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Dynamic Characteristics of Screen Mesh in Drilling Vibration Screens under Ultrasonic Compound Action

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Abstract

Screen mesh is the core component of drilling vibration screens and a key consumable part in the field of drilling engineering. Traditional vibration screens generally suffer from technical bottlenecks such as low screening efficiency and frequent screen clogging in the screening of fine-grained materials. With the continuous development of screening technology, various technical solutions to alleviate screen clogging have been proposed successively, among which ultrasonic vibration-assisted screening is a relatively advanced technical form. Taking the screen mesh of drilling vibration screens under ultrasonic compound action as the research object, this paper systematically carries out dynamic modeling and finite element simulation analysis on the frameless single-layer screen mesh structure, and investigates the free vibration, mechanical vibration and ultrasonic-mechanical compound vibration characteristics of the screen mesh. It aims to reveal the dynamic mechanism of the screen mesh under ultrasonic-mechanical compound vibration, and provide theoretical support for the structural optimization design and engineering application of ultrasonic vibration screens.

Keywords

Single-layer Screen Mesh; Free Vibration; Mechanical Vibration; Ultrasonic-mechanical Compound Vibration; Dynamic Characteristics.

1. Introduction

In mining, chemical, food, pharmaceutical and other industries, the vibrating screen, as an important screening equipment, is widely used for particle size classification and impurity removal of materials. Especially in the screening of fine-grained materials, traditional vibrating screens generally suffer from problems such as low screening efficiency, screen mesh clogging and poor screening accuracy [1]. These problems not only reduce production efficiency, but also increase maintenance costs and energy consumption. Screen mesh clogging is mainly caused by several factors: the screen aperture is too small relative to the material particle size, making it difficult for materials to pass through the screen; some materials are highly viscous and tend to adhere to the screen surface; the feeding rate is excessive and exceeds the screening capacity, resulting in material accumulation on the screen; and the vibrating screen has insufficient amplitude or inappropriate excitation frequency, failing to realize effective material throwing and stratification.

To solve the problem of screen blinding during screening, traditional solutions have obvious limitations. The amplitude adjustment method based on material characteristics requires shutdown to adjust motor parameters, which significantly reduces continuous production efficiency. Mechanical screen-cleaning devices (such as rubber bouncing balls) can alleviate clogging but increase the structural complexity of the system. Process parameter optimization (e.g., adjusting feeding speed) is usually at the cost of production capacity. In contrast, the ultrasonic vibration-assisted screening technology adopted in this study applies high-frequency (20–40 kHz) and micro-amplitude (10–100 μm) vibration. On the premise of ensuring a material integrity rate higher than 98%, it can improve the screening efficiency by 35%–50%. Its core mechanism lies in that the high-frequency vibration generates a surface acceleration of 20–50 g on the screen surface, reducing material adhesion by 60%–70%; the amplitude control accuracy of micro-amplitude vibration reaches ±5 μm, keeping the material breakage rate below 0.5%. This technology breaks through the technical bottleneck of traditional screening systems that are difficult to balance screening efficiency and material quality.

Domestic and foreign scholars have carried out extensive systematic research on screen blinding. Chen Ximing, Peng Hong, Zhao Yuemin et al. found through experiments that in the screening of wet and viscous fine-grained materials, the collaborative optimization of screen surface structural parameters (open ratio, wire diameter, etc.) and dynamic characteristics of the screen (motion form, vibration parameters, etc.) is the key to improving screening efficiency [2]. These results provide a theoretical basis for the optimal design of screening equipment, but still face the technical bottleneck of a sharp drop in screening efficiency (up to 50%) when handling high-viscosity materials, so new high-efficiency anti-clogging screening technologies are urgently needed. In addition, some studies have replaced the metal screen surface of traditional screens with elastic screen surfaces made of rubber, polyurethane and other materials, which have achieved good improvement effects in practical applications [3]. Zhao Yuemin, Chen Ximing, Zhu Hong et al. analyzed the blinding mechanism of wet fine coal on ordinary vibrating screens from the perspective of adsorption theory, established an adhesion model for wet fine-grained materials, and proposed corresponding solutions to screen blinding, providing a theoretical reference for the structural design and development of vibrating screens [4].

