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Tension characteristics analysis of scraper chain of heavy-duty scraper conveyor with time-varying load

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ABSTRACT

With the intensification and large-scale of coal mining, scraper conveyors are developing towards high power, large volume, long haul distance and high reliability. It is more and more important to obtain the dynamic tension of the scraper chain with time-varying load. The purpose of this paper is to obtain the dynamic tension of scraper chains of the scraper conveyor with time-varying load. First, according to the structural characteristics and working environment of the scraper conveyor and the polygon effect of the sprocket, the scraper conveyor dynamics model under the action of the time-varying load is established by the finite unit method; Second, the load variation rule of the bearing section is explored when the scraper conveyor and shearer work together; Furthermore, the element resistance of each discrete element, the stiffness coefficient of the scraper chain and the influence of polygonal effect of sprocket wheel are analyzed; And then, the dynamic tension of the scraper chain is obtained by the Hilber-Hughes-Taylor (HHT) method; Finally, the validity of the scraper conveyor dynamic model is verified by the example analysis and field measurement experiment. The obtained results can provide a theoretical basis for the reliability evaluation and parameter optimization of the scraper conveyor.

Introduction

As one of the key equipment of large-scale, efficient and continuous fully mechanized coal mining, the scraper conveyor (Figure 1) completes the role of coal transport, but also the running track of shearer and the moving fulcrum of hydraulic support, so scraper conveyor occupies an extremely important position in the whole fully mechanized coal mining face. Heavy-duty scraper conveyor is a kind of large and complex mining machinery, its working environment is extremely complex and harsh\textsuperscript{1,2}. The chain drive system of the scraper conveyor consists of a large number of scraper chains and a small number of scrapers and sprockets. The scraper chain is connected to the two sprockets on the head and tail of the scraper conveyor, forming a closed circle\textsuperscript{3,4}. The performance of scraper chains has a direct impact on the overall reliability of the scraper conveyor, which has a high bearing capacity and strong environmental adaptability. In engineering, the dynamic characteristics of scraper conveyors are characterized by nonlinearity, time-varying and strong coupling\textsuperscript{5,6}.

At present, the research on dynamic characteristics of the scraper conveyor mainly focuses on performance simulation and prediction, component optimization design, dynamic design software development, etc. The basic theories applied mainly include the multi-rigid body dynamic method, the elastic wave theory, the finite element method, etc.\textsuperscript{7-10}. Scholars have achieved some research results in the dynamic analysis of scraper conveyors. Among them, He Baiyan et al.\textsuperscript{11} discretized the scraper chain drive system of the conveyor into the Kelvin-Vogit model, established the system dynamics simulation model considering the chain drive preload force and double motor drive, and analyzed the contact characteristics of the sprocket and scraper chain based on nonlinear finite element software. Wauge\textsuperscript{12} used mathematical models to discuss the dynamic characteristics of different drive types of scraper conveyors and their effects on chain tension. Szewerda et al.\textsuperscript{13} considered the longitudinal tilt of the scraper conveyor and analyzed its causes with the mathematical model of the scraper conveyor, so as to minimize the risk of failure. Li et al.\textsuperscript{14} adopted multi-body dynamic technology to establish a dynamic model of a new sprocket drive mechanism, and accurately simulated the meshing process of roller chain drive. Veselin et al.\textsuperscript{15} used the finite element numerical simulation method to analyze the stress of the scraper conveyor, and verified the correctness of the model through experiments. Lu et al.\textsuperscript{16} proposed a compound sliding mode control method based on the permanent magnet direct drive system to realize the smooth start of the scraper conveyor. Jiang et al.\textsuperscript{17} established a finite element model of the chain drive system of the scraper conveyor and studied the dynamic meshing characteristics of the scraper chain and sprocket. Wang et al.\textsuperscript{18} used the
discrete element method (DEM) to analyze the particle size and velocity distribution of lump coal under different transport speeds, transport angles and transport conditions, and analyzed the interaction between scraper conveyors and coal blocks. Lu et al. deeply analysed the longitudinal torsional vibrations of the chain drive system of the scraper conveyor.

In summary, scholars have made a lot of progress in the dynamic characteristics of scraper conveyors. However, from the point of view of the research content, the existing research only considers the uniform distribution of load on the scraper conveyor, which cannot truly reflect the tension change of the scraper chain when the scraper conveyor and shearer are used together in the coal mine. In view of the limitations of the previous studies, the Kelvin-Voigt model and point-by-point tension method were used to establish the dynamics model of the scraper conveyor with time-varying load. This paper analyzes the load variation rule of the scraper conveyor when it is used with shearer, and reveals the tension characteristics of scraper chain drive system.

Considering the time-varying load, the dynamic characteristics of the interaction between the scraper, the scraper chain and the non-constant falling coal of the scraper conveyor are very complicated. The complex and variable working load makes the scraper chain more prone to failure and the reliability is reduced. In order to guarantee the working efficiency of the synthesized mining face, it is inevitable to require the scraper chain to have higher reliability. In addition, the chain drive system of scraper conveyor contains countless degrees of freedom, however, the modeling process containing countless degrees of freedom is extremely difficult. Therefore, the finite unit method is used to discretize the chain drive system into a one-dimensional Kelvin-Voigt model containing a finite number of discrete elements, and the tension of the scraper chain is obtained by the Hilber-Hughes-Taylor (HHT) method. The results can provide theoretical support for fault prediction and reliability analysis of scraper chains. It is worth noting that the higher the number of discrete elements, the more accurate the calculation results are, but then the larger the calculation volume is.

