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Study of simultaneous collisions in agricultural machinery and technology

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Abstract. The paper discusses the process of solid body collisions involving simultaneous multi-point contact, which often occurs in agricultural machinery and related technologies. An analytical method is being developed to study such multiple-impact events, which can be applied to dynamic analyses of various high-speed production equipment and technological processes. The method is grounded in the fundamental laws of mechanics and limitations of object motion, utilizing an integral approach to determine impact parameters. Key examples illustrate the application of the proposed method to translational motion, and an analytical approach is presented for determining the rebound velocity of an object subjected to simultaneous impacts at multiple points. This approach requires prior knowledge of the pre-collision velocity, momentum restitution coefficients, and local linear elasticity coefficients at the points of contact. It also demonstrates how impact duration and average impact force can be estimated using local stiffness values and the object's mass. In cases involving rotational motion with straight thrust pulses at specified points, the rebound angular velocity is derived as a function of the initial angular velocity and the restitution coefficients. It is noted that the analysis remains applicable regardless of the number of collision points.

Key words: agricultural technologies, collision, impact, impulse, restitution, solid body.

INTRODUCTION

Agricultural machinery and technologies play a vital role in the agricultural sector. In this context, increasing productivity is closely linked to the development of high-speed robotic systems and harvesting equipment (Al-Gezawe et al., 2023; Abo-Habaga et al., 2024a; Abo-Habaga et al., 2024b). As a result, collisions involving actuators become inevitable, making their analysis an essential task. Mechanical collision interactions between objects are common across a wide range of applications in engineering, technology, and everyday life. These collisions are characterized by strong repulsive forces during close contact, which significantly exceed typical long-range forces such as gravity, elastic (spring) forces, and air-water interactions. Such forces can be effectively utilized in high-speed, compact systems, providing substantial interaction effects with minimal mass and size, where force magnitudes can increase by hundreds or even thousands of times (Meriam et al., 2016).

The coefficient of restitution is a fundamental particle property essential for setting up discrete element modeling. Hastie (2013) presented an experimental method for determining the coefficient of restitution using high-speed video in a three-dimensional environment to capture the random behavior of irregularly shaped polyethylene pellets. The angular displacement and angular velocity of the particles are measured experimentally, and the process for calculating the coefficient of restitution using various equations is outlined.

A simple method for measuring the recovery coefficient of gravel was proposed based on the coefficient of restitution and the principles of kinematics (Chen et al., 2018). In this study, the recovery coefficient between gravel and slate was determined experimentally. The results were then compared with simulation data from EDEM software. Müller & Huang (2016) investigated coefficient of restitution for wet particles, but Zhang et al. (2011) conducted field tests and numerical calculations to determine restitution coefficients in rockfall collisions.

Numerous experimental studies have been conducted to determine restitution coefficients in collisions between various types of fruits and vegetables in agriculture. For example, Fu et al. (2022) studied apple-to-apple collisions, Feng et al. (2017) analyzed potato tuber collisions, but Huang et al. (2014), Lu et al. (2016), Horabik et al. (2017) and Liu et al. (2020) investigated collisions between different kinds of seeds and nuts. As a result, innovative platforms were developed to conduct and simulate these collisions.

The issue of tuber damage during the potato harvesting process, resulting from impacts with the mechanical components of the machine, was examined by Bentini et al. (2006). Similar experiments related to potato cultivation were conducted in the Po region of Italy (Deng et al., 2021). To investigate the collision characteristics of potatoes striking steel bars with varying parameters, the finite element analysis (FEA) method was employed to study impact contact stress, collision displacement, acceleration, and impact force (Du et al., 2019). Potato tubers are subjected to dynamic loads during harvesting and post-harvest operations, often leading to mechanical damage. The dynamic response of tubers following impacts from different drop heights (200, 400, and 600 mm) onto a rigid potato plate was analyzed using FEA by Gao et al. (2018). The relationship between the bruised area of pear fruits and drop height, including experimental comparisons with a finite element model, is discussed in the paper by Yousefi et al. (2016).