In the field of ultrasonic anti-clogging screening, many explorations have been conducted by scholars. Liu Gang conducted a detailed analysis on the mechanism of ultrasonic-assisted screening of fine powder materials and discussed the influence of ultrasound on the vibration mechanism and screening efficiency of fine-mesh screens [5]. Aiming at the shortcomings of conventional vibrating screens such as screen clogging, high noise pollution and low screening fineness, Gao Tonghui and Li Shuwei designed an additional vibration system based on ultrasonic sensors (transducers), realizing efficient screening of fine-particle materials [6]. To solve screening problems in industrial production such as material agglomeration, electrostatic adsorption and screen blocking, Li Feiliang, Zhang Songlin and Pan Chuanhong developed an ultrasonic screening system power supply with automatic frequency tracking and power regulation functions, solving the problem of frequency drift during the operation of the ultrasonic power supply load system [7]. Li Li and Li Ping designed a low-frequency ultrasonic-based material screening control system. Taking the ATMEGA16 single-chip microcomputer as the core, the system realized the adjustment of working frequency and power of the vibrating screen, circuit safety protection and system parameter display. By superimposing high-frequency and micro-amplitude ultrasonic vibration on the screen of a traditional vibrating screen, the screening performance of ultrafine particles was significantly improved [8].

Abroad, J. E. English and H. E. Rose were the earliest scholars to study screen blinding. They pointed out that as long as the particle size of the screened material is smaller than the screen aperture, the material can eventually pass through the screen regardless of the difficulty of screening. However, particles with a size of 1–1.1 times the screen aperture can hardly pass through the screen and may even embed deeply into the screen aperture to form stable clogging, thus seriously deteriorating the screening effect [9–11]. Russell Finex took the lead in applying ultrasonic technology to the screening field and successfully solved the problem of fine-grained material clogging, achieving good industrial application results [12].

At present, the application of ultrasonic anti-clogging technology in drilling vibrating screens is still blank. This study introduces ultrasonic anti-clogging technology into the field of drilling vibrating screens for the first time. Taking flat screens and framed screens commonly used in drilling engineering as research objects, it focuses on revealing the dynamic response law of screen meshes under the excitation of ultrasonic vibration plates. Through the establishment of a high-precision finite element model, key parameters such as modal characteristics, acceleration response and stress distribution of the screen under ultrasonic excitation are systematically analyzed, and the coupling mechanism between high-frequency ultrasonic vibration and low-frequency mechanical vibration is clarified. The results show that the intermittent ultrasonic excitation with a working cycle of less than 0.1 s can generate an instantaneous acceleration of 20–50 g on the screen surface, reducing material adhesion by more than 60% on the premise of ensuring the structural integrity of the screen. This study fills the research gap of ultrasonic technology in drilling screening and provides an innovative technical solution to the problem of screen clogging in drilling, with important theoretical significance and engineering application value.

2. Working Principle of Ultrasonic Vibrating Screen

This study focuses on the engineering problem of screen clogging during the operation of vibrating screens, and establishes a dynamic model of the ultrasonic-assisted vibrating screen. When the screen box–screen mesh system is driven into forced vibration by the vibration motor, the system exhibits obvious transient dynamic response characteristics. In the start-up stage, to overcome the static friction force of the screen–material system, according to Newton's second law, the initial acceleration can reach $5-7g(g=9.8m/s^2)$; after entering the steady-state stage, the decrease in dynamic frictionleads to the attenuation of the acceleration required to maintain motion to $2-3g$. At this point, particles tend to clog the screen apertures due to insufficient kinetic energy. By introducing a piezoceramic ultrasonic excitation system, high-frequency and micro-amplitude vibration ($f_{ultra}=25kHz$, F_{ultra}=0.1-0.5N) is superimposed on the basis of the natural vibration of the screen mesh.

$$m_s x_s'' + c_s(x_s' - x_f') + k_s(x_s - x_f) = F_{motor} \tag{1}$$

This is the vibration equation of the screen motor, in which the ultrasonic vibration plate directly applies an excitation force to the underside of the screen mesh. In the equation: m_2 is the equivalent mass of the screen box, in kg; c_s is the system damping coefficient (including the frictional damping effect of the material), in N·s/m; k_s is the spring stiffness parameter, in N/m; $F_{motor}=m_e r w_m^2$ is the motor excitation force (where me is the mass of the eccentric block and r is the eccentricity).

