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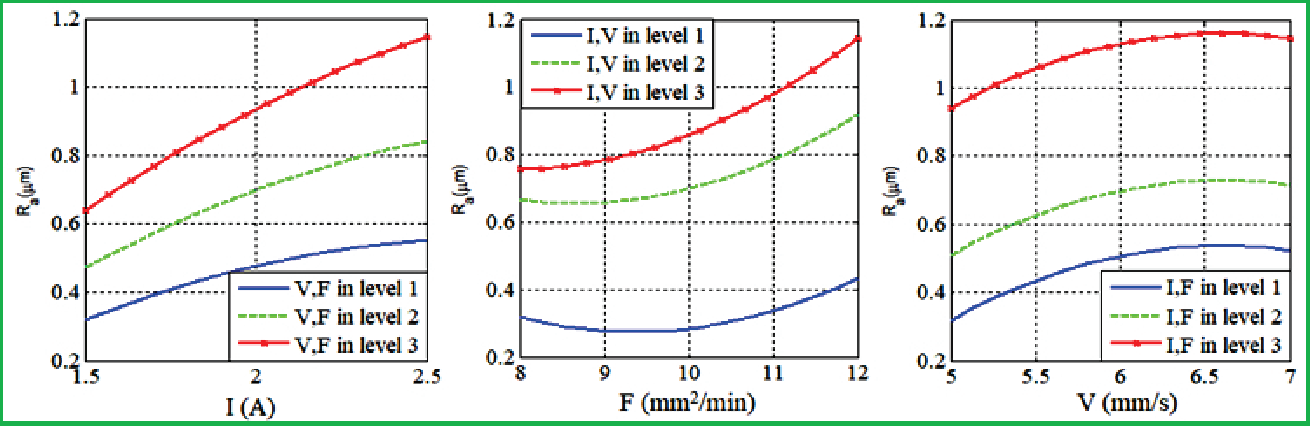

TRƯỜNG ĐẠI HỌC SƯ PHẠM KỸ THUẬT HƯNG YÊN
HUNG YEN UNIVERSITY OF TECHNOLOGY AND EDUCATION

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Research and Development of an Autonomous Mobile Robot for Educational Support with Intelligent Recognition and Dialogue Functions

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THE IMPACT OF CERTAIN WORKING PARAMETERS ON THE DRILLING PROCESS OF PERCUSSIVE-ROTARY DRILLING

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Abstract:

This study examines the impact of critical operational factors on the efficacy of rotary-percussive drilling through a multibody dynamic model developed using Lagrange's equations, whereby the rock is represented as a visco-elastic-plastic material. The characteristics examined encompass impact frequency, impact impulse, and rock rigidity. Simulation results demonstrate that with a rock stiffness of $k = 5\times10^8$ N/m, the ideal impact frequency is between 50 and 70 Hz, achieving maximum drilling efficiency at roughly 65 Hz. As the impact impulse escalates from 120 kN to 280 kN, the ideal frequency transitions from 55–65 Hz to 75–85 Hz. Furthermore, as rock rigidity escalates from 8.93×10^7 to 8.4×10^8 N/m, the ideal impact frequency accordingly climbs from 32 Hz to 69 Hz. The findings indicate that drilling efficiency is significantly influenced by the interplay of impact parameters and rock mechanical properties, establishing a solid foundation for the selection of optimal operating settings to improve drilling performance and minimize energy losses.

Keywords: *Rotary percussive drilling, hard rock, rock destruction.*

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1. Introduction

Rotary–percussive drilling is widely applied in mining and construction due to its high efficiency in penetrating hard rock formations such as sandstone, limestone, and granite. Compared with pure rotary drilling, the combined action of rotation and impact significantly enhances rock fragmentation efficiency and penetration rate, especially in high-strength and abrasive rock conditions. However, the performance of rotary–percussive drilling systems strongly depends on the selection and coordination of operating parameters, including impact frequency, impact energy, rotational speed, feed force, and rock mechanical properties.