The literature review conducted shows that analytical formulas for modeling object collisions have primarily been developed for single-point interactions. However, some studies have also explored collisions occurring at multiple contact points (Viba & Polukoshko, 2004; Dal Pont & Dimnet, 2006; Kovals et al., 2016; Dragna et al., 2021). In these cases, impact impulses and resulting linear or angular velocities are typically calculated either analytically or through computer simulations. However, aspects such as collision duration and interaction forces are rarely addressed in detail.

The aim of this study is to develop a new analytical method for investigating simultaneous collisions in agricultural machinery and technologies using integral equations of collision forces. To achieve this goal, the following objectives have been defined:

- Develop a new analytical method for calculating simultaneous multi-point collisions in translational motion;
- Extend the method to solve the problem of simultaneous multi-point collisions in rotational motion;
- Validate the proposed methods through a numerical example.

This paper demonstrates how, by applying the laws of classical mechanics and the elastic forces of close interactions, it is possible to approximate the forces and impact time in object collisions. Special additional collision rules will be applied to limit the movement of objects, which may involve translation and rotation around a fixed axis.

METHOD OF ANALYSIS OF MULTIPOINT COLLISIONS IN THE RECTILINEAR TRANSLATIONAL MOTION OF A SOLID BODY

The model of multipoint collision in rectilinear translational motion of solid body is shown in Fig. 1. The figure illustrates a solid body with an initial velocity V_0 colliding with five stops, generating local impulses S_1, S_2, and S_5 during the collision. The system also imposes an additional constraint on movement in the perpendicular direction, where shock impulses S_6, S_7, S_8, and S_9 occur. For the purpose of the analysis, it is assumed that there are no dry friction forces in the perpendicular guides of the collision system. Therefore, the transverse collision points $k = 1-5$ can be located at varying distances y_k (Fig. 1).

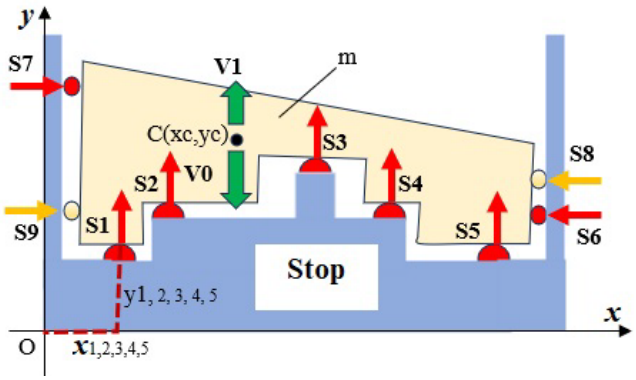

Figure 1. The model of multipoint collision in rectilinear translational motion of solid body.

The imaginary graph of the normal collision forces $P_k(t)$ at all stops ($k = 1-9$) as a function of time t is shown in Fig. 2, where τ_1 and τ_2 represent the times of the first and second phases of the shocks, respectively (Viba & Polukoshko, 2004; Kovals et al., 2016).

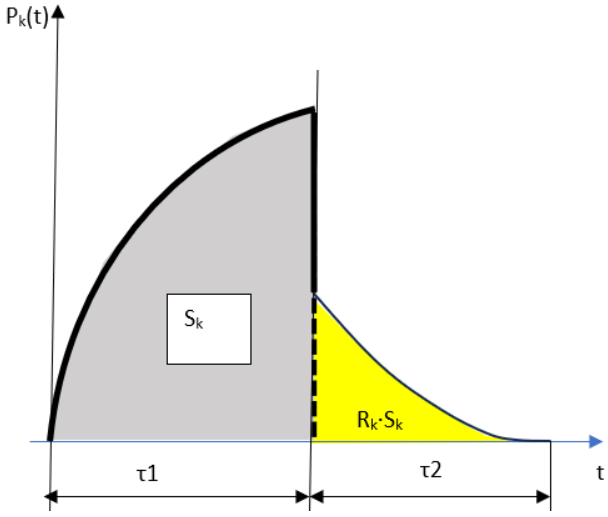

Figure 2. Normal collision forces $P_k(t)$ at all stops ($k = 1-9$) as a function of time t.

Mathematical model

In collision theory (e.g., Kovals et al., 2016), which utilizes the recovery coefficients of shock impulses R_k, the following relation holds at all collision points:

$$S_k^{(2)} = R_k \cdot S_k^{(1)}, \quad (1)$$

where $S_k^{(1)}$ – the impulse of the first phase of the shock; $S_k^{(2)}$ – the impulse of the second phase of the shock; R_k – the impulse recovery coefficient.