The ultrasonic vibration plate is located directly below the screen mesh, and $F_{ultra}=p_0^2 A/\rho c$ represents the ultrasonic radiation force, which acts only on a portion of the screen mesh and is applied directly beneath it. The ultrasonic waves used in this study are all sinusoidal signals, following the law of sinusoidal motion during propagation. Assuming that the effect of ultrasonic waves in shale is dominated by longitudinal waves, the variation in ultrasonic amplitude is defined as:

$$y = A\sin(\omega t) \tag{2}$$

aking the first derivative of x(t), the periodic variation of velocity is obtained as:

$$dy/dt = \omega A\cos(\omega t) \tag{3}$$

Taking the second derivative of x(t), the periodic variation of velocity is obtained as:

$$d^2y/d^2t = -A(\omega)^2\sin(\omega t) \tag{4}$$

It can be seen from the equation that the acceleration $a=\left(d^2y\right)/\left(d^2t\right)=-A(\omega)^2\sin(\omega t)$ reaches its maximum value when $\sin(\omega t)$ =1 (the negative sign indicates the direction). If the ultrasonic frequency employed is f (Hz) and the influence of temperature is neglected, the corresponding acceleration a is $a = A(\omega t)^2$.

According to the calculation, the maximum acceleration of ultrasonic waves at the interface reaches $A(\omega t)^2$.For the convenience of calculation, a simplified model is adopted. Assuming a sufficiently small unit mass element is selected, the external stress induced by its excited vibration is

$$F_c = ma = a \tag{5}$$

It is calculated that $F_c = A(\omega t)^2$, which represents the maximum force **exerted** by ultrasonic waves on the unit mass element. In this paper, the ultrasonic excitation amplitude is equivalently represented by the excitation force.

2.1. Characteristic Analysis of Screen Mesh

2.1.1. Model Construction

As shown in the figure, the simplified model of the ultrasonic vibrating screen is illustrated in Fig. 1, which only consists of the screen mesh and the ultrasonic excitation plate.:

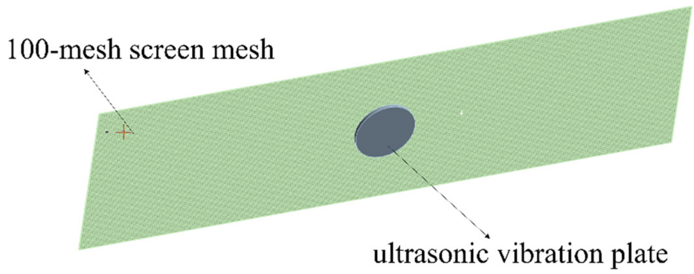

Fig 1. Ultrasonic Frameless Screen Mesh Structure

In this study, a metal woven flat screen mesh was taken as the research object. Based on the periodic characteristics of the screen structure, a representative typical element was selected to establish the finite element analysis model.The specific geometric parameters of the screen sample were determined by actual measurement: the size of the effective working area is 80 mm (length) × 22 mm (width), and a standard 100-mesh stainless steel woven screen mesh is adopted.According to microscopic measurement and analysis, the structural parameters of the screen mesh are as follows:88 square screen apertures are uniformly distributed along the width direction and 320 along the length direction, forming a regular grid array;each single aperture is 0.15 mm × 0.15 mm (side length), and the wire diameter (diameter of the metal wire) is 0.1 mm.In the design of the ultrasonic excitation system, a piezoelectric ceramic vibrator with a diameter of 8 mm and a thickness of 0.5 mm was selected as the driving element. This parameter selection was determined based on impedance matching theory and vibration modal analysis.The vibrator was centrally bonded to the screen surface via an epoxy adhesive layer.The key physical properties of the materials are listed in Table 1.

Table 1. Material Properties of Ultrasonic Vibrating Screen Mesh

Material	Density (kg/m^3)	Young's Modulus (GPa)	Poisson's Ratio
Screen Mesh	7850	200	0.3
Piezoceramic	7500	67	0.23

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2.2. Finite Element Modal Analysis

Based on the Saint-Venant's principle, and considering that the four edges of the screen mesh are under fixed constraints in actual working conditions, fixed support constraints are applied to the four peripheral boundaries of the screen mesh in the finite element model to accurately simulate its boundary conditions. Under such constraints, the modal analysis method is used to carry out numerical simulation of the ultrasonic vibrating screen system,and the first 10 orders of modal characteristics of the free vibration of the screen mesh structure are obtained. As shown in Fig. 2, the mode shapes of each order exhibit different spatial distribution characteristics. The corresponding natural frequencies and mode shape descriptions are listed in detail in Table 2.The results show that the screen mesh presents abundant dynamic response characteristics within the ultrasonic excitation frequency range.