Dynamic model of the scraper conveyor

Basics of Finite Element Method

The scraper chain assembly of the scraper conveyor (comprising the scraper chain and the scraper) can be regarded as a viscoelastic body. Among several commonly used viscoelastic models, Kelvin-Voigt model is more suitable to describe the viscoelastic characteristics of scraper chain components. As shown in Figure 2, the Kelvin-Voigt model is used here to describe the scraper chain component. The chain characteristics can be described by the Kelvin-Voigt model, which comprises a parallel arrangement of a damper and a linear spring. The damper and spring interact and work together to describe the characteristics of the scraper conveyor.

The descriptive equation of the Kelvin-Voigt model can be expressed as

\[ F_i = k_i(x_{i+1} - x_i) + c_i(\dot{x}_{i+1} - \dot{x}_i) \]  

(1)

where \( k_i \) is the stiffness coefficient; \( c_i \) is viscous damping coefficient; \( F_i \) is the tension; \( x_{i+1}, x_i \) are the displacement of \( i+1 \text{th} \), \( i \text{th} \) elements, respectively; \( \dot{x}_{i+1}, \dot{x}_i \) are the velocity of \( i+1 \text{th} \), \( i \text{th} \) elements, respectively.

As shown in Figure 3, there are two identical drive units in the scraper conveyor. According to the finite element model, the input torque is defined as

\[
\begin{align*}
T_h &= k_h(\theta_A - \theta_h) + c_h(\dot{\theta}_A - \dot{\theta}_h) \\
T_i &= k_i(\theta_B - \dot{\theta}_i) + c_i(\dot{\theta}_B - \dot{\theta}_i)
\end{align*}
\]  

(2)

in which \( \theta_A, \theta_B \) are the angular displacements of the head and tail motors, respectively; \( \dot{\theta}_A, \dot{\theta}_B \) are the angular velocities of the head and tail motors, respectively; \( \theta_h, \theta_i \) are the angular displacements of the head and tail sprockets, respectively; \( \dot{\theta}_h, \dot{\theta}_i \) are the angular velocities of the head and tail sprockets, respectively; \( k_h, k_i \) are the stiffness coefficient of coupling, respectively; \( c_h, c_i \) are the viscous damping coefficient of coupling, respectively.

Moreover, the dynamic equation of the \( i \text{th} \) element can be expressed as

\[ m_i\ddot{x}_i = F_i - F_{i-1} - f_i \]  

(3)

where \( F_{i-1} \) and \( F_i \) are the tension of the \( i-1 \text{th} \) and \( i \text{th} \) element, respectively; \( f_i \) is the frictional resistance; \( m_i \) is the lumped mass; \( \ddot{x}_i \) is the acceleration.

Considering the variation of the mass of the element, the dynamic differential equation of the discrete element can be expressed as

\[
\frac{d}{dt}(m_i\ddot{x}_i) = m_i\ddot{x}_i + \frac{dm_i}{dt}\ddot{x}_i = F_i - F_{i-1} - f_i
\]  

(4)
Dynamic Equations of the Scraper Conveyor  

As shown in Figure 3, the translational model of the chain drive system can be seen as a closed-loop model, approximately. According to the finite element method, the scraper conveyor is divided into 2n discrete elements with lumped masses. The elements are assumed to be elastically connected and modeled as Kelvin-Voigt modules.

According to the Eqs. (1), (2) and (3), the dynamic equations of the scraper conveyor can be expressed as

\[
\begin{align*}
\frac{1}{2} m_i R_i \ddot{\theta}_h + F_{2n} - F_1 &= \frac{T_h}{R_h} - f_h \\
m_i \ddot{x}_i + F_1 + F_{i-1} &= -f_i \quad (2 \leq i \leq n) \\
\frac{1}{2} m_i R_i \ddot{\theta}_t + F_n - F_{n+1} &= \frac{T_t}{R_t} - f_t \\
m_i \ddot{x}_i + F_1 + F_{i-1} &= -f_i \quad (n+2 \leq i \leq 2n)
\end{align*}
\]

in which, \(R_h, R_t\) are the pitch radius of the sprocket of the head and tail, respectively; \(f_h, f_t\) are the friction force of the head and tail, respectively; \(m_i, m_t\) are the lumped mass of the head and tail, respectively; \(\dot{\theta}_h, \dot{\theta}_t\) are the angular acceleration of the head and tail sprocket, respectively.

According to Eqs (1), (2) and (4), the dynamic equation of scraper conveyor considering the load changes can be expressed as

\[
\begin{align*}
\frac{1}{2} m_i R_i \ddot{\theta}_h + F_{2n} - F_1 &= \frac{T_h}{R_h} - f_h \\
m_i \ddot{x}_i + \frac{d}{dt} \dot{x}_i - F_1 + F_{i-1} &= -f_i \quad (2 \leq i \leq n) \\
\frac{1}{2} m_i R_i \ddot{\theta}_t + F_n - F_{n+1} &= \frac{T_t}{R_t} - f_t \\
m_i \ddot{x}_i + \frac{d}{dt} \dot{x}_i - F_1 + F_{i-1} &= -f_i \quad (n+2 \leq i \leq 2n)
\end{align*}
\]