Based on the hypothesis that collisions at all points start simultaneously ($t = 0$) and end simultaneously ($t = \tau_1 + \tau_2$), and considering equation (1), the following two equations can be derived in integral form (Meriam et al., 2016):

$$0 - (-mV_0) = S_1 + S_2 + S_3 + S_4 + S_5; \quad (2)$$

$$mV_1 - 0 = R_1 \cdot S_1 + R_2 \cdot S_2 + R_3 \cdot S_3 + R_4 \cdot S_4 + R_5 \cdot S_5, \quad (3)$$

where V_0 and V_1 are the projections of the velocities of the center of mass of the body on the y-axis, and m represents the mass but the k indices are omitted for simplicity. In equations (2) and (3), there are six unknowns: the velocity V_1 and the five impulses of the first phase S_1, S_2, S_3, S_4, and S_5.

To solve this problem, a new hypothesis is introduced, establishing a relationship between the shock impulses in the first phase of the collision as follows:

$$S_2 = \frac{c_2}{c_1} \cdot S_1;\ S_3 = \frac{c_3}{c_1} \cdot S_1;\ S_4 = \frac{c_4}{c_1} \cdot S_1;\ S_5 = \frac{c_5}{c_1} \cdot S_1, \quad (4)$$

where c_1, c_2, c_3, c_4 and c_5 are the linearized stiffnesses of the collision contact points. Using Eqs (2)–(4), the following analytical expressions are derived for determining the bounce velocity V_1 and the impulses S_1, S_2, S_3, S_4, and S_5:

$$V_1 = \frac{V_0 \cdot (R_1 \cdot c_1 + R_2 \cdot c_2 + R_3 \cdot c_3 + R_4 \cdot c_4 + R_5 \cdot c_5)}{c_1 + c_2 + c_3 + c_4 + c_5};$$

$$S_1 = \frac{V_0 \cdot c_1 \cdot m}{c_1 + c_2 + c_3 + c_4 + c_5};$$

$$S_2 = \frac{V_0 \cdot c_2 \cdot m}{c_1 + c_2 + c_3 + c_4 + c_5};$$

$$S_3 = \frac{V_0 \cdot c_3 \cdot m}{c_1 + c_2 + c_3 + c_4 + c_5}; \quad (5)$$

$$S_4 = \frac{V_0 \cdot c_4 \cdot m}{c_1 + c_2 + c_3 + c_4 + c_5};$$

$$S_5 = \frac{V_0 \cdot c_5 \cdot m}{c_1 + c_2 + c_3 + c_4 + c_5}.$$

Analytical formulas (5) can be used in solving various tasks of analysis, synthesis and parametric optimization.

It is worth noting that the hypothesis of impulse calculations, using the linearized stiffnesses (c_1, c_2, c_3, c_4 and c_5), also provides an approximate estimation of impact time. To illustrate this, a numerical example of piecewise nearly harmonic force functions in the impact process is presented below.

Numerical example and discussion

Consider the case where the force of the first stop, $P_1(t)$, is harmonic and undamped during the first stage of collision ($t = 0 – \tau_1$). In the second stage ($t = \tau_1–(\tau_1+\tau_2)$), it takes the form of damped linear oscillations, as expressed in the following equation:

$$P_1(t) = P_0 \sin(pt) \cdot \left[0.5 - 0.5 \cdot \operatorname{sign}\left(t - \frac{2\pi}{4p}\right)\right] + \\ + \left\{P_0 \sin\left(\frac{2\pi}{4}\right) - \left[\frac{P_0}{K_1} \cdot \sin\left(\frac{2\pi}{4}\right)\right] \cdot \left[1 - e^{\frac{-\left(t-\frac{2\pi}{4p}\right)}{q}}\right] \cdot \sin(pt)\right\} \cdot \\ \cdot (0.5 + 0.5 \cdot \operatorname{sign}(t - \frac{2\pi}{4p})) , \tag{6}$$

where $p = \sqrt{\frac{c_1+c_2+c_3+c_4+c_5}{m}}$ and P_0, K_1, q are constants. Accordingly, the other interaction forces, $P_k(t)$, can be expressed in terms of $P_1(t)$ and the elasticities c_1, c_2, c_3, c_4, and c_5 as follows:

