DISCRETE ELEMENT METHOD SIMULATION OF GRINDING MEDIA MOTION IN BALL MILLS: METHODOLOGY, VERIFICATION, AND APPLICATION TO WEAR PREDICTION

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ABSTRACT Predicting the wear of grinding media and liners in ball mills requires detailed knowledge of how the granular charge moves and impacts the mill shell, information that cannot be obtained directly from full-scale industrial operation. This paper presents a Discrete Element Method (DEM) simulation methodology, developed as part of a doctoral study on mining equipment durability and condition diagnostics, for modeling grinding media motion and the resulting contact forces in a tumbling ball mill. The model treats each grinding ball as a discrete body governed by Newton's second law and resolves ball-ball and ball-liner interactions using a linear spring-dashpot contact model with Coulomb friction, integrated in time with an explicit leapfrog scheme and implemented in the ROCKY DEM software. Simulations were carried out for a factorial set of operating conditions spanning rotational speed, fill level, and ball diameter, and the resulting charge kinematics and contact forces were coupled with a finite-element model of the mill drive train to evaluate impact-induced gearbox vibration. The DEM model was verified against full-scale flash-stop experiments on an industrial mill, with predicted charge angles (shoulder, toe, departure, and impact-point) agreeing with measured values to within 4%. Results show that fill level and rotational speed strongly govern contact force magnitude, fall height, and the transition from cascading to cataracting motion, and that DEM-derived impact statistics correlate with acoustic indicators of liner wear. The findings demonstrate that verified DEM simulation provides a reliable basis for wear prediction, operating-regime optimization, and condition-based diagnostics in industrial ball mills.

KEYWORDS Discrete Element Method (DEM); ball mill simulation; grinding media motion; contact mechanics; ROCKY software; charge kinematics; liner wear prediction; impact energy distribution; drive-train vibration; condition diagnostics; cascading and cataracting motion; mineral processing equipment durability

Introduction

Tumbling ball mills remain one of the most energy-intensive units in the mineral processing chain, and the grinding media and liners inside them are subjected to continuous impact, abrasive, and corrosive wear. Predicting how grinding balls and mill liners deteriorate under different operating regimes is essential for planning maintenance, selecting wear-resistant materials, and optimizing comminution efficiency. Because the interior of an industrial mill cannot be observed directly during operation, and because instrumenting a full-scale mill to measure contact forces is costly and disruptive, numerical simulation has become the principal tool for studying the internal dynamics of the charge.

The Discrete Element Method (DEM) is the numerical approach best suited to this task. Unlike continuum methods, DEM treats the grinding charge as an assembly of discrete bodies — balls, particles, and liner segments — whose motion is governed individually by Newton's second law and whose interactions are resolved through contact mechanics at every time step. This paper presents the DEM methodology developed and applied in a doctoral study on the durability and diagnostics of mineral-grinding equipment, covering the mathematical formulation of the contact model, the numerical implementation in the ROCKY DEM software, the simulation parameters used for a laboratory-scale ball mill, and the experimental verification of the model. The discussion then extends to how DEM-derived contact force histories were coupled with a finite-element model of the mill drive train, and how the resulting kinematic and energetic data support the prediction of liner and ball wear.

Grinding media motion inside a rotating drum is a strongly nonlinear, stochastic process: balls cascade, cataract, or centrifuge depending on rotational speed, fill level, and ball size, and the resulting impact energies determine both the comminution rate and the wear rate of the liner. Analytical and empirical wear models, which dominated earlier research, generally rely on averaged or lumped descriptions of the charge and therefore cannot capture the spatial and temporal non-uniformity of impact and contact interactions across the liner surface. DEM removes this limitation by explicitly tracking every individual particle, making it possible to compute local impact energy, contact pressure, and frequency distributions at any point on the mill shell. This capability underlies the growing international interest in DEM-based wear prediction, including work combining DEM outputs with machine-learning models to forecast liner profile evolution, and studies coupling DEM with computational fluid dynamics for wet milling.