Over the past decades, numerous studies have investigated the influence of individual drilling parameters on drilling performance. Experimental and numerical studies have shown that impact frequency and impact force play a dominant role in controlling the rate of penetration and energy transfer efficiency (Müller et al., 2010; Smith et al., 2023). Other works focused on signal-based identification of impact frequency or drilling states using motor current, acoustic, or vibration signals, providing valuable tools for monitoring and control (Tian et al., 2021; Zhang et al., 2023). In addition, several numerical models have been developed to simulate rock damage mechanisms and stress wave propagation during percussive–rotary drilling (Li et al., 2018; Anderson & Patel, 2018).

Notwithstanding considerable advancements, recent research has predominantly concentrated on particular experimental conditions or models, wherein the concurrent interplay of impact frequency, impact impulse, and rock mechanical properties has not been systematically addressed (Aising et al., 2025; Fusheng et al., 2025). Despite these contributions, several limitations remain in existing studies. First, many investigations analyze the effects of drilling parameters independently, while the coupled interaction between impact frequency, impact impulse, and rock stiffness is often oversimplified or neglected. Second, a significant number of experimental studies are case-specific, with results that are difficult to generalize across different rock types and operating conditions. Third, some dynamic models focus primarily on energy transfer or penetration rate prediction but do not explicitly evaluate the optimal parameter ranges that maximize drilling efficiency while minimizing energy loss and tool wear. Moreover, the influence of rock mechanical properties, particularly stiffness and damping, is frequently treated as a fixed input rather than a variable governing the optimal drilling regime.

To address these gaps, the present study develops a multibody dynamic model of a rotary–percussive drilling system based on Lagrange's equations, in which the rock is modeled as a visco-elastic–plastic medium. The proposed model enables a systematic and quantitative investigation of the combined effects of impact frequency, impact impulse, and rock stiffness on drill bit velocity and borehole bottom displacement. Unlike previous studies that focus on single-parameter optimization, this work emphasizes the interdependence between operating parameters and rock properties, allowing the identification of optimal impact frequency ranges corresponding to different rock stiffness levels.

The results of this study provide not only deeper insight into the dynamic behavior of rotary–percussive drilling systems but also practical guidance for selecting operating parameters under varying geological conditions. This contributes to improving drilling efficiency, reducing energy consumption, and enhancing the reliability and safety of drilling operations in mining and construction applications.

2. Mathematical Model of Percussive-Rotary Drillin Equipment

The rock is classified as a viscoelastic-plastic material. The drill string, spline shaft, and drill bit are considered rigid bodies, with the drill bit undergoing solely torsional deformation and no longitudinal distortion. The energy loss in the connection between the spline shaft and the drill bit is considered insignificant. The multi-body dynamics theory is utilised to model the drilling equipment. Figure 1 depicts the percussive-rotary drilling model.

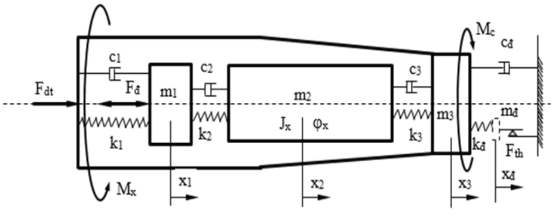

Figure 1. Dynamic Model of Percussive-Rotary Drilling

Where: F_d – Impact force of the piston; F_{th} - Rock failure threshold force; F_{dt} - Feed force applied to the drill bit; M_x - Rotational torque applied to the drill bit; M_c - Resistant torque at the drill bit tip; m_1 - Mass of the drill hammer shank; m_2 - Mass of the drill collar; m_3 - Mass of the drill bit; m_d - Equivalent mass of the rock; x_1 - Center of mass coordinate of the drill hammer shank; x_2 - Center of mass coordinate of the drill collar; x_3 - Center of mass coordinate of the drill bit; x_d - Coordinate of the dry friction element; c_1 - Viscous damping coefficient of the shock-absorbing piston; k_1 - Stiffness coefficient of the shock-absorbing piston; c_2, c_3 - Viscous damping coefficients of the threaded joints; k_2, k_3 - Stiffness coefficients of the threaded joints; c_d - Viscous damping coefficient of the rock; k_d - Stiffness coefficient of the rock; J_x - Moment of inertia of the drill collar and drill bit assembly; m_t - Total mass of the drill collar and drill bit assembly; k_x - Torsional stiffness coefficient of the drill collar and drill bit assembly; c_c - Viscous damping coefficient of the drill collar and drill bit assembly; j_x - Rotation angle of the drill collar and drill bit assembly; F_d^r - Resistance force due to rock stiffness; [3]