$$P_2(t) = P_1(t) \cdot \frac{c_2}{c_1} \cdot \left[0.5 - 0.5 \cdot \operatorname{sign}\left(t - \frac{2\pi}{4p}\right)\right] + \\ + P_1(t) \cdot K_2 \cdot \frac{c_2}{c_1} \cdot \left[0.5 + 0.5 \cdot \operatorname{sign}\left(t - \frac{2\pi}{4p}\right)\right]; \tag{7}$$

$$P_3(t) = P_1(t) \cdot \frac{c_3}{c_1} \cdot \left[0.5 - 0.5 \cdot \operatorname{sign}\left(t - \frac{2\pi}{4p}\right)\right] + \\ + P_1(t) \cdot K_3 \cdot \frac{c_3}{c_1} \cdot \left[0.5 + 0.5 \cdot \operatorname{sign}\left(t - \frac{2\pi}{4p}\right)\right]; \tag{8}$$

$$P_4(t) = P_1(t) \cdot \frac{c_4}{c_1} \cdot \left[0.5 - 0.5 \cdot \operatorname{sign}\left(t - \frac{2\pi}{4p}\right)\right] + \\ + P_1(t) \cdot K_4 \cdot \frac{c_4}{c_1} \cdot \left[0.5 + 0.5 \cdot \operatorname{sign}\left(t - \frac{2\pi}{4p}\right)\right]; \tag{9}$$

$$P_5(t) = P_1(t) \cdot \frac{c_5}{c_1} \cdot \left[0.5 - 0.5 \cdot \operatorname{sign}\left(t - \frac{2\pi}{4p}\right)\right] + \\ + P_1(t) \cdot K_5 \cdot \frac{c_5}{c_1} \cdot \left[0.5 + 0.5 \cdot \operatorname{sign}\left(t - \frac{2\pi}{4p}\right)\right]. \tag{10}$$

For this piecewise linearized approximation, examples of force graphs by Eqs (6)–(10) are shown in Fig. 3, with the system parameters as follows: m = 10 kg; c_1 = 100000 N m^{-1}; $c_2 = c_1 \cdot 1.3^{-1}$; $c_3 = c_1 \cdot 1.3^{-1}$; $c_4 = c_1 \cdot 1{,}4^{-1}$; $c_5 = c_1 \cdot 1.5^{-1}$; p = 199.587 rad s^{-1}; K_1 = 0.5; K_2 = 0.45; K_3 = 0.3; K_4 = 0.2; K_5 = 0.5; k = 0.01.

The following practical conclusions can be drawn from the resulting force graphs (Fig. 3):

- The developed methodology enables the determination of impact duration and maximum forces at contact points.
- For the given local stiffness values c_1, c_2, c_3, c_4, and c_5, the first phase of impact lasts approximately 0.0075 s, while the total impact duration is around 0.015 s.
- The maximum impact force, such as at the first stop with stiffness c_1, reaches approximately 10,000 N at the end of the first phase.
- For the system parameters given above, the graph of the sum pulse of total force $P(t) = \sum P_k(t)$ as a function of time t is shown in Fig. 4.

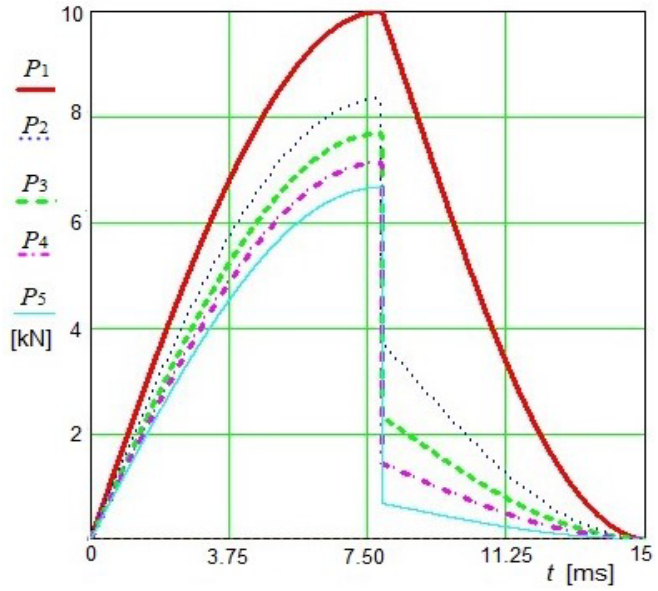

Figure 3. Plots of interaction forces $P_k(t)$ as functions of time t.