The dynamic tension of the scraper chain can be deduced as the following form

\[
\begin{align*}
F_1 &= k_1(x_2 - R_i \dot{\theta}_h) + c_1(\dot{x}_2 - R_i \ddot{\theta}_h) \\
F_i &= k_i(x_{i+1} - x_i) + c_i(\dot{x}_{i+1} - \dot{x}_i) \quad (2 \leq i \leq n-1) \\
F_n &= k_n(R_i \dot{\theta}_h - x_n) + c_n(R_i \ddot{\theta}_h - \dot{x}_n) \\
F_{n+1} &= k_{n+1}(x_{n+2} - R_i \dot{\theta}_h) + c_{n+1}(\dot{x}_{n+2} - R_i \ddot{\theta}_h) \\
F_i &= k_i(x_{i+1} - x_i) + c_i(\dot{x}_{i+1} - \dot{x}_i) \quad (2 \leq i \leq n-1) \\
F_{2n} &= k_{2n}(R_i \dot{\theta}_h - x_{2n}) + c_{2n}(R_i \ddot{\theta}_h - \dot{x}_{2n})
\end{align*}
\]

Substitute Eq. (7) into Eq. (6), the dynamic differential equation matrix expression of scraper conveyor can be expressed as

\[
M \ddot{x} + C \dot{x} + Kx = F
\]

in which \(M\) is the mass matrix; \(C\) is the damping matrix; \(K\) is the stiffness matrix; \(F\) is the external force matrix.

The mass of each element in the dynamic model  

The mass of each discrete element in the dynamic model of scraper conveyor mainly includes the mass of the scraper chain component and the mass of the coal. These two parts are mainly discussed here. The mass of the scraper chain component can be considered constant, while the mass of the coal block shows periodic changes during the shearer’s periodic round-trip along the rack rail track of the scraper conveyor.

**The mass of the scraper chain component in each discrete element**  

The chain drive system of scraper conveyor is composed of the scraper chain and the scraper, then the scraper chain mass contained in each discrete element can be expressed as:

\[
m_{ce} = \left( n_{cn} \int_0^{L_{sc}} \rho_{sh}(x) \, dx + \sum_{i=1}^{N_{fb}} m_{fbi} \right) \frac{\Delta x}{L_{sc}}
\]

where \(m_{ce}\) represents the mass of the chain element, kg; \(n_{cn}\) is the number of scraper conveyor chains (the number of double chain scraper conveyor chains is 2); \(L_{sc}\) represents the total length of each scraper chain, m; \(\rho_{sh}(x)\) represents the linear density of the scraper chain, kg/m; \(x\) represents the length along the direction of the scraper chain, m; \(m_{fbi}\) represents the mass of the scraper, kg; \(N_{fb}\) indicates the number of scrapers contained in the scraper conveyor; \(\Delta x\) represents the length of the scraper chain element, \(\Delta x = L_{sc} / (2n - 2); 2n - 2\) represents the number of discrete elements divided by the scraper chain.
The mass of coal in each discrete element

(1) Mass of coal in each discrete element without load variation

As shown in Figure 4, the load of the scraper conveyor is evenly distributed on the bearing section. At this time, the mass of coal in each element is equal and constant

\[ m_{c,i}(t) = \frac{Q}{3.6v_0 \frac{L}{n-1}} \quad (n+2 \leq i < 2n) \]  

(10)

where, \( Q \) denotes the conveying capacity of the scraper conveyor, t/h; \( L \) denotes the length of the scraper conveyor, m; \( v_0 \) denotes the rated running speed of the scraper conveyor, m/s.

(2) Mass of coal in each discrete element with load variation

In the fully mechanized mining face, the shearer breaks the coal wall along the scraper conveyor, then the change of coal mass of each discrete element is complicated. Most of the coal mined by the shearer will directly fall to the middle trough of the scraper conveyor, and the other small part will gradually load to the scraper conveyor under the action of the shovel coal plate. As the scraper conveyor moves closely with the shearer under the action of hydraulic support, this paper approximates that the coal extracted by the shearer directly acts on the middle trough of the scraper conveyor. Therefore, the mass of the coal loaded to the scraper conveyor depends on the operating state and operating position of the shearer. This section mainly discusses the distribution of coal on the middle trough when the load changes are considered.

As shown in Figure 5, the scraper conveyor runs clockwise at a certain speed, and the shearer moves reciprocally along the length of the scraper conveyor. For convenience, the shearer runs from the head of the scraper conveyor (point A) to the end of the scraper conveyor (point B), which is called go down. Conversely, the shearer runs from point B to point A of the scraper conveyor, which is called go up. For the speed of scraper chain is larger than the traction speed of the shearer (\( v_0 > v_{sh} \)), the coal in the bearing section of the scraper conveyor is single-layer, and there is no multi-layer situation. As shown in Figure 5 (a), after the scraper conveyor runs smoothly, the shearer begins to go down from point A, and there is no coal in the bearing section (AB section). As shown in Figure 5 (b), as the shearer goes down, the coal mined by the shearer is distributed in AE section, and the linear density of coal in BE section is zero. As shown in Figure 5 (c), when the shearer moves to point B, the scraper conveyor is single-layer, and there is no multi-layer situation. As shown in Figure 5 (d), in the initial stage of shearer running, the coal composition of the bearing part of the scraper conveyor is relatively complex. The AE section represents the coal mined when the scraper conveyor is going down, the FE section represents the coal mined when the scraper conveyor is going up, and the line density of the coal in FB section is 0. As shown in Figure 5 (e), as the shearer continues to go up, the coal mined when the shearer goes down is gradually transported away, and the coal mined by the shearer continues to go up is distributed in the AF section only. As shown in Figure 5 (f), when the shearer goes to point A, there is no coal in the bearing part of the scraper conveyor, and the shearer has completed one mining cycle and is about to start the downward stage of the next cycle. In this way, the shearer circulates along the scraper conveyor and continuously carries out coal mining operations. The mass of the coal loaded to the scraper conveyor can be determined by the operating status and operating position of the shearer.

