



STUDY TO REDUCE VELOCITY NON-UNIFORMITY IN JAW CRUSHER

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ABSTRACT: Jaw crushers are widely used in mining and construction for primary rock size reduction, but their conventional designs often exhibit high energy consumption and unstable dynamic behavior due to pulsating crushing loads. This study investigates the dynamic characteristics of a jaw crusher and proposes an improved inertia distribution strategy to enhance load smoothing while reducing flywheel mass. A combined simulation framework integrating the Discrete Element Method (DEM), rigid-body dynamic modeling, and optimization analysis was employed. DEM simulations were used to model ore fragmentation and quantify the cyclic forces acting on the moving jaw, which were found to follow a Gaussian-type distribution with respect to crank phase angle. The resulting load model was incorporated into a dynamic simulation to evaluate angular velocity fluctuations and motor load behavior. The results show that increasing flywheel mass improves rotational stability but increases start-up load. An optimized eccentric mass installed on a low-mass flywheel reduced start-up time by 35% and velocity non-uniformity by 45%, improving crusher dynamic performance.

KEY WORDS: *Jaw crusher, Discrete Element Method (DEM), Dynamic simulation, Flywheel optimization, Velocity non-uniformity.*

1. INTRODUCTION

Jaw crushers are widely used in mining, construction, and various industrial sectors due to their ability to perform primary size reduction of mineral and rock materials. Despite their extensive application, conventional jaw crushers are characterized by relatively high energy consumption and significant manufacturing costs. Consequently, improving their operational efficiency and structural performance has become an important research topic. In particular, reducing energy consumption, minimizing the amount of steel required for machine manufacturing, and enhancing operational stability through improved dynamic characteristics are considered key aspects in the development of more efficient crushing systems.

Numerous studies have therefore focused on understanding the crushing mechanisms and the forces acting within jaw crusher systems. Early investigations mainly relied on analytical and mathematical modeling approaches. For example, Mishchuk and Oduori [4,5] developed mathematical models describing the motion of the moving jaw, allowing the determination of angular velocity and angular acceleration as functions of the crank rotation angle. These models provided an important theoretical foundation for subsequent dynamic analyses of jaw crusher mechanisms. Similarly, Johansson, Deepak, and Oduori [9–11] further developed mathematical models describing the operational characteristics of jaw crushers.



With the advancement of computational methods, numerical simulation techniques have become widely used to investigate particle breakage and crusher performance. Since the introduction of the Discrete Element Method (DEM) by Cundall and Strack in 1979 [2], this method has been extensively applied to study particle flow behavior and fragmentation processes in crushers. For instance, Akin et al. [1] employed DEM to simulate the fragmentation of particles within a jaw crusher and subsequently used finite element analysis (ANSYS) to evaluate the stress distribution in the moving jaw and the forces acting on the toggle plate under varying eccentric distances. In addition, Cleary and Sinnott [6,7] applied DEM simulations to analyze particle flow characteristics, crusher throughput, power consumption, and liner wear in different types of crushers.

Other studies have focused on structural optimization and product quality improvement. Mwangi et al. [3,14] applied a combination of Genetic Algorithms (GA) and DEM to optimize the structural parameters of jaw crushers, while Fladvad et al. [15] investigated the influence of crusher structural parameters on the quality of crushed products. Furthermore, Murithi and Keraita [8] performed structural optimization of the moving jaw by analyzing stress and deformation distributions using ANSYS software. Experimental and numerical investigations have also been conducted to address structural reliability issues; for example, Rusinski et al. [12] proposed an integrated experimental–numerical approach to analyze fatigue failure mechanisms in jaw crusher support structures.

In conventional jaw crusher systems, a flywheel with a high moment of inertia is typically mounted on the spindle to stabilize the energy transfer during the intermittent crushing process. When the crusher operates without load, the energy supplied by the motor is stored in the flywheel, and this stored energy is subsequently released when the crusher encounters crushing loads. This mechanism helps reduce angular velocity fluctuations and smooth the load characteristics experienced by the motor.

However, this traditional design approach has several drawbacks. Increasing the flywheel mass leads to higher steel consumption during manufacturing, thereby raising production costs. Additionally, the large inertial load imposed by the flywheel increases the start-up time of the crusher. In practice, the flywheel-based energy smoothing mechanism does not always provide satisfactory load stabilization for the driving motor.

To address these limitations, dynamic simulation of the crusher working process can be used to redesign the energy balancing mechanism. By reducing the flywheel mass and introducing eccentric inertial masses strategically positioned according to the crusher's working mechanism and crushing load characteristics, it is possible to provide the required moment of inertia while improving load smoothing performance.

Therefore, the objective of this research is to investigate the dynamic behavior of a jaw crusher system through simulation-based analysis in order to optimize the inertia distribution mechanism, reduce flywheel mass, and improve motor load smoothing during the crushing process.

2. SIMULATION OF THE CRUSHING OPERATION OF A JAW CRUSHER AND ITS LOAD CHARACTERISTICS

During the crushing operation, the working mechanism of a jaw crusher generates cyclic forces acting on the moving jaw. These cyclic forces arise from the kinematic characteristics of the crank–linkage mechanism, which drives the periodic motion of the moving jaw relative

to the fixed jaw. As a consequence, the rotational speed of the actuator becomes non-uniform, resulting in fluctuating loads transmitted to the driving motor. This pulsating load behavior significantly affects the dynamic stability of the crusher system.