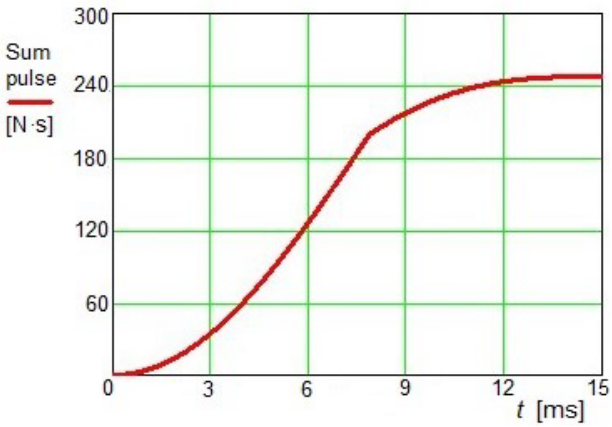

Figure 4. The sum pulse of total force $P(t) = \sum P_k(t)$ as a function of time t.

The following practical conclusions can be drawn from the obtained graph for resulting force pulse (Fig. 4):

- The sum impulse of the total impact force $P(t) = \sum P_k(t)$ at the five contact points at the end of the first phase is 200 N s.
- The total impulse of the impact during the recovery phase is 250 – 200 = 50 N s.
- The total shock impulse recovery coefficient is $R = 50 \cdot 200^{-1} = 0.25$.

This example serves as a numerical validation of the proposed method. It demonstrates how the impact time and average impact force can be estimated using local stiffness values and the object's mass.

ROTATION AROUND A FIXED AXIS

The considered model corresponds to the case of a simultaneous collision at four points, with normal impulses S_1, S_2, S_3, S_4, at which reaction force components X_0 and Y_0 are formed on the axis of rotation (Fig. 5).

Here, by applying the moment of momentum equation about the Oz axis of rotation, the following equations are obtained:

$$t_1 = \tau_1: \quad 0 - (J_0 \cdot \omega_0) = -S_1 \cdot L_1 - S_2 \cdot L_2 - S_3 \cdot L_3 - S_4 \cdot L_4; \tag{11}$$

$$t_2 = \tau_1 + \tau_2: (J_0 \cdot \omega_1) - 0 = -S_1 \cdot R_1 \cdot L_1 - S_2 \cdot R_2 \cdot L_2 - S_3 \cdot R_3 \cdot L_3 - S_4 \cdot R_4 \cdot L_4, \tag{12}$$

where J_0 is the axial moment of inertia about the axis of rotation; ω_0 is the pre-collision angular velocity; ω_1 is the angular velocity after the collision; L_1, L_2, L_3, L_4 are the distances from the collision points to the axis of rotation; R_1, R_2, R_3, R_4 are the impulse recovery coefficients; t_1 is the end time of the first phase of the collision; t_2 is the end time of the collision.

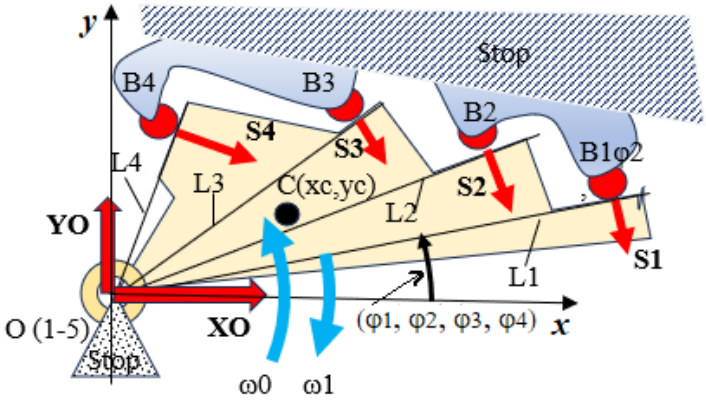

Figure 5. Model of simultaneous straight shocks during rotation around a fixed axis.