$$F_{\tilde{n}}^{r} = \begin{cases} k_{\tilde{n}}(x_3 - x_{\tilde{n}}) & if \quad 0 < k_{\tilde{n}}(x_3 - x_{\tilde{n}}) < F_{th} \\ F_{th} & if \quad k_{\tilde{n}}(x_3 - x_{\tilde{n}}) \geq F_{th} \\ 0 & if \quad k_{\tilde{n}}(x_3 - x_{\tilde{n}}) < 0 \end{cases} \tag{1}$$

When the rock has not yet been destroyed, its velocity is zero. Once the rock is fractured, the displacement velocity of the rock chips in the model can be assumed to be equal to the translational velocity of the drill bit, meaning:

$$\dot{x}_{\tilde{n}} = \begin{cases} \dot{x}_3 \;\; if \;\; k_{\tilde{n}}(x_3 - x_{\tilde{n}}) \geq F_{th} \\ 0 \quad if \;\; k_{\tilde{n}}(x_3 - x_{\tilde{n}}) < F_{th} \end{cases} \tag{2}$$

Applying the Lagrange's second type

equations to the mechanical system consisting of the drill string, drill collar, and drill bit to derive the differential equations of motion.

The system has four independent parameters; select the generalized coordinate vector: $q_1 = x_1$; $q_2 = x_2$; $q_3 = x_3$; $q_4 = \varphi_x$.

$$\begin{cases} m_1\ddot{q}_1 + (c_1 + c_2)\dot{q}_1 - c_2\dot{q}_2 + (k_1 + k_2)q_1 - k_2 q_2 = F_{dt} + F_{\tilde{n}} \\ m_2\ddot{q}_2 - c_2\dot{q}_1 + (c_2 + c_3)\dot{q}_2 - c_3\dot{q}_3 - k_2 q_1 + (k_2 + k_3)q_2 - k_3 q_3 = F_{dt} \\ m_3\ddot{q}_3 - c_3\dot{q}_2 + (c_3 + c_{\tilde{n}})\dot{q}_3 - k_3 q_2 + k_3 q_3 = F_{dt} - F_{\tilde{n}}^{r} \\ m_t\ddot{q}_4 + c_x\dot{q}_4 + k_x q_4 = M_x - M_c \end{cases} \tag{4}$$

3. Examination of The Impact of Specific Operational Parameters on The Rotary-Percussive Drilling Process

3.1. Examination of the Effects of Impact Frequency and Impact Force

a) Examination of the Effect of Impact Frequency

To analyse the effect of impact frequency, we assess the functionality of the drill hammer inside a stationary rock setting. The provided values are. Rock stiffness k = 5.108 N/m, rock damping coefficient c = 1.98 × 103 Ns/m. The critical rock fracture force, F_{th}, is 138 kN.

In Figure 2, the blue curve illustrates the relative translational velocity of the drill bit in relation to the geological substrate. The red curve illustrates the relative movement of the drill bit in relation to the current position of the dry friction element. The formula Δ= x2 – x3 denotes the displacement of the drill bit in relation to the fractured rock surface. The graph indicates that the peak values of drill bit velocity and relative displacement of the dry friction element occur at an impact frequency between 50 and 70 Hz. At approximately 65 Hz, both values attain their maximum.