Mathematical Formulation

In the DEM framework, each spherical particle j — representing a grinding ball — is described by its position, linear and angular velocity, linear and angular acceleration, the resultant force acting at its centre of mass, and the resultant moment. Translational and rotational motion are governed by Newton's second law for both the linear and angular degrees of freedom, with particle mass and moment of inertia computed from the ball radius and material density. The resultant force on each particle is the sum of all mechanical contact forces arising from ball–ball and ball–liner interactions, together with gravity. Contact forces are resolved using a linear spring–dashpot (Kelvin–Voigt) model in both the normal and tangential directions. The normal contact force is proportional to the normal overlap between contacting bodies, augmented by a velocity-dependent viscous damping term governed by the normal stiffness and damping coefficients. The tangential contact force combines an elastic–viscous component, governed by tangential stiffness and damping, with a Coulomb friction limit defined by the normal force and the friction coefficient; whichever of the two yields the smaller magnitude controls the tangential force at that instant, ensuring that sliding contacts cannot exceed the physical friction limit. This formulation captures both the elastic rebound and the energy dissipation that occur during ball–ball and ball–liner collisions, which together determine the impact energy spectrum responsible for wear.

The resulting system of second-order ordinary differential equations is integrated explicitly using a leapfrog (velocity Verlet-type) scheme, in which particle positions and velocities are updated at staggered half-time and full-time steps. This scheme is only conditionally stable, so the time step must remain smaller than a critical value set by the highest natural frequency present in the contact system; in practice this means a very small time step (on the order of microseconds) governed by the stiffness of the ball–liner contact, which is the main computational cost driver in industrial-scale DEM simulations. The numerical model was implemented in ROCKY, an open, object-oriented DEM software package with a C++ computational core and a Python scripting interface for configuring and automating simulation runs. ROCKY runs on Linux and is capable of resolving the interaction of very large particle populations, up to the order of millions of elements, which makes it suitable for representing realistic ball charges. Two geometric components were defined for the mill model: the drum shell and liner geometry, generated in SolidWorks and Compass 3D and imported as discretized triangulated surfaces, and the spherical grinding balls that fill the drum volume. End walls of the drum were represented as flat boundary elements.

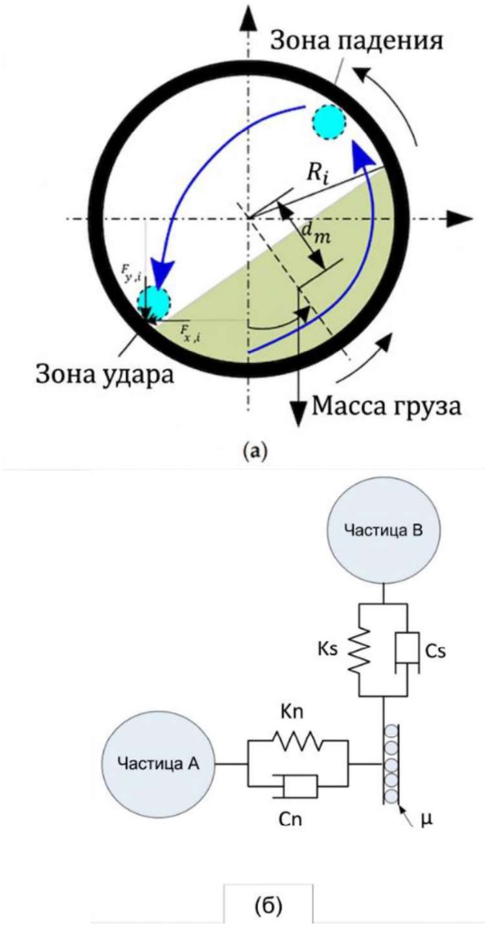

Fig. 1. Discrete Element Method (DEM) modeling of a ball mill: (a) load motion profile inside the ball mill; (b) contact model.

The simulation parameters used to represent a laboratory/industrial ball mill configuration are summarized in Table 1.