It is assumed that the mining height \( h_c \) and cutting depth \( b_w \) of the shearer are constant independent of the shearer position. Then the mass of the coal mined by the shearer can be expressed as:

\[ m_{sh}(x_{sh}) = \rho_m \int_{x_{sh}}^{v_2} h_c b_w dx_{sh} \]  

(11)

in which, \( x_1 \), \( x_2 \) respectively represent the starting and ending positions of the shearer, which can be expressed as a function of time; \( \rho_m \) is the average density of coal block (including coal, coal gangue, etc.) in coal wall of fully mechanized mining face.

According to Eq. 11, when the shearer runs 1 m, the mass of coal mined by the shearer can be expressed as

\[ m_{sh} = \rho_m h_c b_w \]  

(12)

As shown in Figure 5 (b), when the shearer is going down, the linear density of material in the BE section is 0, and the linear density of material in AE section can be expressed as

\[ q_d = \frac{v_{sh}}{(v_0 + v_{sh})} m_{sh} \]  

(13)

As shown in Figure 5 (d), when the shearer is running, the material linear density of the scraper conveyor is relatively complex. At this time, the scraper conveyor not only has the material loaded when the shearer is going down, but also may have the material loaded when the shearer is going up. When the shearer is going down, the linear density of materials loaded by the scraper conveyor (AE section) is given by Eq. 13. When the shearer is going up, the linear density of materials loaded by the scraper conveyor (EF section) can be expressed as

\[ q_u = \frac{v_{sh}}{(v_0 - v_{sh})} m_{sh} \]  

(14)
Because the structure of the scraper conveyor is not enclosed, a small part of the mined coal is brought back along the non-bearing section (CD section) of the scraper conveyor. The linear density of the material in the non-bearing section of the scraper conveyor can be expressed as

\[ q_{cb} = k_b \left( \frac{q_d + q_u}{2} \right) \]  

(15)

in which, \( k_b \) represents the coal return coefficient of the non-bearing section.

According to Eq. 14, the mass of coal in discrete elements \( i \) \((2 \leq i \leq n)\) can be expressed as

\[ m_{c,i}(t) = q_{cb} \Delta x \]  

(16)

The load change process of the scraper conveyor is shown in Figure 5, and the material shows regular changes when the shearer goes up and down. The discrete element \( i \) \((n + 3 \leq i \leq 2n)\) of the bearing section of the scraper conveyor is taken as the research object, and the mass variation of the coal is shown in Figure 6. Where \( t_0 \) indicates the time when the shearer begins to go down; \( t_{i,1} \) represents the time when the shearer runs to the right edge of the discrete element \( i \); \( t_{i,2} \) represents the time when the shearer goes down to the left edge of the discrete element \( i \); \( t_{i,3} \) represents the time when the coal extracted by the shearer is transported to the left edge of the discrete element \( i \); \( t_{i,4} \) represents the time when the coal extracted by the shearer is transported to the right edge of the discrete element \( i \); \( t_{i,5} \) represents the time for the shearer to reach the left edge of the discrete element \( i \); \( t_{i,6} \) represents the time for the shearer to reach the right edge of the discrete element \( i \); \( t_{end} \) indicates the time when the shearer returns to the head of the scraper conveyor.

In the time period \( t_0 \rightarrow t_{i,1} \), the mass of the coal in the discrete element is 0

\[ m_{c,i}(t) = 0 \quad (t_0 \leq t < t_{i,1}) \]  

(17)

In the time period \( t_{i,1} \rightarrow t_{i,2} \), the mass of coal in the discrete element increases linearly

\[ m_{c,i}(t) = q_d \Delta x \frac{t - t_{i,1}}{t_{i,2} - t_{i,1}} \quad (t_{i,1} \leq t < t_{i,2}) \]  

(18)

In the time period \( t_{i,2} \rightarrow t_{i,3} \), the mass of the coal in the discrete element remains constant

\[ m_{c,i}(t) = q_d \Delta x \quad (t_{i,2} \leq t < t_{i,3}) \]  

(19)

In the time period \( t_{i,3} \rightarrow t_{i,4} \), the mass of coal in discrete element increases linearly

\[ m_{c,i}(t) = q_d \Delta x + (q_u - q_d) \Delta x \frac{t - t_{i,3}}{t_{i,4} - t_{i,3}} \quad (t_{i,3} \leq t < t_{i,4}) \]  

(20)

In the time period \( t_{i,4} \rightarrow t_{i,5} \), the mass of the coal in the discrete element remains constant

\[ m_{c,i}(t) = q_u \Delta x \quad (t_{i,4} \leq t < t_{i,5}) \]  

(21)

In the time period \( t_{i,5} \rightarrow t_{i,6} \), the mass of the coal in the discrete element decreases linearly to 0

\[ m_{c,i}(t) = q_u \Delta x \left( 1 - \frac{t - t_{i,5}}{t_{i,6} - t_{i,5}} \right) \quad (t_{i,5} \leq t < t_{i,6}) \]  

(22)

In the time period \( t_{i,6} \rightarrow t_{end} \), the mass of the coal in the discrete element is 0

\[ m_{c,i}(t) = 0 \quad (t_{i,6} \leq t < t_{end}) \]  

(23)