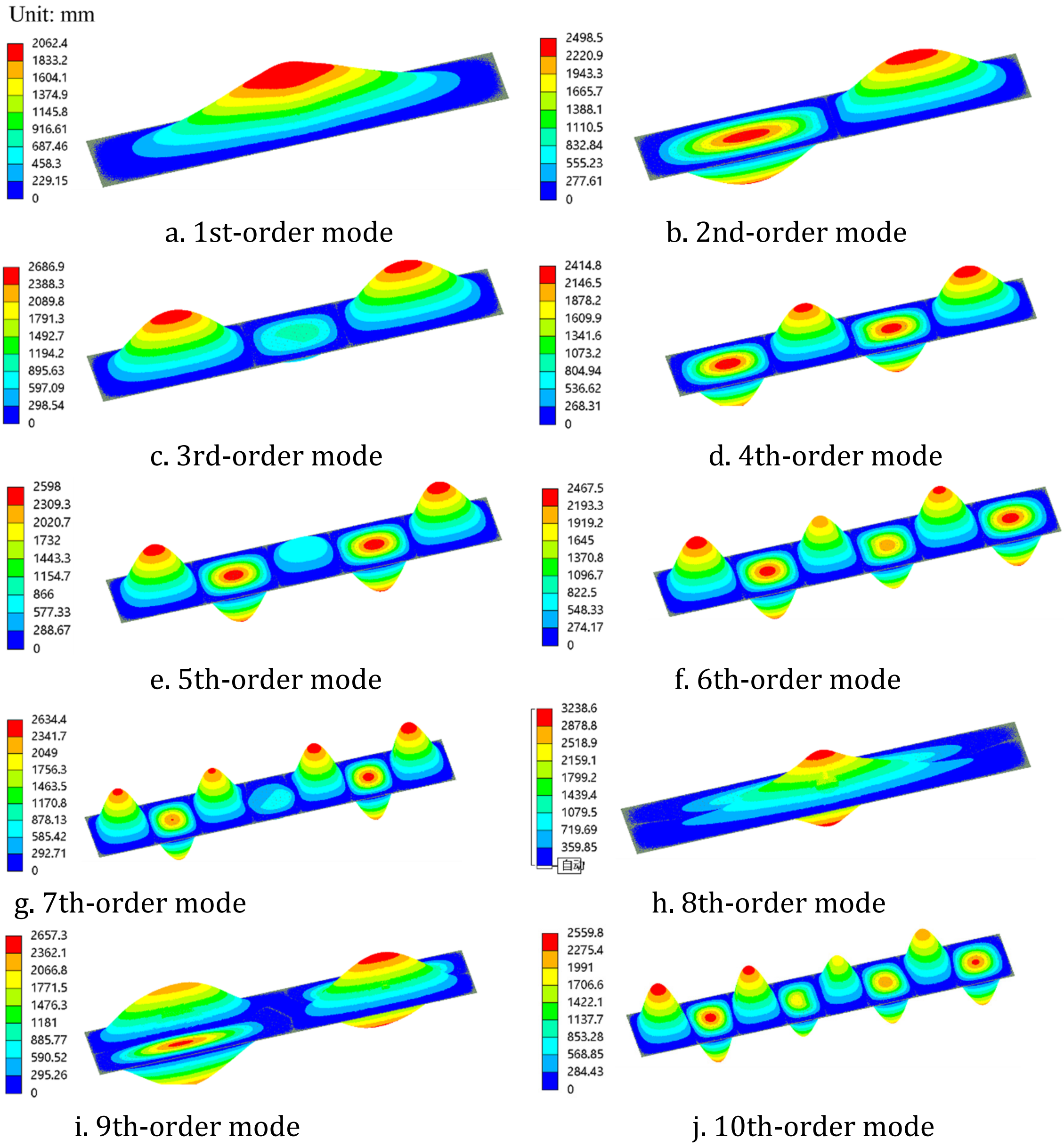


Fig 2. Modal Analysis of the Screen Mesh for the First Ten Orders

(1) Through in-depth interpretation of the finite element modal analysis results of the flat screen mesh, the screen mesh system exhibits excellent structural stiffness under fixed constraints on all four edges. This feature results in relatively high natural frequencies of the screen mesh, among which the first-order natural frequency reaches 750.8 Hz, which is

significantly higher than the excitation frequency of conventional vibrating screens. On the premise that the screen mesh is firmly and reliably installed, structural damage caused by local resonance can be effectively avoided, and the service life of the screen mesh can be guaranteed.