Using this configuration, the simulation plan varied three operating parameters independently: rotational speed expressed as a percentage of critical speed, fill level (degree of charge filling), and ball diameter, each tested across four discrete levels. This factorial arrangement allowed the influence of each parameter on charge kinematics, contact forces, and impact energy distribution to be isolated and quantified.

Table 1.
DEM simulation parameters for the ball mill model

Parameter	Symbol	Value
Ball radius	R_i	50 mm
Ball density	ρ	7640 kg/m³
Liner density	ρ	7640 kg/m³
Friction coefficient (ball–liner)	μ_1	0.30
Friction coefficient (ball–ball)	μ_2	0.30
Restitution coefficient (ball–ball)	e_1	0.75
Restitution coefficient (ball–liner)	e_2	0.75
Mill diameter	D	0.80 m
Mill length	L	0.40 m
Normal contact stiffness	K_n	10^6 N/m
Tangential contact stiffness	K_s	10^6 N/m

5. Charge Kinematics and Contact Force Results

DEM simulations reproduced the characteristic cascading and cataracting motion of the ball charge and allowed extraction of key kinematic descriptors of the load profile: the shoulder angle, at which the charge begins to lift away from the shell; the toe angle, where the falling balls re-enter the bed; the departure (kidney) angle; and the impact point angle. These angles, together with the maximum fall height of the balls, characterize the trajectory and energy of the impacting charge and are the primary drivers of localized liner wear.

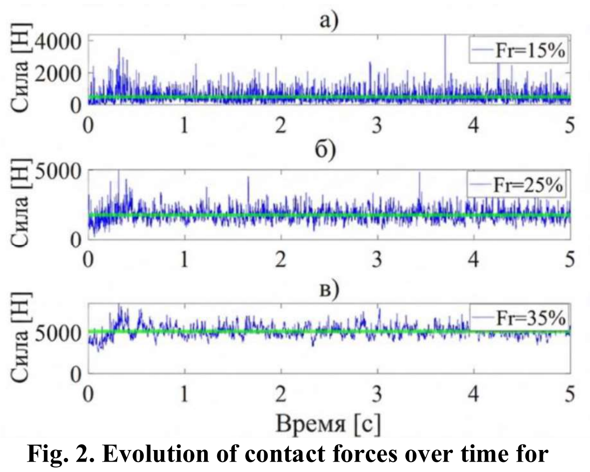

Fig. 2. Evolution of contact forces over time for three fill levels: (a) Fr = 15%, CAF = 496.5 N, (b) Fr = 25%, CAF = 1772.5 N, (c) Fr = 35%, CAF = 5145.8 N, at Nr = 0.3 Cs and Db = 50 mm.

Increasing the degree of fill produced a clear and consistent increase in the maximum fall height of the balls and in the resulting contact forces transmitted to the shell. For example, at a fixed rotational speed the maximum fall height rose from approximately 0.63 m at 15% fill to approximately 0.89 m at 35% fill, and the corresponding average contact force on the shell increased from roughly 0.5 kN to over 5 kN across the tested fill range. This increase in contact force directly elevates the amplitude of impact-induced vibration in the drive train and the local energy deposited on the liner surface, both of which are indicators of accelerated wear. Rotational speed had an even stronger effect once the mill approached its critical speed: increasing the speed from 70% to 90% of critical speed produced a 44% increase in vibration velocity, reflecting a transition from a cascading regime, where balls roll over one another, to a cataracting regime, where balls are thrown free of the bed and strike the liner directly with much higher kinetic energy. This regime transition is a key practical finding, since operating too close to critical speed substantially increases liner wear without necessarily improving grinding efficiency.

To evaluate how the impact loads generated by the grinding charge propagate into the mill's mechanical transmission, the DEM model of the ball charge was coupled with a finite-element model of the gearbox and shafts. Shafts were represented using Timoshenko beam elements, capturing both bending and shear deformation, while gear meshes were modeled as lumped-parameter elements positioned at the corresponding shaft nodes. The resultant horizontal and vertical contact forces exerted by the ball charge on the mill shell, computed in ROCKY, were applied as time-varying external loads at the corresponding node of the global drive-train model, which was assembled into a 24-degree-of-freedom system of equations of motion. Damping was introduced through a proportional (Rayleigh) damping matrix, and the equations were integrated in time using the Newmark method in MATLAB.