To develop effective strategies for smoothing the pulsating load, it is necessary to first analyze the load characteristics of the jaw crusher during the crushing process. Recent developments in numerical simulation techniques, particularly the Discrete Element Method (DEM), enable detailed modeling of particle breakage and interaction forces within crushing equipment. Through DEM-based simulations, the forces acting on the moving jaw can be quantified, allowing the dynamic load characteristics of the crusher to be systematically investigated.

2.1. DEM Simulation of the Jaw Crusher Fracture Process

A DEM-based crushing model of the jaw crusher was developed to simulate the fragmentation process and determine the force characteristics acting on the moving jaw. As illustrated in Fig. 1, the simulation model consists of two primary components: the ore particle assembly and the mechanical structure of the jaw crusher. The interaction between particles is modeled using the Hertz–Mindlin contact model with bonding, which allows simulation of particle fracture.

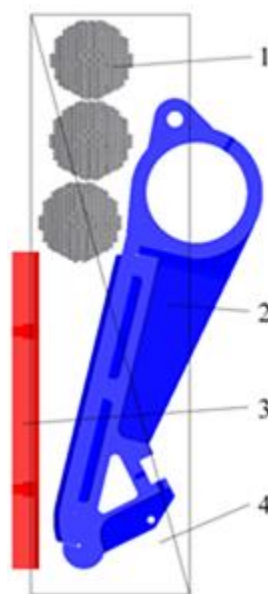


Fig. 1. Threshold crusher crushing model by DEM: 1. ore block, 2. moving jaw, 3. fixed jaw, 4. side plate

To accurately simulate particle breakage, a realistic ore lump model must first be constructed. Previous research [13] introduced a DEM-based approach for constructing lump models using mineralogical close-packing structures. Following this approach, spherical particle assemblies were used in this study to represent the ore feed. Specifically, spherical ore lumps with a diameter of 150 mm were generated using particles with a diameter of 10 mm arranged in a hexagonal close-packed structure, consistent with the feed size of the jaw crusher.

The micro-mechanical parameters governing the particle bonding properties were defined as follows: a bond radius of 0.381 mm, a normal stiffness per unit area of $3.412 \times 10^8 \text{ N/m}^3$, a

tangential stiffness per unit area of $2.435 \times 10^8 \text{N/m}^3$, a critical normal stress of $6.571 \times 10^6 \text{Pa}$, and a critical tangential stress of $5.308 \times 10^6 \text{Pa}$.

The mechanical model of the jaw crusher was created in **SolidWorks** and subsequently imported into **EDEM** for simulation. A key aspect of this model is the definition of the motion of the moving jaw. The motion consists of a combined rotational and oscillatory movement governed by the crank–connecting rod mechanism. The moving jaw rotates with angular velocity ω about the crank axis *A*, while simultaneously rotating about the connecting rod axis *B* with angular velocity $-\omega$ to maintain its orientation. Additionally, the moving jaw performs a sinusoidal oscillation about axis *B* with a constant amplitude *a*.

In the present model, the crank rotational speed was set to $\omega = 300 \text{rpm}$ and the oscillation amplitude was $a = 0.96^\circ$.

The DEM simulation results illustrating the fragmentation process at different crank phase angles are shown in Fig. 2.

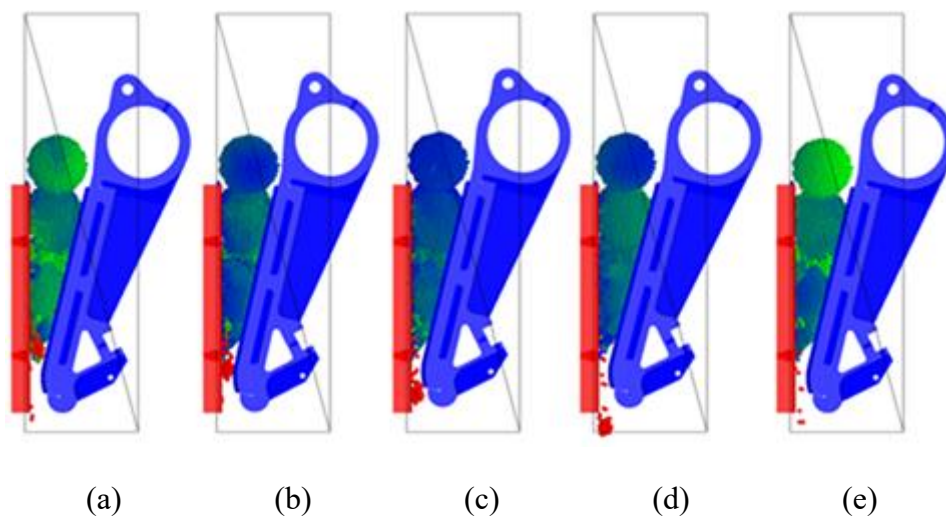


Fig. 2. Fracture simulation process of a complex rocking jaw crusher
(a) 0° , (b) 90° , (c) 180° , (d) 270° , (e) 360°

During operation, ore particles are fed into the crushing chamber between the stationary and moving jaws under gravity. As the moving jaw approaches the fixed jaw, compressive forces are applied to the ore particles, leading to particle breakage. When the moving jaw moves away, the crushed particles expand and rearrange within the chamber. This cyclic compression–release process repeats continuously, resulting in progressive fragmentation of the ore material.