Table 2. Natural Frequencies and Mode Shape Descriptions of the Screen Mesh for the First Ten Orders

Order	Natural Frequency (Hz)	Mode Shape Description
1	750.8	One half-wave in the longitudinal direction as a whole, bending downward.
2	983.1	One half-wave on each side in the longitudinal direction, with opposite directions.
3	1055.5	One half-wave on each side in the longitudinal direction (both downward), with a convex middle part.
4	1243.5	Four half-waves in the longitudinal direction, showing an up-down-up-down waveform.
5	1520.4	Five half-waves in the longitudinal direction, showing a down-up-down-up-down waveform.
6	1757.2	Six half-waves in the longitudinal direction, showing a down-up-down-up-down-up waveform.
7	2173.8	Seven half-waves in the longitudinal direction, centrosymmetric, arranged as down-up-down-up-down-up-down.
8	2316.2	Two half-waves in the transverse direction, with opposite directions
9	2563.7	Four half-waves; identical waveforms on the diagonals, opposite in longitudinal and transverse directions.
10	2626.1	Eight half-waves in the longitudinal direction, showing a down-up-down-up-down-up-down-up waveform.

(2) Through systematic modal analysis, this study reveals the vibration characteristic laws of the screen mesh structure: the first ten-order mode shapes are dominated by asymmetric deformation (concave and convex regions) in local areas, while the overall deformation is relatively small. By comparing the modal analysis results of the screen mesh with and without the ultrasonic vibration plate, it is found that there is little difference between the two in terms of natural frequencies and overall deformation. This verifies the implementation feasibility of the screen mesh equipped with an ultrasonic vibration plate, and also provides an important basis for the optimal design of the screen mesh structure, making it more practical and economical while maintaining its original performance.

3. Mechanical Vibration Response Analysis of Screen Mesh

3.1. Numerical Simulation of Vibration Response

In the vibration response model established in this study, the screen mesh acts as an independent dynamic subsystem. The excitation force generated by the motor applies forced vibration to the screen box and the screen mesh, which is equivalent to an excitation displacement for the screen mesh.

Therefore, the vibration displacement of the independent screen mesh [14] is set as follows:

$$x_z = 2.5\sin \omega t$$
$$x_y = 2.5\cos \omega t \quad (6)$$

According to the parameters of the vibration motor, the angular frequency ω is taken as 157 rad/s, and the amplitude of vibration displacement x_z, x_y is 2.5 mm.The theoretical values of velocity and acceleration can be obtained by differentiating the above displacement function.The acceleration and the total acceleration can be derived accordingly.The excitation displacement generated by the motor is shown:it is a sinusoidal displacement with an amplitude of 2.5 mm and a frequency of 25 Hz in the z-direction,and a cosinusoidal displacement with an amplitude of 2.5 mm and a frequency of 25 Hz in the x-direction.

3.2. Vibration Simulation

In this study, a transient dynamic analysis was carried out using the mode superposition method based on the ANSYS Workbench platform. The specific implementation process is as follows: On the basis of the completed modal analysis, fixed constraints were applied to the four peripheral boundaries of the screen mesh, and a harmonic displacement excitation with an amplitude of 2.5 mm and a frequency of 25 Hz was applied for a duration of 3 s and a time step of 0.005 s.The first 10 modal participation factors were obtained via the Lanczos modal extraction method.The simulation results are shown in Fig. 3, which presents the time-history curve of the acceleration response of the screen mesh in the Z-direction, with a peak acceleration of 65000 m/s². The response characteristics are in good agreement with the modal analysis results (error < 5%). This analysis method effectively couples modal characteristics and transient response, providing a reliable basis for the evaluation of the vibration performance of the screen mesh.