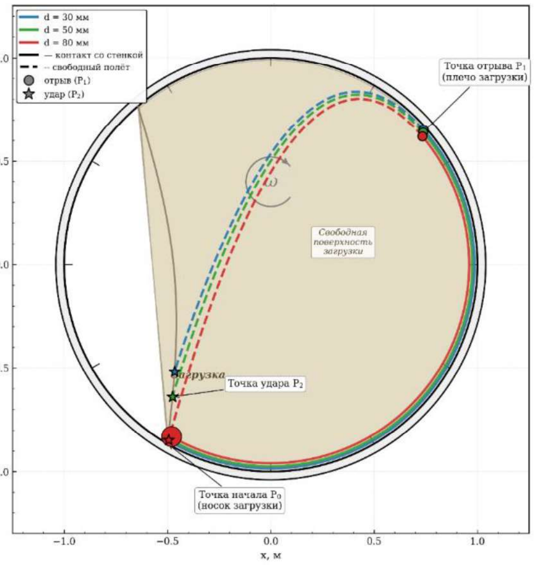

Fig. 3. Trajectories of grinding media of different diameters.

This coupled approach showed that the operating parameters of the milling process — fill level, rotational speed, and ball diameter — exert a determining influence on the impulsive component of the vibration signal measured on the transmission. At low fill levels, masking noise from normal gear meshing dominated the vibration spectrum, but as fill level increased beyond roughly 25%, impulsive components associated with ball impacts became the dominant feature of the signal. This result is significant for condition monitoring, since it demonstrates that vibration signatures recorded on the gearbox carry usable information about internal charge dynamics and impact severity, not only about mechanical defects in the gear train itself.

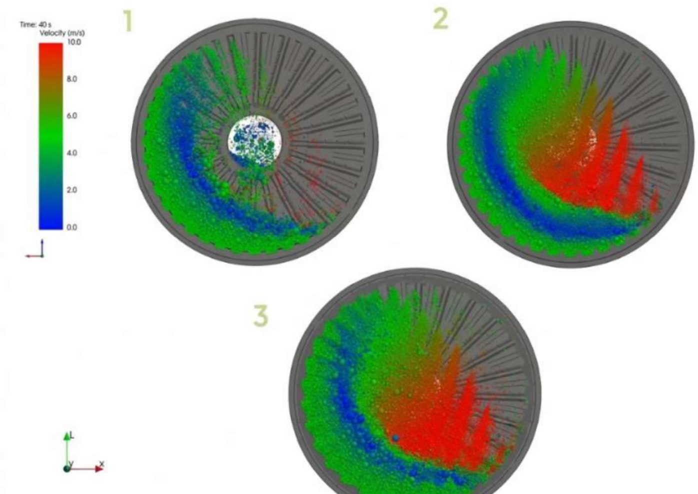

Fig. 4. Dependence of the grinding media fill level on the operating mode of the ball mill

Experimental Verification of the DEM Model

Numerical predictions are only useful if they can be shown to agree with physical behaviour, so the DEM model was verified against full-scale experimental data using a 'flash-stop' (snapshot) procedure on an industrial ball mill. In this procedure, the mill was first run at a fixed operating point — defined rotational speed, fill level, and feed size distribution — until a steady-state charge motion was established. A set of balls pre-painted red was added to the charge to aid visual identification, and after twenty minutes of steady operation the drive was emergency-stopped, bringing the drum to a complete halt within 8 to 12 seconds using the shoe brakes. The frozen charge profile was then photographed and measured to determine the actual shoulder, toe, departure, and impact-point angles, which were compared against the corresponding angles predicted by the DEM model under the same operating conditions. The procedure was repeated five times, yielding 150 individual angular measurements. The averaged comparison between the DEM predictions and the experimental measurements is summarized in Table 2