2.2. Force Characteristics Acting on the Moving Jaw

The DEM simulation enables direct measurement of the forces acting on the moving jaw during the crushing process. The normal force acting on the moving jaw surface is shown in Fig. 3.

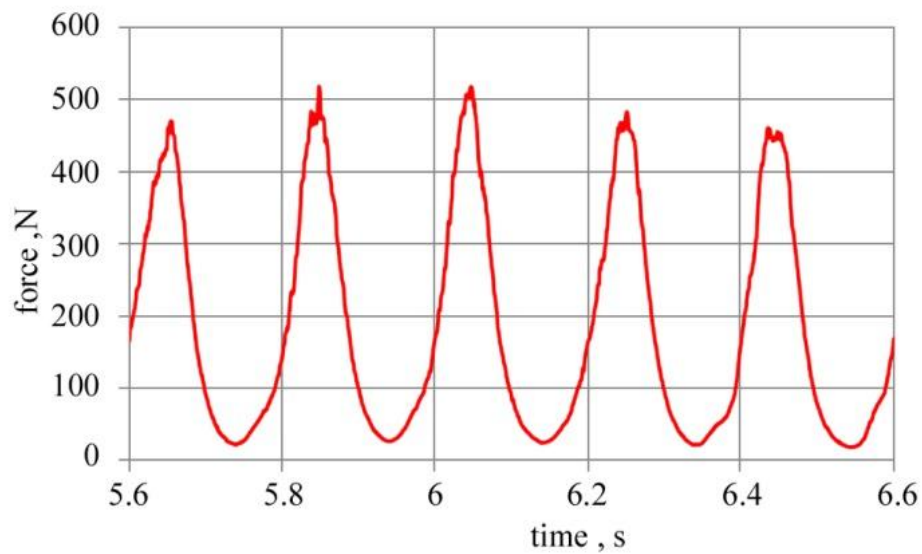


Fig. 3. Force acting on the moving jaw during crushing

The results indicate that the moving jaw experiences cyclic loading during operation due to the periodic nature of the crushing process. These cyclic forces contribute to significant fluctuations in the angular velocity of the crank–linkage mechanism. As a result, the driving motor must withstand pulsating loads that can exceed the average operating load. To mitigate this dynamic imbalance, conventional jaw crushers are typically equipped with large flywheels.

To further analyze the force variation, the time-dependent force acting on the moving jaw is expressed as a function of the crank phase angle, as illustrated in Fig. 4.

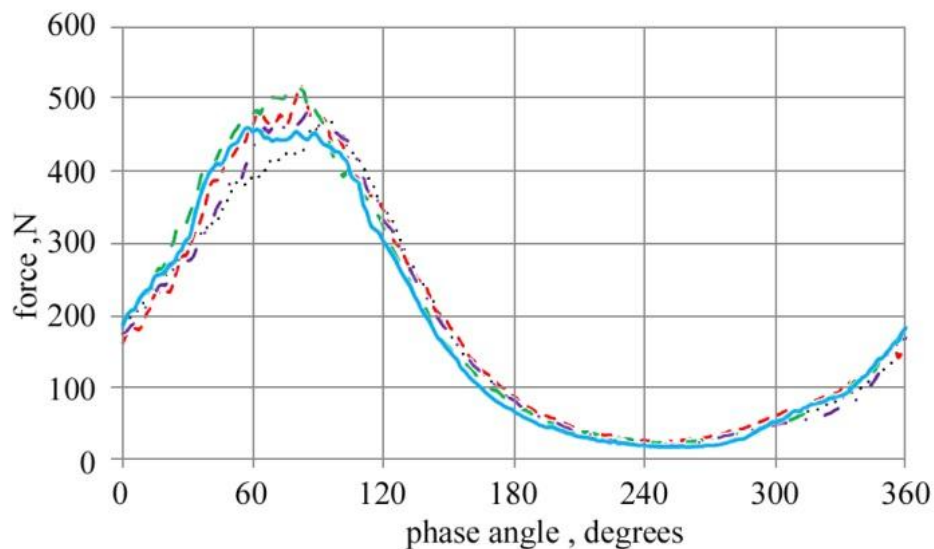


Fig. 4. Force variation on the moving jaw with respect to crank phase angle

Because the crushing process involves complex particle–structure interactions, the force profiles in individual crushing cycles exhibit similar shapes but vary slightly in magnitude. To obtain a representative force distribution, the force curves from multiple crushing cycles were averaged, resulting in the mean force diagram shown in Fig. 5.