Compared with other discrete elements in the bearing section of the scraper conveyor, the n+2 element is slightly different. When the shearer goes down to the left endpoint of the n+2 element, it immediately returns upward. So the mass of the coal in element n+2 is changing from time to time. The change of coal block in the n+2 element is shown in Figure 7. And \( t_0 \) indicates the time when the shearer starts to go down; \( t_{n+2,1} \) represents the time when the shearer goes to the right edge of the n+2 element; \( t_{n+2,2} \) represents the time when the shearer goes to the left edge of the n+2 element; \( t_{n+2,3} \) represents the time when the coal from the shearer is transported to the right edge of the n+2 element; \( t_{n+2,4} \) represents the time when the shearer reaches the right edge of the n+2 element; \( t_{n+2} \) indicates the time when the shearer returns to the head of the scraper conveyor.
In the time period \( t_0 \to t_{n+2,1} \), the mass of the coal in element \( n+2 \) is 0
\[
m_{c,n+2}(t) = 0 \quad (t_0 \leq t < t_{n+2,1})
\] (24)

In the time period \( t_{n+2,1} \to t_{n+2,2} \), the mass of coal in the element \( n+2 \) increases linearly
\[
m_{c,n+2}(t) = q_d \Delta x \frac{t - t_{n+2,1}}{t_{n+2,2} - t_{n+2,1}} \quad (t_{n+2,1} \leq t < t_{n+2,2})
\] (25)

In the time period \( t_{n+2,2} \to t_{n+2,3} \), the mass of the coal in the \( n+2 \) element continues to increase
\[
m_{c,n+2}(t) = q_d \Delta x + \left( \frac{v_0 - v_{sb}}{v_0} - q_d \right) \Delta x \frac{t - t_{n+2,2}}{t_{n+2,3} - t_{n+2,2}} \quad (t_{n+2,2} \leq t < t_{n+2,3})
\] (26)

In the time period \( t_{n+2,3} \to t_{n,4} \), the mass of the coal in the element \( n+2 \) decreases linearly to 0
\[
m_{c,n+2}(t) = \frac{v_0 - v_{sb}}{v_0} q_d \Delta x \left( 1 - \frac{t - t_{n+2,3}}{t_{n+2,4} - t_{n+2,3}} \right) \quad (t_{n+2,3} \leq t < t_{n,4})
\] (27)

In the time period \( t_{n+2,4} \to t_{n,nd} \), the mass of the coal in element \( n+2 \) is 0
\[
m_{c,n+2}(t) = 0 \quad (t_{n+2,4} \leq t < t_{n,nd})
\] (28)

### Running resistance of each element

As shown in Figure 8, there may be a certain laying Angle during the use of the scraper conveyor. The resistance during the operation of the scraper conveyor mainly includes two parts: the running resistance of the bearing section and the running resistance of the non-bearing section. In addition, due to the non-enclosed structure of the scraper conveyor, a small portion of the coal is returned from the head to the tail. Therefore, the scraper conveyor not only has the coal mined by the shearer in the bearing section, but also has a small amount of coal in the non-bearing section because of the return of coal.

In the process of operation, the discrete element of the non-bearing section of the scraper conveyor is affected by the friction resistance and gravity component generated by the annular chain assembly and part of the coal return. The operating resistance of each discrete element in the non-bearing section can be expressed as
\[
f_i(t) = (\mu_{cs} m_{c,i}(t) + \mu_{nc} m_{cc}) g \cos \alpha_s - (m_{c,i}(t) + m_{ce}) g \sin \alpha_s \quad (2 \leq i \leq n)
\] (29)

Similarly, the resistance of each discrete element in the bearing section of the scraper conveyor can be expressed as
\[
f_i(t) = (\mu_{cs} m_{c,i}(t) + \mu_{nc} m_{cc}) g \cos \alpha_s + (k_0 m_{c,i}(t) + m_{ce}) g \sin \alpha_s \quad (n+2 \leq i \leq 2n)
\] (30)

where, \( f_i(t) \) denotes the frictional resistance of the discrete element \( i \); \( m_{ce} \) represents the mass of the scraper chain component in a discrete element; \( m_{c,i}(t) \) represents the mass of coal in the discrete element \( i \); \( g \) represents the acceleration of gravity; \( \alpha_s \) indicates the inclined Angle of the scraper conveyor; \( \mu_{cs} \) and \( \mu_{nc} \) represent the coefficient of dynamic friction between steel and steel, coal and coal, respectively.

### Stiffness coefficient of the scraper chain

The stiffness coefficient of the scraper chain is a very important basic physical quantity in dynamic analysis. Scholars have carried out force analysis on the scraper chain and given the expression of the stiffness coefficient of the scraper chain
\[
k_{ci} = \left\{ \frac{k_0 r_c^2 (2 - \pi)}{E J_1 (l_c + \pi r_c)} + \frac{l_c}{2E} + \frac{\pi r_c}{8} \left( \frac{1}{EB} + \frac{1}{GB} \right) + \frac{k_0 r_c^2}{2E J_2} - \frac{\pi r_c^2}{2E J_2} \right\}^{-1} \frac{1}{L_c}
\] (31)

in which
\[
k_0 = \frac{r_c^2}{J_2} \left( \frac{\pi}{2} - 1 \right) \left( \frac{l_c}{J_1} + \frac{\pi r_c}{2J_2} \right)^{-1}
\]
\[
G = E / (2 - 2\mu)
\]
\[
l_c = L_c / 2 - b / 2
\]
\[
J_1 = \pi r_b^4 / 4
\]
\[
J_2 = J_1 + A r_c^2 B
\]
\[
\Delta r_c = r_c - r_b^2 \left( 2r_c \left[ 1 - \sqrt{1 - \left( \frac{r_b}{r_c} \right)^2} \right] \right)^{-1}
\]
where, \( F_i \) denotes the tension of the element \( i \); \( E \) represents the equivalent elastic modulus of the scraper chain; \( \mu \) represents Poisson’s ratio of the scraper chain; \( B \) represents the cross-sectional area of the scraper chain bar material; \( b \) represents the inner width of the scraper chain; \( r_b \) represents the radius of the scraper chain bar material; \( L_c \) represents the pitch of the scraper chain; \( J_1, J_2 \) represent the section moment of inertia of the straight section and the arc section of the scraper chain, respectively.