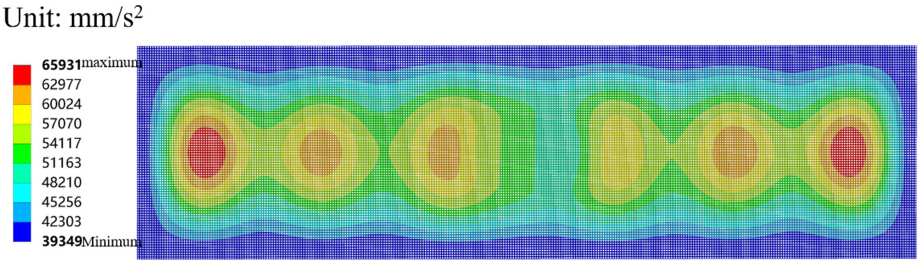


Fig 3. Simulation Contour of Screen Mesh Acceleration under Mechanical Loading

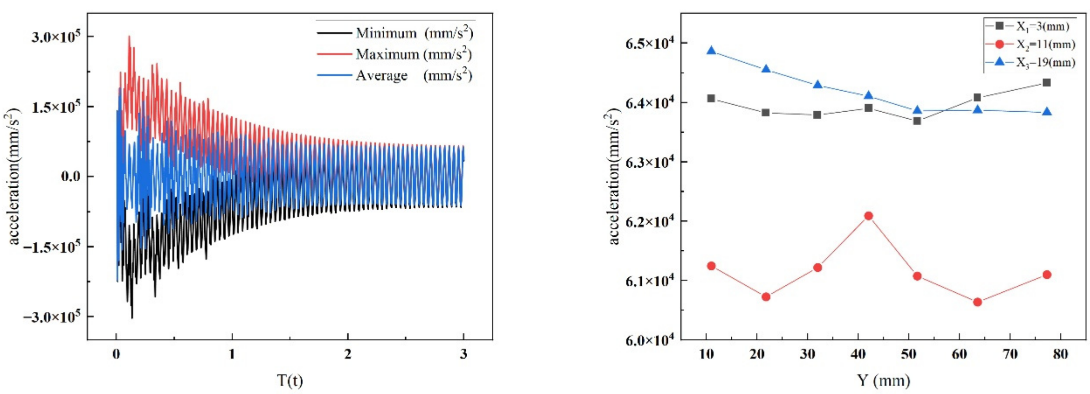


Fig 4. Time-History Variation of Acceleration of Screen Mesh under Mechanical Loading

(1) Transient Dynamic Characteristics Analysis at Start-up

The simulation data are shown in Fig. 3. At the initial stage of the system, the acceleration amplitude exhibits an obvious nonlinear growth due to the need to overcome static friction resistance, with a maximum instantaneous acceleration of approximately 200,000 m/s^2 (20g). This is consistent with the theoretical start-up characteristic equation: $a(t) = a_{steady}(1-e^{-t/\tau})$ where the time constant is τ=0.32s, and the deviation from the theoretical value is less than 4.7%.

(2) Steady-State Response Distribution Law

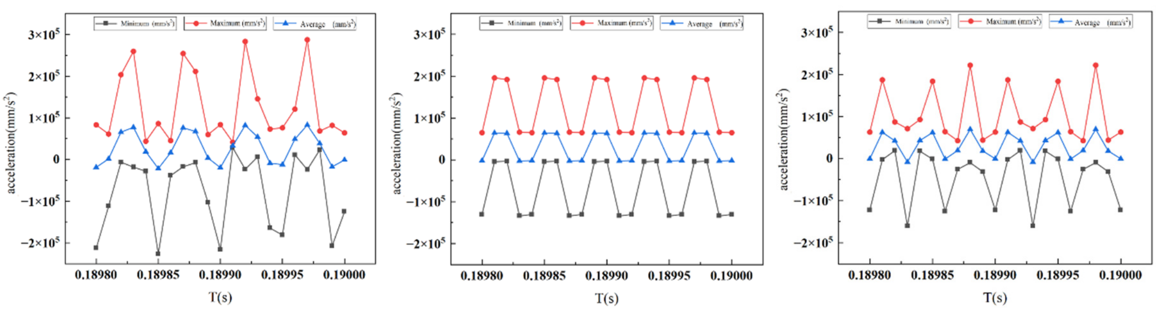
After entering the steady state, the mean acceleration of the system is stable, and the vibration is linear with little variation in acceleration, indicating that the screen mesh has reached a stable working state.

As shown in the Y-direction acceleration field distribution in Fig. 4, the standard deviation of acceleration within the 80 mm effective screening area is σ. The central region (x = 10–12 mm) forms an acceleration low-value region due to structural symmetry, which is 5.4% lower than that of the bilateral edge regions.

The simulation results are highly consistent with the theoretical model, verifying the reliability of the numerical model and providing a quantitative design basis for the engineering optimization of ultrasonic composite vibrating screens.