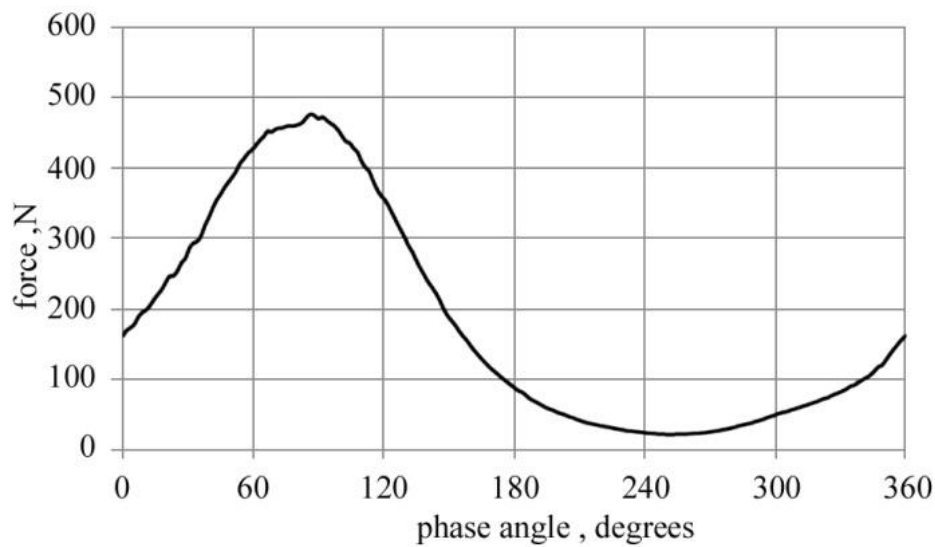


Fig. 5. Average force distribution with respect to crank phase angle

Mathematical analysis of the averaged force curve indicates that the force variation closely follows a Gaussian distribution, which can be expressed as

$$F(t) = a \cdot e^{-\frac{(t-b)^2}{c^2}} \quad (1)$$

where t represents the crank rotational phase angle, a is the peak value of the Gaussian function, and b and c are constants defining the position and width of the distribution.

2.3. Load Characteristics of the Jaw Crusher

During crushing, the rotational speed of the crank varies in response to the instantaneous load conditions. Consequently, the force acting on the moving jaw is influenced not only by the crank phase angle but also by the rotational speed of the crank. Therefore, the load characteristics of the jaw crusher can be defined as a function of both crank phase angle and rotational speed.

To determine these characteristics, DEM simulations were conducted at several crank rotational speeds around the rated operating speed. The resulting average force curves acting on the moving jaw are shown in Fig. 6.

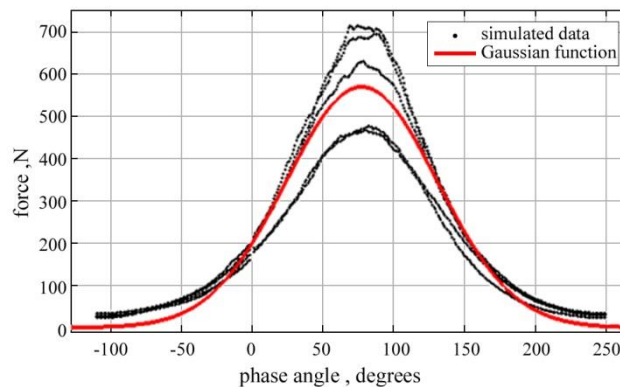


Fig. 6. Gaussian regression of crushing force



The results show that although the shape of the force curve remains consistent and follows a Gaussian distribution, the peak force value varies depending on the crank rotational speed. Therefore, the load characteristics of the crusher can be described by expressing the Gaussian coefficient as a function of crank rotational speed.

Using MATLAB curve fitting, the Gaussian function was fitted to the simulation data, resulting in the following regression model with a correlation coefficient of $R^2 = 0.936$:

$$F(t) = 562.5 \cdot e^{-\frac{(t-77.22)^2}{75.27^2}} \quad (2)$$

To account for the influence of rotational speed, the maximum crushing forces obtained from simulations at different crank speeds are listed in Table 1.

Table 1: Maximum crushing force at different rotational speeds

Rotational speed, r/min	maximum value of force, N
282	470.633
288	715.045
294	695.302
300	476.166

Polynomial regression of these data shows that the peak force coefficient a can be expressed as a function of the crank rotational speed n with a correlation coefficient of $R^2 = 1$:

$$a = 0.04997n^3 - 46.84n^2 + 14563n - 1502000 \quad (3)$$

By combining this relationship with the Gaussian force model, the load characteristics of the jaw crusher can be formulated as a unified function describing the relationship between crank phase angle, rotational speed, and crushing force.

$$F(t, n) = (0.04997n^3 - 46.84n^2 + 14563n - 1502000) \cdot e^{-\frac{(t-77.22)^2}{75.27^2}} \quad (4)$$

3. DYNAMIC SIMULATION OF JAW CRUSHER OPERATION AND EVALUATION OF VELOCITY NON-UNIFORMITY

The dynamic performance of a jaw crusher is strongly influenced by the pulsating load generated during the crushing process. Due to the kinematic characteristics of the crank-linkage mechanism and the intermittent interaction between ore particles and the moving jaw, the rotational speed of the crankshaft does not remain constant during operation. This variation in angular velocity leads to vibration, increased noise levels, and higher motor power requirements.

To improve the dynamic behavior of the crusher, an appropriate evaluation criterion must first be established. In rotating machinery, one of the most commonly used indicators for assessing dynamic stability is the velocity non-uniformity index, which quantifies fluctuations in angular velocity during operation. Therefore, analyzing the dynamic response of the jaw crusher and evaluating its velocity non-uniformity is essential for improving the overall performance of the system.

