-axis of the acceleration of the center of mass of the system.

Let’s determine the horizontal coordinate of the center of mass $y_c$ at any time

$$y_c = \sum \frac{m_k y_{ck}}{m} = -\frac{m_1 y_{c1}}{m_1 + m_2} = -\frac{m_1}{m_1 + m_2} r_c \sin \omega t.$$  

(9)

By means of equation (9) we define the horizontal acceleration of the vibration exciter

$$\ddot{y}_c = \frac{m_1}{m_1 + m_2} r_c \omega^2 \sin \omega t.$$  

(10)

By means of equation (8) we define the horizontal exciting force at any time

$$P_{dy} = m_1 r_c \omega^2 \sin \omega t.$$  

(11)

Figure 6 shows the vibratory drum kinematic characteristic for the vibratory roller Sakai SW652-1 with parameters: $m_1 = 9.192$ kg, $m_2 = 3450$ kg, $r_c = 0.042356$ m, angular speed of the vibration exciter rotation $\omega = 420.97$ rad/s (vibration frequency $f = 67$ Hz).

The maximum force $P_{dymax}$ corresponds to the angles $\varphi = \pi/2$ and $\varphi = 3\pi/4$, has a horizontal direction back and forth along the roller’s movement.

Figure 6. Kinematic characteristics of the vibratory drum on an non-deformable bearing surface:

$A(y_c)$ – amplitude of movement of the center of mass; $A(\dot{y}_c)$ – amplitude of the speed of the center of mass; $A(\ddot{y}_c)$ – amplitude of the acceleration of the center of mass.

Table 2 shows the maximum values of the horizontal exciting forces for modern vibratory rollers and values of static friction forces of the vibratory drum on the bearing surface for the coefficient of sliding friction $f_1 = 1.0$.

According to Table 2 it can be seen that the exciting inertia force several times exceeds the drum friction force relative to the bearing surface with the horizontal position of the vibration exciter mass (see Figure 3).

During the vibratory drum forward movement and relative rotation of the vibration exciter around the drum axis, sliding friction force appears at the drum contact with the bearing surface, which depends on the variable reaction force $R_z$ of the bearing surface.
Table 2. Parameters characterizing the horizontal oscillating movements of a vibratory roller.

| Manufacturer, band | Weight of vibration exciter, $m_1$, kg | Weight of vibratory drum, $m_2$, kg | Eccentricity of vibration exciter, $r_c$, m | Angular rotation speed of vibration exciter, $\omega$, rad/s | Horizontal force of vibration exciter, $P_d = m_1 r_c \omega^2$, kN | Static traction force in bearing surface at $f_T = 1$, $F_T = f_T m_2 g$, kN |
|--------------------|-----------------------------------|-----------------------------------|---------------------------------|-----------------|--------------------------|---------------------------------|
| Sakai SW652H-1    | 13.503                            | 3900                              | 0.0463                          | 314.16          | 61.704                   | 38.39                           |
| Sakai SR20M       | 79.028                            | 10000                             | 0.0858                          | 175.93          | 209.90                   | 98.88                           |
| CHTZ VK24.01.03   | 107.255                           | 10000                             | 0.0946                          | 188.5           | 360.52                   | 99.15                           |
| Magistral MC-85   | 36.241                            | 5050                              | 0.0655                          | 251.33          | 149.940                  | 49.90                           |

At the same time the reaction force $R_y$ depends on the periodic vertical exciting force $P_d$ and on the static gravity of the drum. The component of the friction force from the mass of the vibratory drum is determined by the formula

$$F_T = f_T m_2 g,$$

(12)

where $f_T$—coefficient of sliding friction of the roller with the bearing surface, $f_T = 1.0$.

During one turn of the vibration exciter rotation the drum forward movement at some positions of the vibration exciter becomes non-uniform, i.e. takes the oscillating form. In certain positions of the vibration exciter the vibratory drum performs microsliding back and forth. Tangential shear deformations appear in contact of the drum with the bearing surface.

When analyzing the horizontal oscillating vibrations of vibratory rollers, it is proposed to use the following rules and conditions of mechanics.