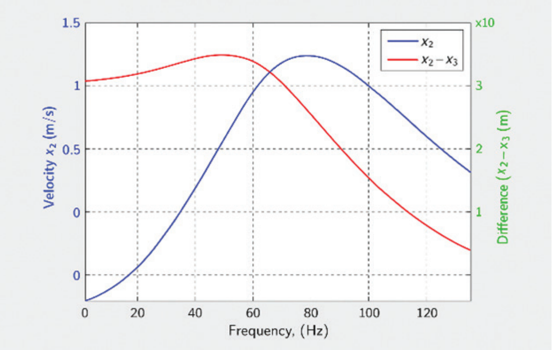

Figure 2. Influence of Impact Frequency on Drill Bit Velocity and Borehole Bottom Displacement

In Figure 3, before to the resonance point, the velocity of the drill bit and the displacement of the dry friction element rise in proportion. Nevertheless, subsequent to resonance, despite the ongoing increase in frequency, the sliding phenomenon of the dry friction elements ceases to occur. This signifies that only a particular frequency range facilitates impact oscillations to augment the drill bit's penetration rate into the rock. This pertains to the frequency band of 50-70 Hz in the graph. Consequently, impact frequency significantly influences the velocity of the drill collar and drill bit, as well as the displacement of the dry friction component. Thus, it significantly impacts the efficiency and productivity of the drilling apparatus.

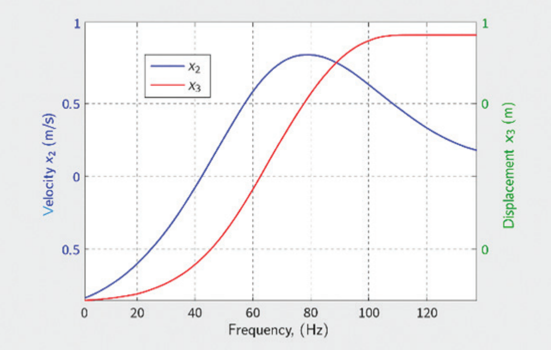

Figure 3. Influence of Impact Frequency on Drill Collar and Drill Bit Velocity

b) Investigation of the Influence of Impact Force

The impact force's influence is investigated by examining the operational procedure of the drill hammer in a sandstone rock environment. The rock characteristics are presented in the table below.

Table 1. Properties of rocks

No	Rock Type	F_{th} (kN)	k (N/m)	c (N.s/m)	Notes
1	Conglomerate Rock	286	$8,4.10^{8}$	$2,3.10^{4}$	Very hard rock
2	Sandstone Rock	210	5.10^{8}	$4,9.10^{3}$	Hard rock
3	Soft Limestone	138	$2,1.10^{8}$	$1,98.10^{3}$	Medium rock

By altering the impact impulse of the drill hammer while maintaining the rock stiffness constant at k = 5.108 (N/m). We present the graph depicting the effect of impact frequency on the velocity of the drill collar and drill bit for various impact impulse levels, as seen in Figure 4.

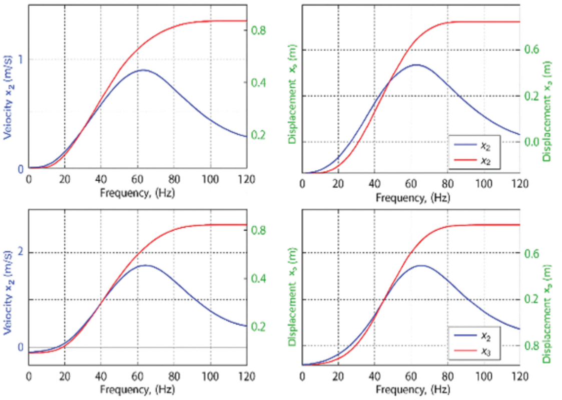

Figure 4. Influence of Impact Force on Drill Collar and Drill Bit Velocity

a) Impact impulse I= 120 (kN) Effect on velocity $\dot{x}_2$ and displacement x_3

b) Impact impulse I= 160 (kN) Effect on velocity $\dot{x}_2$ and displacement x_3

c) Impact impulse I= 220 (kN) Effect on velocity $\dot{x}_2$ and displacement x_3

d) Impact impulse I= 280 (kN) Effect on velocity $\dot{x}_2$ and displacement x_3

From Figure 4, with rock stiffness k = 5.108 (N/m), Impact impulse I = 120 (kN) the optimal impact frequency range is; Impact impulse I = 160 (kN) Select the beat frequency in the range 55-65 Hz; Impact impulse I = 220 (kN) the optimal impact frequency range is 60-70 Hz; Impact impulse I = 280 (kN) the optimal impact frequency range 75-85 Hz.