3.1. Dynamic Simulation Model of the Jaw Crusher

To evaluate the dynamic characteristics of the crusher, a rigid-body dynamic simulation was conducted using MSC.VisualNastran. The developed model represents the main components of the jaw crusher mechanism, including the eccentric shaft, moving jaw, rocker, and driving system. The simulation model is illustrated in **Fig. 7**.

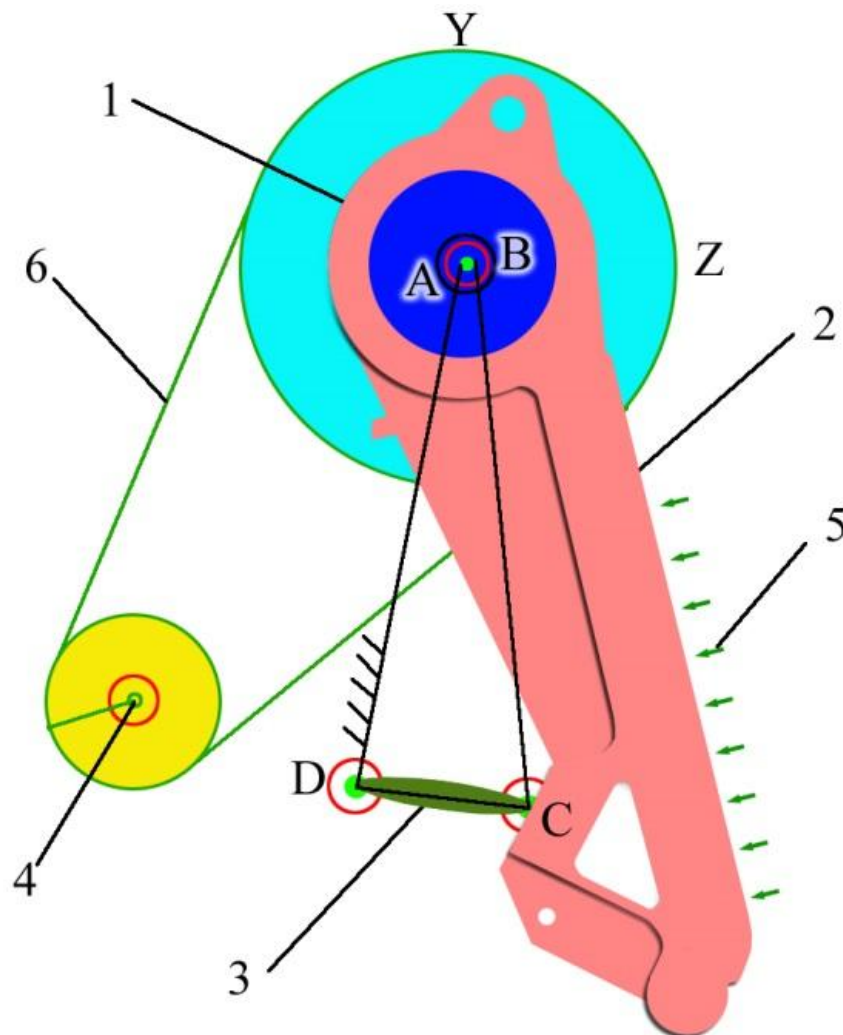


Fig. 7. Dynamic simulation model of the jaw crusher

1–eccentric shaft, 2–moving jaw, 3–rocker, 4–motor constraint, 5–load, 6–belt constraint

In this model, the crusher mechanism is driven by a motor constraint that transmits torque to the eccentric shaft through a belt drive. The crank–linkage system converts this rotational motion into the oscillatory motion of the moving jaw. The forces acting on the moving jaw are generated by the interaction between the crusher plates and the ore particles during the crushing process.

The crusher considered in this study is driven by a 5.5 kW induction motor. Based on the motor characteristics, the motor torque can be expressed as a function of the slip ratio, which defines the relationship between motor speed and generated torque.

The crushing load acting on the moving jaw is represented using the load characteristic function obtained from DEM simulations described in the previous section. By incorporating this load function into the dynamic model, the temporal variations of angular velocity, motor torque, and power output can be simulated.

The simulation results during the **start-up stage** are shown in **Fig. 8**, while the dynamic behavior during **steady-state operation** is presented in **Fig. 9**.