1. The vibratory drum bearing surface represents a unilateral constraint, that’s why the exciting dynamic force can increase the normal reaction or vice versa ensure the drum takeoff from the bearing surface.
2. The vibratory drum is connected with the front frame of the roller with rubber-metal shock absorbers. The roller front frame of the roller provides an additional vertical load, which has a constant vertical value and it is taken into consideration by the gravity $m_2 g$ together with the vibratory drum gravity.
3. The circular vibration exciter changes the normal bearing reaction of the vibratory drum, as a result of which the friction force between the drum and bearing surface is changed. For angular values of the vibration exciter, when the normal reaction of the vibratory drum is equal to zero, then the entire horizontal active force of the vibration exciter is perceived by rubber-metal shock absorbers.
4. For angular values of the vibration exciter, when the friction force in the drum support exceeds the active horizontal force of the vibration exciter, the drum doesn’t slide relative to the support and rubber-metal shock absorbers are not loaded with additional horizontal force, horizontal reaction $R_y$ in this case is equal to the active horizontal force $R_y = P_d$.
5. For this study the coefficient of sliding friction is assumed to be equal to $f_T = 1.0$. In this case there is possibility to assess the system state in case of other lower values of the sliding friction coefficient.
6. The drum sliding relative to the support takes place under the condition that the friction force in contact is less than the active horizontal force of the vibration exciter. In this case, the difference between the vibration exciter force $P_d$ and friction force in contact is perceived by rubber-metal shock absorbers $F_{d_y}$ as an excess active force.
7. Figure 5 doesn’t show conventionally the connection of the vibratory drum with the front frame by means of rubber-metal shock absorbers. The analysis of oscillating movements can be performed by means of the following equations (Figure 5)
\[ \sum Y_k = 0; \quad R_y + R_f - P_d \sin \omega t = 0. \]  
(13)

\[ \sum Z_k = 0; \quad R_z - m_2 g + P_d \cos \omega t = 0, \]  
(14)

where \( R_f \) – friction force on the vibratory drum bearing surface.

From equation (14) we determine

\[ R_z = m_2 g - P_d \cos \omega t. \]  
(15)

From equation (13) we find

\[ R_y = P_d \sin \omega t - (m_2 g - P_d \cos \omega t)f. \]  
(16)

By means of the submitted rules, the analysis of power characteristics of the vibratory drum interaction with the bearing surface has been performed according to equation (16).

5. Consideration of the results

Figure 7 shows the dependences of the normal reaction \( R_z \) of the drum bearing surface on the angle \( \varphi \) according to equation (15). In zones \( A \) and \( B \) the drum’s takeoff from the support occurs, in this case the reaction \( R_z = 0 \). The maximum value \( R_{z_{\text{max}}} \) appears in the lower position of the vibration exciter, when the friction force also has the maximum value in figure 3.

![Figure 7](image)

**Figure 7.** Dependence of the vertical reaction \( R_z \) of the bearing surface on the angle \( \varphi \) of the vibration exciter for the roller Sakai SW652H-1: \( A, B \) – the angles when the drum’s takeoff occurs from the bearing surface.

Figure 8 represents the diagram of the vibratory drum slides relative to the bearing surface. The values of the force \( F_{ay} \) in rubber-metal shock absorbers are given when the drum slides according to condition 6 of the rules of mechanics.
Figure 8. Dependence of the horizontal force $F_{\phi}$ of the vibratory drum sliding on the rotation angle $\phi$ of the vibration exciter for the roller Sakai SW652H-1.

6. Conclusion

- The analytical method has been developed to analyze the kinematic characteristics of horizontal oscillating vibrations of a vibratory roller in the form of amplitudes of movement, speed and acceleration of the vibratory drum horizontal vibrations.
- The rules and conditions have been developed for the analysis of the vibratory roller performance data of the vibratory roller, taking into account the drum takeoff from the bearing surface during vibration, conditions of the drum sliding under the action of the exciting and friction force. The connection of the sliding forces with the loading mode of rubber-metal shock absorbers has been established.

7. References

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