Table 2.
Comparison of DEM-predicted and experimentally measured charge angles

Charge Parameter	DEM Model	Experiment	Relative Error, %
Shoulder angle, θ_S (deg)	42.5	44.1	3.6
Toe angle, θ_T (deg)	216.0	212.8	1.5
Departure (kidney) angle, $\theta_{\{TD\}}$ (deg)	248.2	246.5	0.7
Impact point angle, $\theta_{\{IP\}}$ (deg)	198.4	195.2	1.6

Across all four measured parameters, the discrepancy between the DEM model and the physical experiment did not exceed 4%, with the smallest error recorded for the departure angle (0.7%) and the largest for the shoulder angle (3.6%). These results confirm that the linear contact model, the chosen stiffness and damping coefficients, and the overall numerical implementation in ROCKY provide an adequate representation of the real charge kinematics, and that the model can be used with confidence to predict charge behaviour and, by extension, wear patterns under industrial operating conditions that were not directly tested experimentally.

Fig. 5. Process of measuring worn liners and dismantling of worn liner plates (characteristic wear profile)

The practical value of a verified DEM model lies in its ability to translate charge kinematics and contact force histories into quantitative wear predictions. Because DEM resolves the spatial distribution of impact energy and contact pressure across the liner surface rather than a single averaged value, it becomes possible to map the regions of the liner subject to the most severe impact wear, to estimate the rate at which liner thickness and geometry change over an operating campaign, and to relate these predictions back to operating parameters that can be controlled in practice, namely rotational speed, fill level, and ball size distribution. In the underlying study, the optimized operating regime, derived from the DEM-informed analysis, increased fill level from 32% to 42% and rotational speed from 12.5 to 14.2 rpm relative to the baseline regime, illustrating how simulation results were translated into concrete recommendations for mill operation.

A further extension explored in the research couples DEM-derived contact and impact statistics with acoustic monitoring of the mill, using wavelet power spectral analysis of the noise signal as a non-intrusive proxy for internal impact intensity. As liner wear progressed over an extended observation period, the spectral power in the informative 20–150 Hz frequency band, which corresponds to ball–liner impacts, showed a consistent downward trend, dropping on average from about –55 dB to about –80 dB over a 250-second analysis window. This decline in impact-related spectral energy is physically consistent with the DEM-predicted reduction in restitution and contact stiffness that accompanies a thinning, more compliant worn liner, and demonstrates how DEM simulation results can be linked to indirect, in-service diagnostic signals.

Discussion

The results obtained through this DEM-based methodology highlight several points of broader relevance to comminution research and mill operation. First, the strong sensitivity of contact forces and fall height to fill level and rotational speed confirms that DEM is necessary, rather than merely convenient, for accurate wear and energy analysis: lumped or empirical models cannot reproduce the nonlinear transition between cascading and cataracting regimes that governs impact severity. Second, the close agreement between the DEM model and the flash-stop experimental verification, with errors below 4% across all measured angles, supports the broader literature consensus that properly calibrated linear contact models are adequate for predicting bulk charge kinematics in tumbling mills, even though they simplify the true elastic–plastic behaviour of individual particle collisions. Third, coupling the DEM charge model with a structural model of the drive train extends the value of the simulation beyond the mill shell itself, allowing impact-driven vibration in the gearbox to be predicted and interpreted, which has direct implications for condition-based maintenance strategies in mining operations where transmission systems operate under elevated noise and impulsive loading.

A practical limitation of the approach, consistent with observations elsewhere in the DEM literature, is the relative scarcity of experimental data describing worn media and worn liner geometries, which constrains the validation of long-term wear evolution predictions as opposed to short-term kinematic predictions. Addressing this gap by combining periodic liner-thickness measurement campaigns, as performed in the underlying study at thirty-day intervals over several months, with DEM and acoustic monitoring represents a promising direction for closing the loop between simulation and field observation.