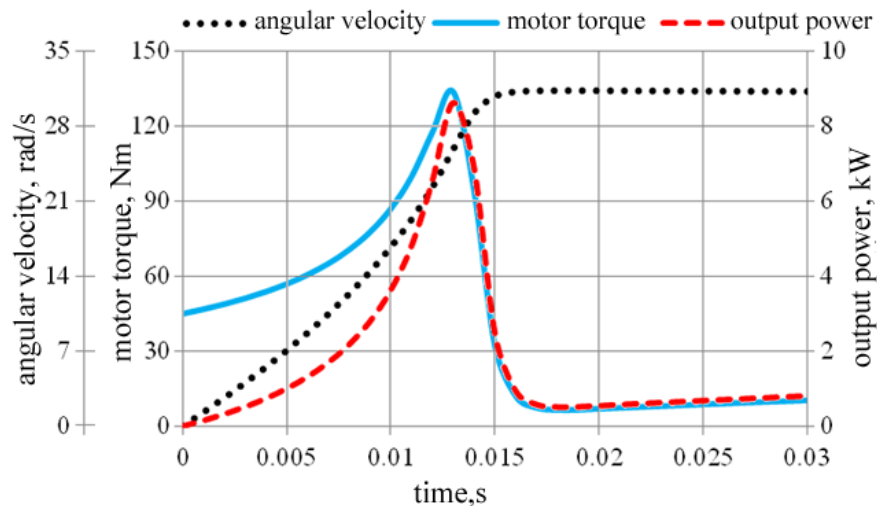


Fig.8. Dynamic simulation results at start-up

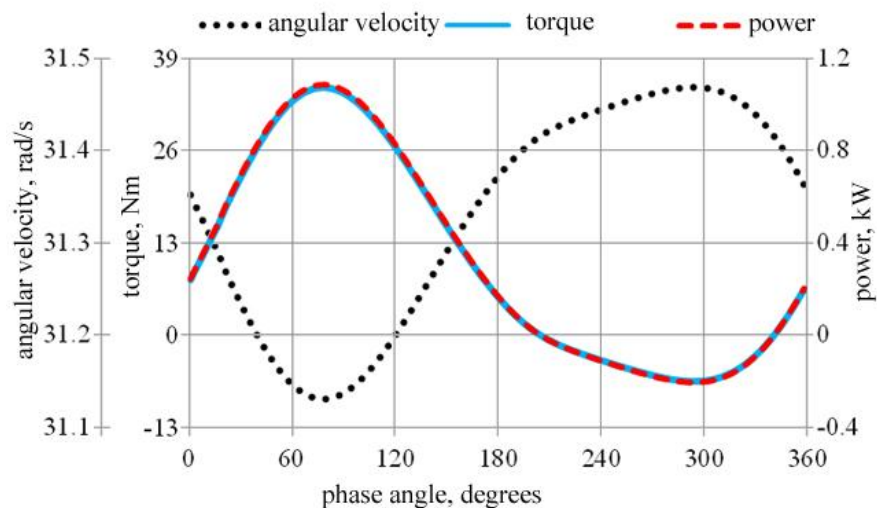


Fig.9. Dynamic simulation results at steady-state operation

The results indicate that the crusher requires a relatively large torque and power during start-up before reaching the rated rotational speed of the eccentric shaft. During steady-state operation, the angular velocity, torque, and power fluctuate periodically due to the cyclic forces generated during crushing. These periodic fluctuations demonstrate that the crusher operates under dynamically unbalanced conditions.



3.2. Dynamic Simulation Model of the Jaw Crusher

The degree of speed fluctuation in rotating machinery is typically quantified using the velocity non-uniformity coefficient, defined as

$$\delta = \frac{\omega_{max} - \omega_{min}}{\omega_{ave}} \quad (5)$$

Where ω_{max} is the maximum angular velocity, ω_{min} is the minimum angular velocity, and ω_{ave} is the average angular velocity.

A large value of δ indicates strong speed fluctuations and poor dynamic stability. Therefore, minimizing this parameter is an important objective in the design and operation of jaw crushers.

However, this index only considers the extreme values of angular velocity and does not fully describe the temporal variation of dynamic behavior during the entire operating cycle. To obtain a more comprehensive evaluation, the velocity fluctuation can also be expressed using the variance of angular velocity:

$$\delta_{\omega} = \sqrt{\frac{1}{T} \sum_{i=1}^T (\omega_i - \omega_{ave})^2} \quad (6)$$

Where ω_i represents the instantaneous angular velocity at time step i , ω_{ave} is the average angular velocity, and T is the duration of one operating cycle.

Using this method, the calculated velocity non-uniformity of the crusher is

$$\delta_{\omega} = 1.435 \text{ rad/s} \quad (7)$$

This value reflects the degree of dynamic instability of the crusher during operation.

3.3. Influence of Flywheel Mass on Dynamic Performance

In conventional jaw crushers, flywheels are installed to reduce angular velocity fluctuations by storing kinetic energy during low-load periods and releasing it during high-load periods. To investigate the influence of flywheel mass on dynamic behavior, additional simulations were performed by introducing flywheels with different masses into the model, as illustrated in Fig. 10.

The simulation results for the start-up process are shown in Fig. 11. Increasing the flywheel mass leads to a longer start-up time because the flywheel introduces additional inertial load that must be accelerated by the motor.

