Dynamics of the System Intended for Destruction of Buildings and Constructions by a Shock Method

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Abstract. The article deals with the dynamics of the system intended for destruction of objects by the shock method. The working organ is a spherical body suspended by a rope on a crane boom. The ball is considered to be absolutely solid. All the potential energy of the ball is converted into kinetic energy before impact. Geometric and energy conditions of interaction are obtained. The boundaries of the parameter region in which the ball touches the wall are presented. The dependences of the normal and tangential velocity before impact on the relative cable length are obtained. In the first stage, the flat rough wall does not deform on impact. The dependence of the dimensionless ball speed of the center of mass and angular velocity after impact on the relative length of the cable are presented. An increase in the dimensionless distance to the wall leads to a decrease in the kinetic energy losses of the ball and an increase in the normal dimensionless shock pulse. The algorithm and graphics allow in the process of developing projects for the demolition of buildings and structures to make a choice of technological parameters that ensure the effective operation of construction equipment.

1. Introduction
Problems arising in the demolition and disposal of buildings, attract the attention of researchers. Hydraulic machines and mechanisms are widely used in the construction, demolition and disposal of buildings [1, 2]. An analysis of the costs of the life cycle of reinforced concrete structures, an estimate of CO₂ emissions over the life cycle of a representative sample of reinforced concrete structures in China were carried out in [3]. Gas CO₂ emissions during the demolition phase are relatively small, making up only 3% -12% of the building life cycle. The impact on the stages of utilization and demolition of buildings of windows, roofing coatings are considered in [4, 5]. The effect on building systems of explosive, ballistic or seismic loads is considered in [6, 7]. Potentially sustainable strategies of waste treatment at the stages of construction, operation and end of life of buildings are given in [8,9]. Mathematical models of planning of waste management of construction and demolition of buildings, disposal of materials in landfills after the expiration of their service life were developed within the framework of studies [10-12].

Special equipment is necessary for the implementation of programs for the demolition of dilapidated and emergency buildings and structures. The use of simple and affordable methods is due to the lack of special equipment in the proper amount. In particular, the destruction of a solid
suspended by a cable on a crane boom is widely used [13]. The mathematical model of interaction of the system of boom-cable-ball-wall is of particular interest in recent years in connection with the use in engineering applications [14].

2. Process schematization (physical model)
The ball is an absolutely solid body with radius $R$; a cable of length $L$ is considered weightless and inextensible. Before starting the process, the cable was located along the beam, as shown in figure 1, and the ball touched her. All potential energy $II$ is converted into the kinetic energy of the ball before the impact. The motion of the ball before hitting the wall is rotational around the axis $Z_O$, conducted through the point of suspension $O$, perpendicular to the plane of the drawing. The flat rough wall at the first stage is not deformed upon impact.

3. Mathematical model
According to the scheme shown in figure 1, the initial height $H$ is calculated by the formula

$$H = \left( L + R - \frac{R}{\cos \alpha} \right) \cdot \left( 1 - \sin \alpha \right) - (L + R) \cdot \left( 1 - \cos \varphi \right); \ \varphi = \arcsin \left( \frac{B - R}{L + R} \right) = \arcsin \left( \frac{b - 1}{l + 1} \right),$$  \hspace{1cm} (1)

where $\alpha$ – the angle of inclination of the boom to the horizon, $\varphi$ – the angle of deviation from the vertical cable before hitting the ball on the wall, $B$ – the distance from the suspension point to the vertical wall, $l = L/R, b = B/R$. $II = mgH, g$ – acceleration of gravity.

The kinetic energy of the sphere is calculated by the formula

$$T = \frac{1}{2} J_{Z_o} \Omega^2 = \frac{1}{2} \left( \frac{2}{5} m R^2 + m (L + R)^2 \right) \Omega^2.$$  \hspace{1cm} (2)

Equating (2) to the potential energy of the sphere in the upper position, we obtain the angular velocity and the velocity module of the center of mass of the ball before impact

$$\Omega = \sqrt{\frac{2 g H}{0.4 R^2 + (L + R)^2}}, \ \ W_1 = \Omega (L + R).$$  \hspace{1cm} (3)

The transverse (normal to the wall) and longitudinal (along the wall) components of the velocity of the center of mass of the ball before impact are calculated by the formulas

$$V_t = \Omega (L + R) \cos \varphi, \ \ U_1 = \Omega (L + R) \sin \varphi .$$  \hspace{1cm} (4)

In the framework of the elementary theory of impact, the problem is reduced to determining the kinematic characteristics of a solid body after hitting a wall. For a completely smooth surface, this
problem is not difficult. Special calculation methods are required for rough wall. It was found that for sufficiently large bodies and relatively small velocities the calculation by the method described below gives a good agreement with the experimental data [15].

Consider the planar problem of the impact of a spherical rigid body on a rough wall. We consider not the impact force. These are the force of gravity and the tension of the cable, as the body during the impact tends to move up along the wall. Choosing the direction of X, Y axes, as in Fig. 2, write down theorems about the change in the amount of motion and kinetic moment during the impact:

\[ m (V - V_1) = N, \quad m (U - U_1) = F, \quad I (\Omega - \Omega_1) = F \cdot R. \tag{5} \]

Here and further \( V_1, U_1, \Omega_1 \) – projections of the velocity of the center of mass on the x, y axis, respectively, and the angular velocity of the sphere before impact; \( V_2, U_2, \Omega_2 \) – the same after impact; \( N, F \) – projections of the interaction force on the normal and tangent to the wall, respectively.