Conclusion

This paper has outlined a complete DEM-based methodology for simulating grinding media motion in ball mills, from the underlying Newtonian equations of motion and linear spring–dashpot contact model, through implementation in the ROCKY software environment, to coupling with a finite-element drive-train model and experimental verification against full-scale flash-stop measurements. The verified model reproduced the principal kinematic descriptors of the charge — shoulder, toe, departure, and impact-point angles — within 4% of measured values, and showed that fill level and rotational speed strongly govern both the impact energy delivered to the liner and the resulting impulsive vibration transmitted through the gearbox. These findings demonstrate that DEM simulation, when properly verified against physical measurements, provides a reliable basis for predicting wear distribution, optimizing operating regimes, and supporting acoustic-based condition diagnostics in industrial ball mills, offering a practical bridge between fundamental particle-scale mechanics and equipment-level durability and maintenance decisions.

DISKRET ELEMENTLAR USULI BILAN SHARLI TEGIRMONLARDA TUVURLOVCHI MUHIT HARAKATINI SIMULYATSIYA QILISH: METODOLOGIYA, TEKSHIRISH VA YEYILISHNI BASHORAT QILISHDA QO‘LLANILISHI

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ANNOTATSIYA Sharli tegirmonlarda maydalovchi muhit va futerovkalarning yeyilishini bashorat qilish donador zaryadning qanday harakatlanishi va tegirmon korpusiga ta'sir etishi haqida batafsil ma'lumotga ega bo'lishni talab qiladi, bu ma'lumotni to'liq hajmdagi sanoat ekspluatatsiyasidan bevosita olish mumkin emas. Ushbu maqolada kon-texnika uskunalarining chidamliligi va holat diagnostikasi bo'yicha ishlab chiqilgan Diskret Elementlar Usuli (DEM) simulyatsiya metodologiyasi taqdim etilgan bo'lib, u aylanuvchi sharli tegirmonda maydalovchi muhit harakatini va natijada yuzaga keladigan kontakt kuchlarini modellashtirish uchun mo‘ljallangan. Model har bir maydalovchi sharni Nyutonning ikkinchi qonuniga bo‘ysunuvchi alohida jism sifatida ko‘rib chiqadi va sharlararo hamda sharlar-futerovka o‘rtasidagi o‘zaro ta'sirlarni Kulon ishqalanishiga ega chiziqli prujina-damper kontakt modeli yordamida hal qiladi, vaqt bo‘yicha aniq "leapfrog" sxemasi bilan integrallaydi hamda ROCKY DEM dasturiy ta'minotida amalga oshiriladi. Simulyatsiyalar aylanish tezligi, to‘ldirish darajasi va shar diametrini qamrab olgan omilli ish sharoitlari to‘plami uchun o‘tkazildi hamda hosil bo‘lgan zaryad kinematikasi va kontakt kuchlari tegirmon qo‘zg‘alish tizimining chekli elementlar modeli bilan bog‘lanib, zarba ta'siridan kelib chiqadigan reduktor tebranishlarini baholashga imkon berdi. DEM modeli sanoat tegirmonida to‘liq hajmdagi "flash-stop" (to‘satdan to‘xtatish) tajribalari asosida tekshirildi, bunda bashorat qilingan zaryad burchaklari (yelka, oyoq, chiqish va zarba nuqtasi) o‘lchangan qiymatlar bilan 4% gacha xatolikda mos keldi. Natijalar shuni ko‘rsatadiki, to‘ldirish darajasi va aylanish tezligi kontakt kuchining kattaligi, tushish balandligi hamda kaskadli harakatdan kataraktli harakatga o‘tishga kuchli ta'sir ko‘rsatadi va DEM asosida olingan zarba statistikasi futerovkalarning yeyilishining akustik ko‘rsatkichlari bilan bog‘liqdir. Olingan xulosalar tasdiqlangan DEM simulyatsiyasi sanoat sharli tegirmonlarida yeyilishni bashorat qilish, ish rejimini optimallashtirish va holatga asoslangan diagnostika uchun ishonchli asos yaratishini ko‘rsatadi.