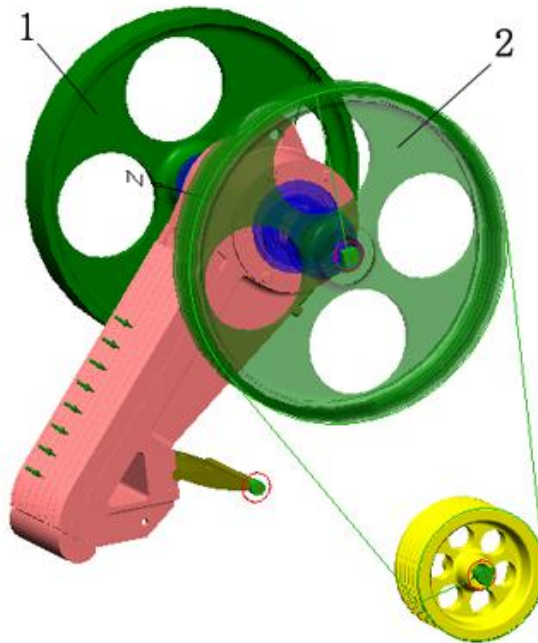


Fig.10. Model with the addition of pulley and flywheel
1-flywheel, 2-pulley

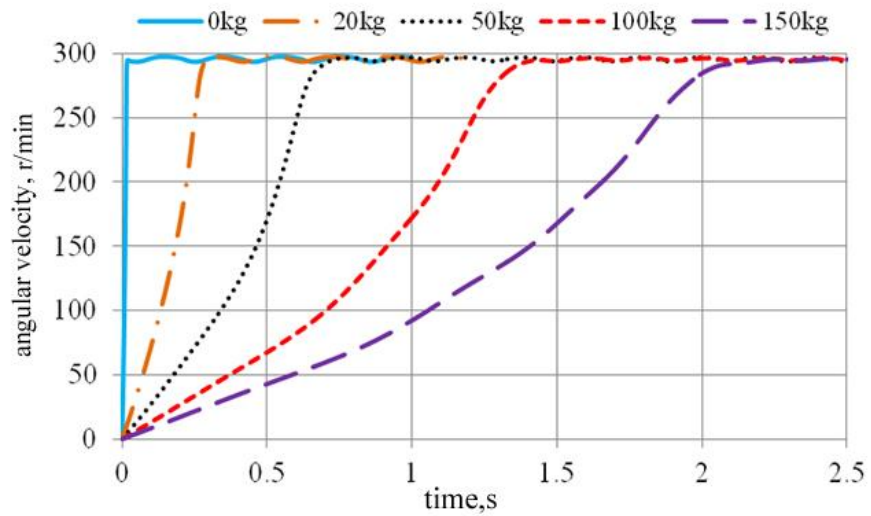


Fig.11. Starting process with mass change of flywheel

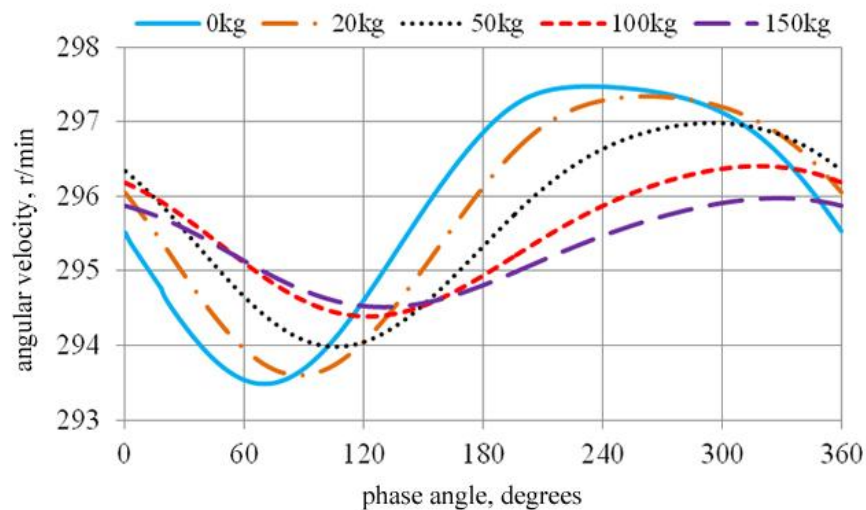


Fig.12. Angular velocity profile with mass change of flywheel

Although this effect is relatively small for small-scale crushers, it becomes significant for large industrial crushers. In mining operations where energy consumption is high, large starting loads may cause voltage and frequency fluctuations in the power supply system.

The influence of flywheel mass on the angular velocity of the eccentric shaft and the motor power output is shown in Figs. 12 and 13, respectively.

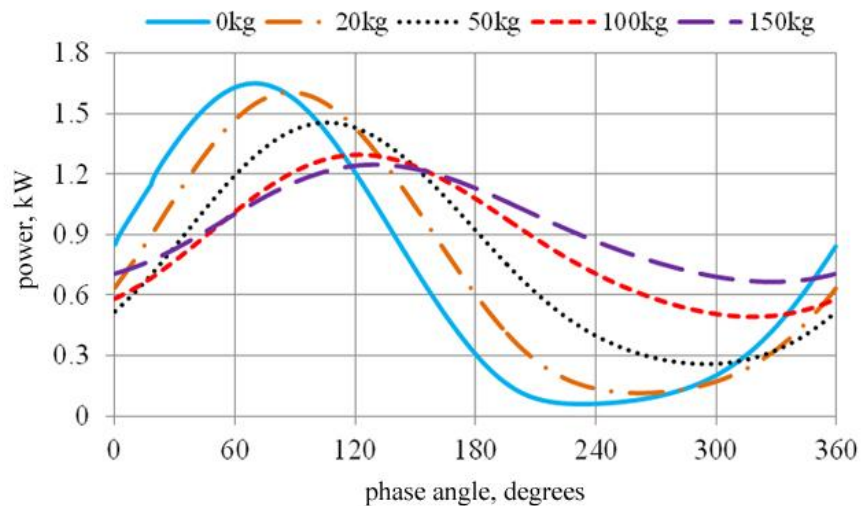


Fig.13. Power curve with mass change of flywheel

The results indicate that increasing the flywheel mass reduces the fluctuation amplitude of both angular velocity and power during the working cycle. Consequently, the velocity non-uniformity coefficient decreases as the flywheel mass increases.