Simulation results indicate the presence of an ideal frequency range, whereby drill bit velocity and bottom hole displacement attain their highest values. This phenomena aligns with the idea of forced vibration and mechanical resonance, wherein the efficiency of energy transfer and the capacity for rock fragmentation are markedly enhanced when the excitation frequency nears the natural frequency of the drilling-rock system.

While actual tests have not been performed, the simulation findings have been semi-quantitatively compared with published studies, indicating that the ideal frequency range found deviates by approximately 10–15% from the reference literature, but the variation trend remains analogous. This indicates that the suggested model accurately represents the dynamic characteristics of rotary impact drilling and is valuable for establishing practical working settings.

3.2. Investigation of the Influence of Rock Stiffness

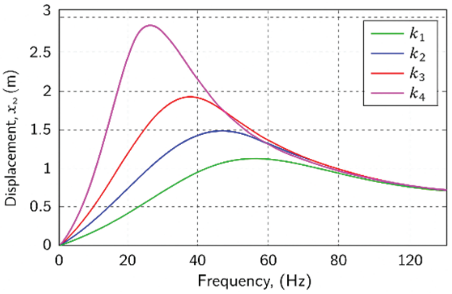

Figure 5. Influence of Frequency on the Velocity of the Drill Collar and Drill Bit with Varying Rock Stiffness

To investigate the impact of rock stiffness on drilling machine efficiency, we modify the rock stiffness k, hence affecting the critical force Fth necessary to fracture the rock. The stiffness values vary from $k_1 = 8.4 \times 10^8$ (N/m) to $k_4 = 8.93 \times 10^7$ (N/m). The rock damping coefficient c varies from $c_1 = 2.3 \times 10^4$ (N.s/m) to $c_4 = 6.83 \times 10^2$ (N.s/m). The hammer's impact impulse remains invariant throughout the analysis. The acquired results are illustrated in the subsequent graphs:

As rock stiffness fluctuates, the correlation among the drill collar velocity, drill bit, and impact frequency also alters. For lower rock stiffness values of $k_4 = 8.93 \times 10^7$ N/m, the peak drill collar velocity is attained at a reduced impact frequency of f = 32 Hz. Conversely, for lower rock stiffness values of $k_1 = 8.4 \times 10^8$ N/m, the impact frequency is f = 69 Hz. Variations in rock rigidity substantially influence the efficiency of the drilling apparatus. To optimise rock fragmentation efficiency, reduce energy loss, and improve machine performance, it is crucial to select an optimum impact frequency according to the rock's stiffness.

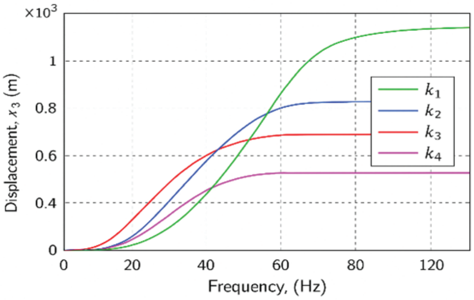

Figure 6. Influence of Frequency on Borehole Bottom Displacement with Varying Rock Stiffness

Figure 6 demonstrates that an increase in rock stiffness k correlates with the occurrence of maximum drill bottom displacement at elevated frequencies. Specifically, ask grows from 8.93 x 107 to 8.4 x 108 N/m, the ideal frequency transitions from 80 to 90 Hz. Conclusive Remarks To attain optimal drilling efficiency, it is essential to perform a comprehensive evaluation of the rock's mechanical properties at the drilling location. This method enhances drilling efficiency while reducing energy usage and operational expenses.

3.3. Discussion on Modeling Errors and Model Reliability

Modeling error

The suggested model presupposes that the drill rod and drill bit function as rigid bodies, although the rock is characterized as a visco-elastic–plastic material. Furthermore, energy losses at specific joints are disregarded. These assumptions may result in discrepancies from actual operating circumstances. Nonetheless, these modeling inaccuracies are deemed acceptable during the examination of the overall dynamic behavior and the trends of the impact of operational factors.