KALIT SO'ZLAR Discrete Element Method (DEM); ball mill simulation; grinding media motion; contact mechanics; ROCKY software; charge kinematics; liner wear prediction; impact energy distribution; drive-train vibration; condition diagnostics; cascading and cataracting motion; mineral processing equipment durability

МОДЕЛИРОВАНИЕ ДВИЖЕНИЯ ИЗМЕЛЬЧАЮЩЕЙ СРЕДЫ В ШАРОВЫХ МЕЛЬНИЦАХ МЕТОДОМ ДИСКРЕТНЫХ ЭЛЕМЕНТОВ: МЕТОДОЛОГИЯ, ВЕРИФИКАЦИЯ И ПРИМЕНЕНИЕ ДЛЯ ПРОГНОЗИРОВАНИЯ ИЗНОСА

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АННОТАЦИЯ Прогнозирование износа измельчающей среды и футеровки в шаровых мельницах требует детального знания того, как движется гранулированная загрузка и как она воздействует на корпус мельницы, — информация, которую невозможно получить непосредственно в условиях полноценной промышленной эксплуатации. В данной статье представлена методология моделирования методом дискретных элементов (DEM), разработанная в рамках докторского исследования по вопросам долговечности горно-шахтного оборудования и диагностики его состояния, для моделирования движения измельчающей среды и возникающих при этом контактных усилий во вращающейся шаровой мельнице. Модель рассматривает каждый измельчающий шар как дискретное тело, подчиняющееся второму закону Ньютона, и описывает взаимодействия между шарами, а также между шарами и футеровкой с использованием линейной контактной модели «пружина-демпфер» с кулоновским трением, интегрируя их во времени с помощью явной схемы «leapfrog»; реализация выполнена в программном обеспечении ROCKY DEM. Моделирование проведено для факторного набора рабочих условий, охватывающих скорость вращения, уровень заполнения и диаметр шаров, а полученные кинематические характеристики загрузки и контактные усилия были сопряжены с конечно-элементной моделью трансмиссии мельницы для оценки вибрации редуктора, вызываемой ударными нагрузками. Модель DEM была верифицирована путем сопоставления с полноразмерными экспериментами по внезапной остановке (flash-stop) на промышленной мельнице, при этом расчетные углы положения загрузки (плечо, подошва, точка отрыва и точка удара) совпали с измеренными значениями с погрешностью не более 4%. Результаты показывают, что уровень заполнения и скорость вращения в значительной степени определяют величину контактных усилий, высоту падения и переход от каскадного к катарактному режиму движения, а также что статистические данные об ударах, полученные на основе DEM, коррелируют с акустическими индикаторами износа футеровки. Полученные результаты свидетельствуют о том, что верифицированное DEM-моделирование обеспечивает надежную основу для прогнозирования износа, оптимизации рабочих режимов и диагностики состояния промышленных шаровых мельниц.

КЛЮЧЕВЫЕ СЛОВА Метод дискретных элементов (DEM); моделирование шаровой мельницы; движение измельчающей среды; контактная механика; программное обеспечение ROCKY; кинематика загрузки; прогнозирование износа футеровки; распределение энергии удара; вибрация трансмиссии; диагностика состояния; каскадное и катарактное движение; долговечность оборудования для переработки полезных ископаемых.

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УСОВЕРШЕНСТВОВАНИЕ КОНСТРУКЦИИ ШНЕКА

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АННОТАЦИЯ В статье приведены сведения о конструкции, принципе работы и областях применения существующих шнековых конвейеров. Рассмотрены конструкции различных типов, проанализированы последние патенты и указаны их недостатки. Подробно описан усовершенствованный шнековый конвейер, на который получен новый патент. В конце статьи приведены выводы

КЛЮЧЕВЫЕ СЛОВА шнек, сыпучий, конвейер, пластина, частота, производительность, стенд.

Введение

Винтовые (шнековые) конвейеры применяются в различных областях промышленности для транспортирования сыпучих, пылевидных, порошкообразных и реже мелкокусковых грузов.

К достоинствам винтовых конвейеров относятся надежность работы, простота конструкции, отсутствие наружных движущихся частей, а также возможность перемещения груза в герметичном кожухе.