The length of the scraper chain is about \( 2L \) and is divided into \( 2n \) discrete elements on average. Therefore, the stiffness coefficient in the dynamic model can be expressed as

\[
k_i = \frac{n_c(n-1)k_{ci}}{L}
\]

in which, \( n_c \) represents the number of scraper conveyor chains (the number of double-chain scraper conveyor chains is 2).

**Polygon effect of sprocket**

As shown in Figure 9, the polygon effect of the sprocket refers to the phenomenon where the scraper chain’s speed in the horizontal direction at the engagement site varies from small to large and then from large to small, corresponding to the rotation angle of a gear tooth on the sprocket. This fluctuating speed and acceleration caused by the polygon effect result in unevenness and vibration impact during chain transmission with the sprocket\(^\text{21}\). Considering this effect, the speed and acceleration of the scraper chain at the engagement point of the sprocket can be defined as

\[
\begin{align*}
v_t &= R_h \theta_h \cos (\phi_t) \\
a_t &= R_h \left[ \dot{\theta}_h \cos (\phi_t) - \phi_t \dot{\theta}_h \sin (\phi_t) \right] \\
\phi_t &= \phi_{t0} + \theta_t - \text{Floor} \left[ \theta_h \cdot \frac{Z}{2\pi} \cdot \frac{2\pi}{Z} - \frac{\pi}{Z} \right]
\end{align*}
\]

in which

\[
R_h = \frac{1}{2} \sqrt{\frac{L_c^2}{\sin \left( \frac{\pi}{2Z} \right)^2} + \frac{(2r_b)^2}{\cos \left( \frac{\pi}{2Z} \right)^2}}
\]

where, \( Z \) indicates the number of sprocket teeth; \( R_h \) represents the pitch circle radius of the sprocket; \( \dot{\theta}_h \) represents the angular speed of the sprocket; \( \phi_{t0} \) represents the initial phase Angle; \( \phi_t \) represents the angle between the tangent line of the meshing point and the conveyor laying line; \( \theta_t \) represents the angular displacement of the sprocket; Floor represents the largest integer function.

Usually, the scraper conveyor realizes soft start by arranging the hydraulic coupler and speed regulating coupler between the drive motor and the reducer. The paper aims to consider the tension change law of the scraper chain when the load changes. When the shearer starts to run, the scraper conveyor has been running stably. Therefore, in order to simplify the calculation, this paper adopts the simplest linear speed curve to describe the starting process of the scraper conveyor. The angular speed of the scraper conveyor drive sprocket can be expressed as

\[
\dot{\theta}_h = \begin{cases} 
\frac{v_0}{R_h} \cdot \frac{t}{t_{sq}} & (0 \leq t < t_{sq}) \\
\frac{v_0}{R_h} & (t_{sq} \leq t)
\end{cases}
\]

in which, \( t_{sq} \) indicates the starting time of the scraper conveyor.

**Illustrative example**

In this section, the SGZ1000/1400 scraper conveyor (double motor, single power 700KW) is taken as an example to verify the rationality of the established model. The main parameters of the scraper conveyor are shown in Table 1.

The MGTY400/900-3.3D electric traction shearer is used for coal mining with the SGZ1000/1400 scraper conveyor. It adopts AC frequency conversion speed regulation mode for speed regulation, and its main parameters are shown in Table 2.

In the example, the scraper conveyor is dispersed into 102 discrete elements (n=50), and the calculation step is set to 0.01s. The initial condition is that the acceleration, velocity and displacement of each discrete element are 0

\[
\{\ddot{x}\}_{t=0} = \{\dot{x}\}_{t=0} = \{x\}_{t=0} = 0
\]

Eq. 36 gives the angular speed of the driving sprocket of the head and tail. By substituting the main parameters of the scraper conveyor and shearer into the established dynamic model, the following analysis results can be obtained by analyzing the dynamic tension and speed changes of the scraper conveyor with or without considering load changes.
Dynamic tension and speed changes of scraper conveyers without load changes

The main parameters of the SGZ1000/1400 scraper conveyor are shown in Table 1. Eq 10 gives the mass of coal in each discrete element without considering the change of load. The resistance of each element to be overcome is given by Eq 29 and Eq 30. When the load changes are not considered, the dynamic tension and speed fluctuation curves of the scraper conveyers are shown in Figure 10. Figure 10 (a) shows the dynamic tension of the scraper chain at different positions. Figure 10 (b) shows the speed variation of the scraper chain at different positions. Due to the polygon effect of the sprocket, the speed and tension of the scraper chain show regular fluctuations. In particular, the tension fluctuation near the head and tail is more obvious, and the maximum tension of the scraper chain appears in the position of the head of the bearing section. In addition, in this paper, the linear speed curve is used to start the calculation, so that the speed of the scraper conveyor is linearly increased to the rated speed, in order to minimize the huge impact of the start moment. However, due to the influence of heavy starting, the maximum tension of the scraper chain during the starting process is 751.6kN, which is significantly higher than the tension with smooth running.