Like the translational collision, here the hypothesis that the collision forces are proportional to the stiffness at the impact points is also applied:

$$S_2 = \frac{c_2}{c_1} \cdot S_1 \cdot \frac{L_2}{L_1}; \; S_3 = \frac{c_3}{c_1} \cdot S_1 \cdot \frac{L_3}{L_1}; \; S_4 = \frac{c_4}{c_1} \cdot S_1 \cdot \frac{L_4}{L_1}. \tag{13}$$

From Eqs (11)–(13), all the unknown quantities can be found in the following form:

$$\omega_1 = \frac{\omega_0 \cdot (R_1 \cdot c_1 \cdot L_1^2 + R_2 \cdot c_2 \cdot L_2^2 + R_3 \cdot c_3 \cdot L_3^2 + R_4 \cdot c_4 \cdot L_4^2)}{c_1 \cdot L_1^2 + c_2 \cdot L_2^2 + c_3 \cdot L_3^2 + c_4 \cdot L_4^2}; \tag{14}$$

$$S_1 = \frac{\omega_0 \cdot J_0 \cdot L_1 \cdot c_1}{c_1 \cdot L_1^2 + c_2 \cdot L_2^2 + c_3 \cdot L_3^2 + c_4 \cdot L_4^2}; \tag{15}$$

$$S_2 = \frac{\omega_0 \cdot J_0 \cdot L_2 \cdot c_2}{c_1 \cdot L_1^2 + c_2 \cdot L_2^2 + c_3 \cdot L_3^2 + c_4 \cdot L_4^2}; \tag{16}$$

$$S_3 = \frac{\omega_0 \cdot J_0 \cdot L_3 \cdot c_3}{c_1 \cdot L_1^2 + c_2 \cdot L_2^2 + c_3 \cdot L_3^2 + c_4 \cdot L_4^2}; \tag{17}$$

$$S_4 = \frac{\omega_0 \cdot J_0 \cdot L_4 \cdot c_4}{c_1 \cdot L_1^2 + c_2 \cdot L_2^2 + c_3 \cdot L_3^2 + c_4 \cdot L_4^2}. \tag{18}$$

Based on the analytical formulas (14–18) derived, various problems involving simultaneous multi-point collisions in rotational motion can be addressed. Specifically, the following conclusions can be drawn:

- By applying the hypothesis of linearized stiffnesses, along with the distances of the impact points to the axis of rotation and the impulse recovery coefficients, all impact impulses at individual contact points have been determined.
- If needed, further study can explore the determination of impact time and forces, given the system parameters, like in the translational case.
- By applying the momentum change theorem, the impact impulses at the rotation axis O can also be determined.

RESULTS AND DISCUSSION

In line with the aim and objectives of the research, this paper presents a theoretical method for analyzing multiple simultaneous collisions in both translational and rotational motion. The method enables the prediction of colliding system behavior by providing analytical formulas for determining linear and angular velocities, given at least approximate momentum restitution coefficients. Furthermore, the developed theory allows for the estimation of impact duration when the linearized stiffness values at the local collision points are known. Future research will focus on extending the application of restitution coefficients to the analysis and synthesis of spatial collision problems.

CONCLUSIONS

The research conducted leads to the following broader conclusions:

1. A new analytical method has been developed for studying simultaneous collisions in both translational and rotational motion. This method is applicable to the analysis, optimization, and design of agricultural machinery and related technologies.
2. The proposed method has been validated through a numerical example involving a multipoint collision in the rectilinear translational motion of a solid body. The example illustrates how impact time and average impact force can be estimated using local stiffness values and the object's mass.
3. The analytical approach introduces a novel capability to model multiple simultaneous collisions involving different restitution coefficients.
4. The method also enables the estimation of collision duration, provided the elasticity parameters at the local interaction points are known.
5. It has been shown that, in a linearized system, collision duration depends on the object’s mass or moment of inertia, as well as the reduced stiffness of the contact points.
6. The current scope of the method is limited to the analysis of translational and rotational motion. Future research will focus on extending the approach to planar and spatial (spherical) motion.
7. The method is best suited for analyzing collisions involving massive objects with relatively small elastic elements at the points of interaction.

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