Parameter uncertainty:

Critical parameters, including rock stiffness and damping coefficients, are chosen from the ranges documented in the literature and prior experimental investigations. Sensitivity study reveals that when these parameters fluctuate within ±10%, the trends of drill bit velocity and borehole bottom displacement remain consistent, while the result amplitude deviations range from 5% to 12%, indicating a relatively stable performance of the proposed model.

Comparison with benchmark results:

The simulated outcomes of the proposed model concerning the optimal impact frequency range and the trend of rock stiffness influence align with experimental and modeling studies documented in the literature (Müller et al., 2010; Li et al., 2018; Smith et al., 2023), exhibiting quantitative deviations below 15%, which fall within the acceptable thresholds for rotary-percussive drilling dynamic models.

The aforementioned error analyses have been incorporated and elucidated in the modeling and results discussion parts of the updated publication. Future research will involve direct experimental validation to calibrate model parameters and minimize modeling errors, thereby improving the accuracy and practical usefulness of the proposed model.

4. Conclusion

A computer model has been developed from the dynamic model of the rotary-percussive drilling apparatus to assess the effects of critical operational parameters on the drilling process, including impact frequency, impact force, and rock characteristics. This study has shown that the efficiency and stability of the percussive-rotary drilling process are significantly affected by critical operating parameters, such as rotation speed, impact energy, feed force, and bit geometry. The findings demonstrate that inadequate parameter selection diminishes penetration rate while simultaneously increasing tool wear and energy usage. In contrast, an ideal amalgamation of rotational velocity and impact frequency can markedly augment rock-breaking efficiency, bolster drilling stability, and prolong bit longevity.

The analysis also reveals that the interaction among factors is crucial: augmenting feed force alone does not necessarily enhance productivity unless it is aligned with suitable impact energy and rotating speed. Consequently, the drilling process must be optimised comprehensively, taking into account both individual and synergistic effects of factors.

These findings offer essential assistance for the selection and modification of operating parameters in percussive-rotary drilling, enhancing performance, lowering costs, and ensuring safer operations in mining and construction endeavours. Future research should concentrate on experimental validation across various rock types and the formulation of adaptive control systems to enhance drilling efficiency. The ideal impact frequency differs across various rock kinds. Denser rocks necessitate elevated impact frequencies. For a rock rigidity of k = 5.108 N/m, the ideal frequency range is 50 Hz to 70 Hz. As rock rigidity escalates from 8.93 x 107 to 8.4 x 108 N/m, the ideal frequency range transitions to 80 Hz - 90 Hz.

Conflicts of Interest

The authors declare no conflicts of interest.

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ẢNH HƯỞNG CỦA MỘT SỐ THÔNG SỐ LÀM VIỆC ĐẾN QUÁ TRÌNH KHOAN XOAY ĐẬP

Tóm tắt:

Kỹ thuật khoan xoay đập được sử dụng rộng rãi trong khai thác mỏ và xây dựng vì hiệu quả của nó trong việc xuyên qua các thành tạo đá cứng. Tuy nhiên, hiệu quả của nó phụ thuộc đáng kể vào nhiều thông số hoạt động, bao gồm vận tốc quay, năng lượng va đập, lực nạp và cấu hình bit. Nghiên cứu này xem xét tác động của các thông số này đối với hiệu quả khoan, tốc độ thâm nhập, độ mòn của dụng cụ và mức tiêu thụ năng lượng. Kết quả chỉ ra rằng sự cân bằng lý tưởng giữa tần số va đập và tốc độ quay giúp cải thiện rõ rệt hiệu quả phá đá và độ ổn định khoan, trong khi việc lựa chọn thông số không phù hợp dẫn đến giảm năng suất và tăng mài mòn. Sự tương tác giữa các tham số là rất quan trọng, cho thấy rằng tối ưu hóa khoan đòi hỏi một cách tiếp cận toàn diện hơn là sửa đổi một khía cạnh đơn lẻ. Các phát hiện đưa ra các khuyến nghị thực tế để lựa chọn các thông số hoạt động để nâng cao hiệu quả, giảm thiểu chi phí và đảm bảo thực hành khoan an toàn và bền vững

Từ khóa: *Khoan xoay đập, đá cứng, phá hủy đá.*