Dynamic tension and speed changes of scraper conveyers with load changes

The main parameters of the SGZ1000/1400 scraper conveyor and the MGTY400/900-3.3D shearer are shown in Table 1 and Table 2 respectively. Eqs 11-28 give the mass of coal in each discrete element with the load change. The simulation results considering load changes are shown in Figure 11. Figure 11(a) shows the dynamic tension of the scraper chain at different positions. Figure 11(b) shows the speed of the scraper chain at different positions. As can be seen from the figure, the maximum tension of the scraper chain appears at the head of the bearing section of the scraper conveyor, and the maximum tension is 702.9KN.

Figure 12 shows the dynamic tension variation curve of the discrete element of the head. In the figure, point O represents the scraper chain tension when the scraper conveyor is started; Point A represents the scraper chain tension when the shearer goes down to the tail of the scraper conveyor; Point B represents the scraper chain tension when all the coal collected by the shearer is transported out; Point F indicates the tension of the scraper chain when the scraper line returns to the head of the scraper conveyor. The increase rate of dynamic tension of the scraper chain from point A to point B is significantly higher than that from point O to point A. The reasonable explanation for this phenomenon is: from point O to point A corresponds to the shearer from under the head to the tail, because the shearer’s speed is low, the scraper chain tension increases slowly; From point A to point B, the shearer begins to move upward, and the coal collected by the shearer down is quickly transported away by the scraper conveyor, and the coal collected by the scraper in the scraper line quickly occupies the entire bearing section. At the corresponding time point B, only the coal collected when the shearer goes up exists in the bearing section of the scraper conveyor. So the tension of the scraper chain increases rapidly at this stage. In addition, it can be seen from the local magnification that the scraper chain reaches its peak tension (point C) for the first time at 0.7 seconds, with a peak tension of 442.5 KN. After reaching two peaks at 1.58 seconds and 1.78 seconds (point D and point E), the dynamic tension of the scraper chain tends to be stable, but still shows obvious tension fluctuation due to the influence of polygon effect. Thanks to the no-load start and the linear speed curve start, the maximum tension of the scraper chain is about 448.9 KN, which is much smaller than the 751.6 kN with the heavy load start. It can be seen that heavy load start-up will bring great impact to the scraper chain, and then affect the reliability of the scraper chain. Therefore, in the actual production process, it is necessary to take no-load starting, soft starting and other measures to reduce the damage to the scraper conveyor. It is worth noting that the dynamic tension of a single scraper chain chain is approximately represented as half of the dynamic tension shown in the diagram.

Experimental verification and analysis

The strain and acceleration measurement platform for the scraper chain is illustrated in Figure 13. The test platform consists of the strain gauge, acceleration sensor, wireless dynamic strain acquisition instrument, and upper computer. Among these components, the strain gauge has a sensitivity coefficient of 2.1±1% and a resistance of 120±0.5 ohm. The axial sensitivity of the acceleration sensor is 4958 mV/g with a measurement range of ±1 g, frequency range from 0.2 to 1600 Hz, and resolution of 0.000004 g. The wireless dynamic strain test and analysis system has four channels enabling simultaneous acquisition of physical quantities such as strain stress and acceleration. And the sampling frequency is set to 1 kHz.

As depicted in Figure 13(a), the scraper chain possesses a ring structure with an arc surface. To facilitate installation of the strain gauges, it is necessary to use sandpaper for polishing purposes on both coarse (200 mesh) and fine (400 mesh) areas respectively before cleaning them with organic solvents like acetone or ethanol. Figure 13(b) illustrates the treated polished surface along with the position and connection points for the strain gauge. To ensure more effective and reliable experimental results, temperature compensation is carried out by employing half-bridge connections in the measurement circuit to eliminate nonlinear errors during measurements as shown in Figure 13(c). Additionally, this figure demonstrates where to install both wireless dynamic strain test analysis system and acceleration sensor.
which are firmly attached above four magnetic seats installed at bottom side directly onto the scraper itself allowing convenient disassembly/assembly operations while running synchronously with it. Similarly, the acceleration sensor is equipped with a magnetic base attached directly in front of the scraper at a relatively flat position. The strain gauge and acceleration sensor are connected to the wireless dynamic strain measurement and analysis system via cable. Figure 13(d) represents the upper computer, which establishes an effective wireless communication line with the wireless dynamic strain test and analysis system.

To provide a clearer description of the measurement process, it can be outlined as follows: Before starting the scraper conveyor, it is necessary to balance the bridge and clear any zero values. Then, initiate the operation of the scraper conveyor. The strain gauge collects real-time data on strains experienced by the scraper chain and transmits it through wires to wirelessly connect with the dynamic strain test and analysis system (the acceleration sensor collects data on scraper chain accelerations transmitted through cables). The wireless dynamic strain test and analysis system receives, amplifies, filters, A/D converts this dynamic data before transmitting it wirelessly to the upper computer. The upper computer enables storage, display, and querying functions for the measurement data.

Figure 14 illustrates variations in strains experienced by the scraper chain during its movement from tail to head. Strain measurements obtained from point 1 and point 2 exhibit similarities. During startup stages of operating a scraper conveyor (close to t=0), the scraper chain is significantly affected. In the actual production process, measures such as no-load starting and soft starting can be implemented to mitigate the impact on the scraper chain during startup. The measurement results exhibit evident fluctuation patterns, particularly in the tail and near the head of the scraper conveyor due to the polygon effect of sprocket.

Figure 15 illustrates the acceleration curve of a scraper chain. The acceleration of the scraper chain fluctuates considerably during startup and stabilizes within a range of ±1 m/s². Subsequently, it experiences a sudden decrease followed by gradual increase in acceleration. Through numerous experiments and field observations, it has been determined that this phenomenon is caused by collisions between scrapers and gaps in the middle trough.