The calculated heterogeneity values for different flywheel masses are summarized in Table 2.

Table2: Heterogeneity values with the change of mass of flywheel



Flywheel weight, kg	Angular velocity heterogeneity, rad/s
0	0.092
20	0.086
50	0.076
100	0.062
150	0.053

These results demonstrate that increasing the flywheel mass improves rotational stability by increasing the stored kinetic energy. However, this improvement comes at the expense of increased starting load and longer start-up time.

Therefore, an effective design strategy should aim to reduce velocity non-uniformity while minimizing the inertial load during start-up.

4. INSTALLATION OF ECCENTRIC MASS ON THE FLYWHEEL

The previous analysis shows that increasing flywheel mass can reduce velocity non-uniformity but negatively affects start-up performance. Conventional flywheel design attempts to smooth the energy demand by storing excess energy during low-load periods and releasing it during high-load periods throughout the entire working cycle.

However, recent DEM-based simulations make it possible to identify the exact timing of peak pulsating loads during the crushing cycle. This information allows a more targeted approach to load compensation.

Instead of increasing the flywheel mass, this study proposes the installation of an eccentric mass on a low-mass flywheel. The eccentric mass generates an additional torque that can be synchronized with the peak crushing load, thereby compensating for the pulsating torque without significantly increasing the overall inertia of the system.

The dynamic equilibrium of the mechanism can be expressed by the following equation of motion:

$$M_1 = M_2 + I_{eq} \frac{d\omega}{dt} + \omega^2 \frac{dI_{eq}}{dt} \quad (8)$$

Where M_1 is the driving torque transmitted from the motor, M_2 is the resistance torque generated by crushing forces and gravity, and I_{eq} is the equivalent moment of inertia of the mechanism.

The eccentric mass generates an additional torque acting directly on the eccentric shaft, which modifies the motion torque characteristics of the mechanism. The total motion torque of the modified mechanism can therefore be expressed as the sum of the original motion torque and the eccentric mass torque.

To determine the optimal eccentric mass and its installation angle, the motion torque obtained from dynamic simulation was approximated using harmonic regression with MATLAB. The resulting function accurately represents the torque variation over one operating cycle.

The torque generated by the eccentric mass can be expressed as

$$y_2 = mgl \sin(\phi + \phi_0) \quad (9)$$



Where m is the eccentric mass, l is the eccentric arm length, g is gravitational acceleration, and ϕ_0 is the installation angle.

The optimal configuration is obtained by minimizing the variance of the total torque function. This optimization problem was solved using a genetic algorithm implemented in MATLAB.

The optimized parameters significantly improved the dynamic performance of the crusher. Compared with the conventional method of increasing flywheel inertia, the proposed eccentric mass approach reduced:

- start-up time by 35% (from 0.71 s to 0.46 s)
- velocity non-uniformity by 45% (from 0.07 to 0.038)

These results demonstrate that the eccentric mass method can effectively improve both start-up performance and steady-state dynamic stability while reducing flywheel mass.

5. CONCLUSION

This study investigated the dynamic behavior of a jaw crusher through an integrated simulation framework combining the Discrete Element Method (DEM), rigid-body dynamic modeling, and optimization analysis. The results confirmed that the crushing process generates cyclic forces on the moving jaw due to the kinematic characteristics of the crank-linkage mechanism and the intermittent interaction between the ore particles and the crushing chamber. These cyclic forces produce pulsating loads, which in turn cause angular velocity fluctuation, unstable motor loading, and reduced dynamic stability of the crusher system.

The DEM-based fracture simulation successfully captured the crushing process and quantified the force acting on the moving jaw throughout the operating cycle. The results showed that the force variation can be represented by a Gaussian-type function with respect to crank phase angle, while the peak force is influenced by crank rotational speed. By combining these relationships, a load characteristic model of the jaw crusher was established as a function of both crank phase angle and rotational speed. This model provided a reliable basis for subsequent dynamic simulation.

The rigid-body dynamic simulation demonstrated that the jaw crusher operates under dynamically unbalanced conditions, both during start-up and steady-state operation. The periodic variation in angular velocity, torque, and power output confirmed the existence of significant load pulsation in the system. The calculated velocity non-uniformity further indicated that dynamic instability is an important issue in jaw crusher operation and must be addressed to improve performance.

The analysis of flywheel mass revealed that increasing flywheel inertia can reduce angular velocity fluctuation and improve rotational stability. However, this approach also increases start-up time and imposes a higher inertial load on the motor. Therefore, although a heavier flywheel improves steady-state smoothness, it reduces start-up performance and increases structural and manufacturing demands.

To overcome this limitation, this study proposed the installation of an eccentric mass on a low-mass flywheel as an alternative inertia distribution strategy. By synchronizing the additional torque generated by the eccentric mass with the peak pulsating load during crushing,



the proposed method was able to compensate for load fluctuation more effectively than the conventional inertial mass increase approach. The optimized eccentric mass configuration, determined using a genetic algorithm, reduced start-up time by 35% and velocity non-uniformity by 45% compared with the conventional high-inertia flywheel method.

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