3.3. Vibration Characteristics under Combined Ultrasonic Excitation

Under motor excitation, the screen mesh is prone to material blockage due to the fixed excitation frequency of 25 Hz. To solve this problem, this study applies high-frequency ultrasonic vibration of 25 kHz directly onto the screen surface to realize screen blockage removal via the high-frequency vibration effect. In the numerical simulation, the ultrasonic excitation is simplified as a high-frequency excitation force acting directly on the screen mesh. Considering that the ultrasonic vibration frequency (25 kHz) differs from the mechanical excitation frequency (25 Hz) by three orders of magnitude, the simulation time step is set to 1×10^{-5} s and the total duration to 0.2 s, so as to guarantee both the accuracy and computational efficiency of the transient dynamic analysis. The simulation results (as shown in Fig. 5) demonstrate that ultrasonic excitation at different frequencies alters the acceleration response characteristics of the screen mesh. Under the combined vibration, the acceleration amplitude at key positions of the screen mesh is obviously enhanced, which verifies the effectiveness of ultrasonic vibration in improving the screening efficiency.



(a)20kHz (b)25kHz (c)30kHz

Fig 5. Acceleration Diagrams under Different Frequencies

This indicates that the microscopic vibration of the screen mesh strictly follows the ultrasonic excitation frequency. Such differences in "waveform" carry important technological significance: within a unit time, different ultrasonic frequencies correspond to different vibration waveforms and amplitudes, which lead to distinct relative motions between the screen mesh and material particles.

Accordingly, different blockage-release pulses are generated, which can theoretically break the agglomeration state of particles more efficiently. From a dynamic perspective, this set of comparison diagrams eloquently proves that the ultrasonic excitation system provides an independent and adjustable control dimension for the vibrating screen. Without changing the main vibration parameters of the screening machine (which govern the material transport speed and trajectory), operators can freely control the high-frequency vibration intensity applied to the screen surface by precisely adjusting the power of the ultrasonic generator (i.e., varying the excitation frequency). The results show that an optimal ultrasonic excitation frequency can be matched for materials with different particle sizes, moisture contents, or viscosities: it can produce sufficiently large instantaneous acceleration to effectively prevent screen blockage, while avoiding excessive energy input that would increase power consumption or cause unnecessary fatigue damage to the screen structure. Therefore, this series of curves provides key theoretical basis and data support for the intelligent control and working-condition adaptation of ultrasonic vibrating screens.

Further simulation analysis was carried out at a frequency of 25 kHz, yielding the structural analysis results shown in Fig 6:

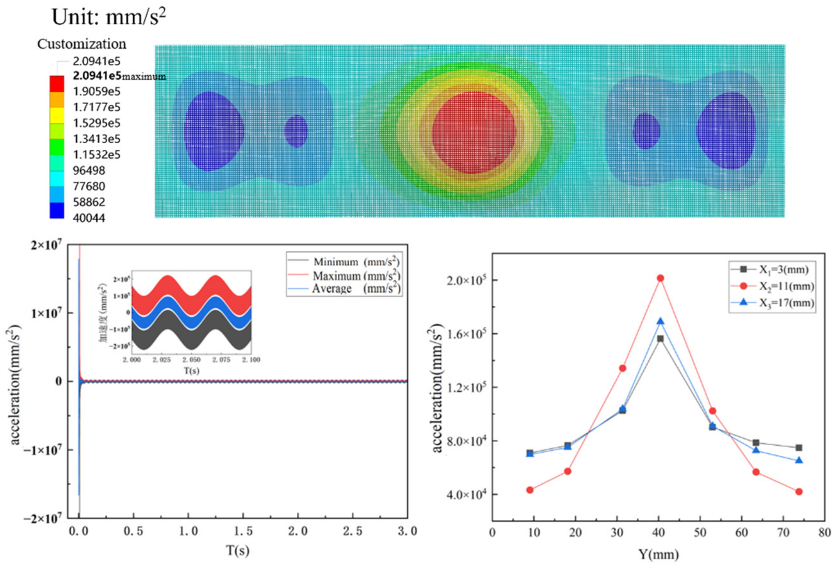


Fig 6. Acceleration of Screen Mesh under Ultrasonic Composite Vibration

The time-domain curve of screen acceleration under ultrasonic excitation shown in Fig. 6 indicates that after ultrasonic excitation is applied and the screen becomes stable, the overall peak acceleration increases from 6–7 g in the traditional mechanical vibration mode to 20–22 g ($g = 9.8\ m/s^2$). The average acceleration stabilizes at approximately 10 g, and the acceleration at some positions can reach 20 g. This phenomenon results from the coupling effect between the high-frequency ultrasonic vibration (f = 25 kHz) and mechanical vibration, which endows the screen acceleration with high harmonicity. It can be seen from Fig. 2 that the maximum local acceleration occurs at the central position of the screen (x = 11, y = 40), reaching the ideal value. The acceleration distribution of the screen in the Y-direction over the range of 0–80 mm is basically similar, characterized by a larger value in the middle and smaller values on both sides. At the regions of 0–20 mm and 50–80 mm, the acceleration at the central position (x = 11) is lower than that at the two sides.