Conclusions

To accurately evaluate the reliability of the scraper chain, comprehensive understanding of its dynamic characteristics and acquisition of dynamic load data are essential. This study establishes a dynamic model for the scraper conveyor considering factors such as coal dropping behavior from shearer and polygon effect from sprocket, etc. The main research contents and conclusions are summarized as follows:

(1) Considering structural characteristics like polygon effect from sprocket, coal dropping behavior from shearer, interaction between scraper chain and coal block, etc., the dynamic model of the scraper conveyor is established to determine the tension and speed of the scraper conveyor.

(2) During startup stage, significant impacts occur on both motors and scraper chains which may lead to damage. To protect these components effectively, control strategies like "soft start" or no-load start hold crucial engineering significance in achieving reliable operation of the scraper conveyor.

Data availability

All data generated or analysed during this study are included in this published article [and its supplementary information files].

References


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**Author contributions statement**

Shuai Li built a dynamic model and conceived the experiment, Zhencai Zhu grasped the overall research idea, Hao Lu and Yujun Xue analyzed the results and carried out the experiment. All the authors reviewed the manuscript.

**Additional information**

**Competing interests**

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, there is no professional or other personal interest of any nature or kind in any product, service or company.
that could be construed as influencing the position presented in, or the review of, the manuscript entitled "Tension characteristics analysis of scraper chain of heavy-duty scraper conveyor with time-varying load".

**Figure 1.** The structure of scraper conveyor.

![Figure 1](image1)

**Figure 2.** Kelvin-Vogit model.

![Figure 2](image2)
Figure 3. Finite element model of the scraper conveyor.

Figure 4. Loading situation without considering load changes.
Figure 5. Loading situation when load changes are considered.

Figure 6. Schematic diagram of coal distribution in discrete element.
Figure 7. Schematic diagram of coal changes in element n+2.

Figure 8. Analysis diagram of running resistance of scraper conveyor.

Figure 9. Speed analysis of sprocket drive system.

Figure 10. Dynamic tension and speed of the scraper chain without considering load changes.
Figure 11. Tension and speed changes of the scraper chain when load changes are considered.

Figure 12. Dynamic tension curve of the head meshing point.
Figure 13. Strain and acceleration measurement test bench of scraper chain. (1-strain gauge, 2-scraper chain, 3-scraper, 4-wireless dynamic strain test and analysis system, 5-cable, 6-acceleration sensor, 7-upper computer)

Figure 14. Strain of scraper chain under normal working conditions.
Figure 15. Acceleration curve of scraper chain under normal working conditions.
### Table 1. Main parameters of the scraper conveyor.

<table>
<thead>
<tr>
<th>Physical description</th>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmission capacity</td>
<td>Q</td>
<td>2500</td>
<td>t/h</td>
</tr>
<tr>
<td>Specification of scraper chain</td>
<td>d × Lc</td>
<td>42 × 146</td>
<td>mm</td>
</tr>
<tr>
<td>Installed power</td>
<td>P_{SG}</td>
<td>2 × 100</td>
<td>kW</td>
</tr>
<tr>
<td>Inner width of scraper chains</td>
<td>h</td>
<td>48</td>
<td>mm</td>
</tr>
<tr>
<td>Design length</td>
<td>L</td>
<td>250</td>
<td>m</td>
</tr>
<tr>
<td>Velocity of scraper chain</td>
<td>v_0</td>
<td>1.31</td>
<td>m/s</td>
</tr>
<tr>
<td>Inclination of the scraper conveyor</td>
<td>α</td>
<td>0</td>
<td>rad</td>
</tr>
<tr>
<td>Number of sprocket teeth</td>
<td>Z</td>
<td>7</td>
<td>-</td>
</tr>
<tr>
<td>Coefficient of dynamic friction between steel and steel</td>
<td>(\mu_{ss})</td>
<td>0.3</td>
<td>-</td>
</tr>
<tr>
<td>Coefficient of dynamic friction between coal and steel</td>
<td>(\mu_{cs})</td>
<td>0.432</td>
<td>-</td>
</tr>
<tr>
<td>Coal return coefficient</td>
<td>k_b</td>
<td>0.02</td>
<td>-</td>
</tr>
</tbody>
</table>

Note: The symbol “-” denotes the dimensionless variables without units.

### Table 2. Main parameters of MGTY400/900-3.3D shearer.

<table>
<thead>
<tr>
<th>Physical description</th>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mining height</td>
<td>h_c</td>
<td>3.4</td>
<td>m</td>
</tr>
<tr>
<td>Supply voltage</td>
<td>V_{SG}</td>
<td>3.3</td>
<td>KV</td>
</tr>
<tr>
<td>Total installed power</td>
<td>P_{SH}</td>
<td>900</td>
<td>KW</td>
</tr>
<tr>
<td>Drum speed</td>
<td>(v_{sh})</td>
<td>32.7</td>
<td>r/min</td>
</tr>
<tr>
<td>Traction speed</td>
<td>(v_{sh})</td>
<td>11.5</td>
<td>m/min</td>
</tr>
<tr>
<td>Traction effort</td>
<td>(F_{sh})</td>
<td>500</td>
<td>KN</td>
</tr>
<tr>
<td>Drum diameter</td>
<td>D_{sh}</td>
<td>1.8</td>
<td>m</td>
</tr>
<tr>
<td>Drum depth</td>
<td>b_w</td>
<td>800</td>
<td>mm</td>
</tr>
</tbody>
</table>
Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- rawdata.xlsx