Under the conditions of this problem, the velocities before impact are calculated by formulas

\[ U_1 = \Omega (L + R) \sin \varphi = \Omega (B - R), \quad V_1 = \Omega (L + R) \cos \varphi. \tag{6} \]

If the condition is met (7),

\[ \mu < \psi = \frac{2}{7} \frac{|U_1|}{|V_1|} = \frac{2}{7} \frac{tg \varphi}{1 + k}, \tag{7} \]

the wall is slightly rough, and the velocities after impact are calculated by formulas

\[ U_2 = U_1 + \mu (1 + k) V_1, \quad \Omega_2 = -2.5 \mu (1 + k) V_1 / R, \tag{8} \]

where \( \mu \) is the coefficient of sliding friction during impact, \( k \) is the coefficient of recovery on impact. If the condition (7) is not met, we have the case of a strongly rough wall. During the impact, the sliding stops, the speed after the impact does not depend on \( \mu, k \):

\[ U_2 = 5/7 U_1, \quad \Omega_2 = -5/7 U_1 / r. \tag{9} \]

In all cases considered for the normal component of the velocity is the ratio

\[ V_2 = -k V_1. \tag{10} \]

Let’s move from dimensional parameters to dimensionless

\[ v = \frac{V}{V_0}; \quad u = \frac{U}{V_0}; \quad \omega = \frac{\Omega}{V_0 R}; \quad V_0 = \sqrt{g \cdot R}. \tag{11} \]

From (1) we obtain dimensionless height and angular velocity

\[ h = \left( l + 1 - \frac{1}{\cos \alpha} \right) \cdot (1 - \sin \alpha) - (l + 1) \cdot (1 - \cos \varphi), \quad \omega_1 = \left( \frac{2 \cdot h}{0.4 + (l + 1)^2} \right)^{1/2}. \tag{12} \]

For slightly rough walls of the dimensionless speed ratio performed

\[ u_2 = u_1 + \mu (1 + k) v_1, \quad \omega_2 = -2.5 \mu (1 + k) v_1. \tag{13} \]

For a strongly rough wall, dimensionless velocities are determined by formulas

\[ u_2 = \omega_1 \cdot \left( \frac{5}{7} p - 1 \right), \quad \omega_2 = \omega_1 \left( 1 - \frac{5}{7} p \right). \tag{14} \]

4. Mathematical model analysis

From the second formula (1) and inequality follows a geometric condition for the implementation of the interaction. From the first formula (1) we obtain the energy condition of interaction \( h > 0 \). For figure 3 the boundaries of the parameter area at which the wall will touch (\( h = 0 \)) are presented. The interaction area lies below and to the right of the corresponding boundary. For example, if \( \alpha = 50^\circ \) (line 3 in figure 3), then at \( b=4, l=4 \) the interaction of the ball with the wall will not occur, and at \( b=4, l=5 \) will occur.

For figure 4 the dependences of the normal and tangential velocity before impact on the relative length of the cable at \( \alpha = 50^\circ \) are presented. The mathematical model shows which combinations of dimensionless quantities \( l \) and \( b \) are physically feasible for the scheme under study. For example, if the
distance B = 5R (b = 5), the length of the cable should exceed the radius of the ball more than 6 times. Otherwise, the collision with the wall will not occur.

**Figure 3.** The border region of parameters for h = 0 (the wall touching it): 1 ⨯ α = 30°; 2 ⨯ α = 40°; 3 ⨯ α = 50°; 4 ⨯ α = 60°

**Figure 4.** The dependence of the dimensionless velocity of the center of mass of the ball before impact on the relative length of the cable at α = 50°: 1 ⨯ b = 3; 2 ⨯ b = 5; 3 ⨯ b = 7; 4 ⨯ b = 9. a - normal speed; c - tangential speed.

For figure 5 shows calculated at α=50° by the second formula (1) the angles of incidence of the ball on a flat wall φ and calculated by the formula (7) the roughness parameter ψ. When this is possible combination of parameters l and b, in which the interaction of the ball with the wall is energetically impossible. It can be seen that under these conditions, the angles of incidence are noticeably less than 40 degrees, and the parameter ψ is less than the sliding friction coefficient µ=0.15. So, the impact mode is implemented much rough wall. Calculations should be carried out according to the formulas (14), as in figure 6.

**Figure 5.** Interaction of a ball with a flat wall at α=50°; k =0.7; 1 ⨯ b = 3; 2 ⨯ b = 5; 3 ⨯ b = 7; 4 ⨯ b = 9. a – angle of incidence; c – roughness parameter
5. Analysis of the results and conclusions
The dependence of the loss of specific kinetic energy of the ball at impact and the dimensionless normal shock pulse from the relative length of the cable. With growth l both characteristics increase. An increase in the dimensionless distance to the wall b leads to a decrease in the loss of the kinetic energy of the ball and an increase in the normal dimensionless shock pulse.

The algorithm (1)-(14) and the graphs in figures 3-6 allow in the course of development of projects on demolition of buildings and constructions to make the choice of parameters of the arrow, the rope, the sphere providing the most effective work of the crane or the excavator at destruction of construction objects.

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Figure 6. Dimensionless speed after impact at $\alpha=50^\circ$; $k =0,7$: $1 - b = 3$; $2 - b = 5$; $3 - b = 7$; $4 - b = 9$. a – the speed of the center of mass; c – angular velocity.
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