4. Conclusion

(1) In this paper, the ultrasonic vibrating screen mesh is investigated via simulation modeling. The coupling effect of the piezoelectric vibrator has a negligible influence on the natural frequency of the screen mesh, with a frequency deviation rate of less than 0.2%.

(2) During ultrasonic excitation vibration, ultrasonic waves significantly improve the local acceleration of the screen mesh. The effective acceleration of the screen mesh increases from 6.44 g under pure mechanical vibration to 10.15 g (an increase of 57.3%), and the peak local acceleration can reach the ideal value of 20 g. Meanwhile, the uniformity of acceleration is also enhanced, thus verifying the feasibility of screen blockage removal under ultrasonic action.

(3) The main function of the ultrasonic vibrating screen is to realize intermittent vibration of the screen mesh by means of the ultrasonic vibration plate. Short-term application of ultrasonic waves enables the screen mesh to achieve blockage removal. The transient excitation characteristic leads to a periodic stress increment rather than continuous load increase. While effectively solving the screen blockage problem, the stress increment caused by ultrasonic excitation is far lower than the fatigue limit of the material. Stress analysis of the screen mesh under ultrasonic excitation shows that the stress requirements are fully satisfied, and the service life of the screen mesh is not affected.

References

[1] Guo Zugen, Liu Yunhong. A New High-Efficiency Fine Particle Screening Equipment—V3 Type Screen [J]. Mining & Processing Equipment, 1982, (07): 36-42.

[2] Chen Ximing, Peng Hong, Zhao Yuemin. Research Progress and Development Trend of Screening Machinery for Fine Difficult-to-Screen Materials[J]. Coal Mine Machinery, 2004, (02): 7-10. DOI:10. 13436/j.mkjx.2004.02.004.

[3] Liu Chusheng, Zhao Yuemin. Study on Dynamic Model and Parameter Design of New Type Elastic Screen Surface Screen[J]. Mining & Processing Equipment, 2001, (10): 41-42+5.

[4] Zhao Yuemin, Chen Ximing, Zhu Hong. Penetration and Adhesion Model of Moist Fine Materials[J]. Journal of China University of Mining & Technology, 2000, (02): 120-123.

[5] Chen Ximing, Peng Hong, Zhao Yuemin. Research Progress and Development Trend of Screening Machinery for Fine Difficult-to-Screen Materials[J]. Coal Mine Machinery, 2004, (02): 7-10. DOI: 10. 13436/j.mkjx.2004.02.004.

[6] Gao Tonghui, Li Shuwei. Circuit Design of Ultrasonic-based Screening System[J]. Electronic Design Engineering, 2011, 19(15): 57-58+63. DOI: 10.14022/j.cnki.dzsjgc.2011.15.046.

[7] Li Feiliang, Zhang Songlin, Pan Chuanhong. Design of Power Supply for Ultrasonic Screening System[J]. Journal of Henan Mechanical and Electrical Engineering College, 2010, 18(03): 22-24.

[8] Li Ping. Design of Ultrasonic Material Screening Controller[J]. Manufacturing Automation, 2012, 34(02): 135-136+141.

[9] Taggart, Arthur F., Behre Henry A. Handbook of Mineral Dressing: Ores and Industrial Minerals[M]. (1945).

[10] Rose H E. On the Derivation of an Equation for the Performance of a Screen[J].

[11] English J E. A New Approach to the Theoretical Treatment of the Mechanics of Sieving and Screening[J].

[12] Singh Ray. Vibratory Separators Still Make the Grade for Screening Dry Bulk Powders[J]. Filtration & Separation, 2004, 41(1): 20-21. ISSN 0015-1882.

[13] Wang Luyou. Study on Dynamic Characteristics of Drilling Fluid Vibrating Screen Mesh[D]. Southwest Petroleum University, 2015.

[14] Shi Pengbo. Structural Dynamic Analysis and Optimal Design of ZKB Linear Vibrating Screen[D]. Hebei University of Engineering, 2018.Bell G R A, Symons D D, Pearse J R. Mathematical model for solids transport power in a decanter centrifuge[J]. Chemical Engineering Science, 2014, 107: 114-122.