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Dynamics Analysis and Modeling of Rubber Belt in Large Mine Belt Conveyors

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Abstract: Rubber belt not only is one of the key components of belt conveyor, but also affects the overall performance of the core part. Research on dynamics analysis of large conveyor not only helps to improve the reliability and design level, but also can guide the rational selection of conveyor safety factor, and effectively reduce the cost of the conveyor belt. Based on unique viscoelastic properties of belt conveyor, it was simplified as one-dimensional viscoelastic rod in this study, and then a discrete element model of conveyor systems was established. The kinetic equations of each discrete unit was derived using kinetic energy, potential energy of driving segment, bearing segment and return segment and equation of energy dissipation and Lagrange equation. Based on Wilson-θ algorithm, the kinetic equation of DT1307-type ST2000's conveyor belt was solved by using Matlab to write computer programs. Research on the change rule of conveyor displacement, velocity, acceleration and dynamic tension during the boot process revealed the working mechanism of nonlinear viscoelastic, which lay the theoretical foundation for dynamic performance optimization of large belt conveyor. The calculation results were used to optimize design and analysis of conveyor system, the result showed that it could reduce the driven tension peaks about 12 %, save 5 % of overall manufacturing cost, which bring considerable profits for enterprises. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Belt conveyor, Rubber belt, Discrete element model, Dynamics analysis.

1. Introduction

The most important question of large mining belt conveyor system is how to choose design standards that meet the actual needs to design fully functional, reliable systems to meet the actual needs of the project. The biggest difference of selection of design standards was from a different calculation of running resistance and dynamic performance design. Too small running resistance will cause that the system cannot operate properly, but too much will result in wasted power, only the right running resistance calculation can select the match power and conveyor belt. Sometimes the dynamic tension peaks of large mine belt conveyor at work was several times or even dozens of times during normal operation, If it was still designed in accordance with the static standards, the performance and reliability of the conveyor system can be ensured only by choosing a larger safety factor. Clearly, there is a contradiction which a large safety factor would increase the manufacturing cost of the conveyor and waste investment [1]. Conveyor belt is the bearing component of whole large belt conveyor, and its investments are generally accounted for 30 %-50 % of the machine [2, 3], sometimes even more. Rational calculation and allocation of dynamic tension is the premise of choosing the right conveyor belt, but also one of the most effective means to save manufacturing cost. Conveyor belt not only is one of the key components

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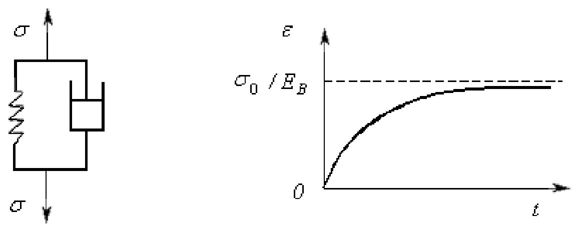
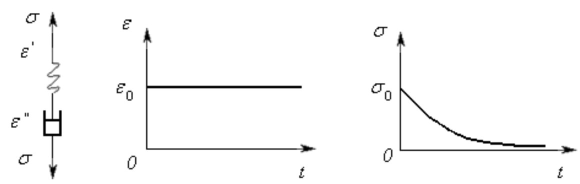
of belt conveyor, but also affects the overall performance of the core part. Its dynamic characteristics research is the primary question of conveyor design and manufacturing.

Most of the traditional conveyor designs use the static method, with a larger safety factor to compensate dynamic performance for the startup, operation and braking process. However, large capacity, high efficiency and long distance conveyor is composed by a rubber layer and the core wire or fabric rope, it not only has static characteristics, but also has complex dynamic characteristics. The specific manifestations was nonlinear characteristics of stress and strain, hysteresis characteristics, creep properties, relaxation properties, dynamic modulus of elasticity, therefore it has obvious features of dynamic viscoelastic properties. In engineering applications, the mechanical relationship of the conveyor can be expressed using combinations of an ideal elastic model (ideal spring) and the ideal viscous (damper) model. In 1962, Matling and Vierling worked in University of Hannover, Germany studied the viscoelastic of belt, and the first used it into the kinetic analysis of the conveyor belt, and proposed the viscoelastic model of conveyor belt. Then Vogit model Fig. 1(a) has been widely used, it paralleled the viscosity and the elastic elements, which can reflect response of the material to stress, but it do not simulate a good response of the belt to the instantaneous strain [4]. Maxwell model Fig. 1(b) was in series with the viscosity and the elastic element, it can simulate the response of the material to the strain, but not the responses to the stress. In 1984, Nordell first proposed a four parameter viscoelastic model [5], it further improve the analysis accuracy of the model. S. N. Ganeriwala [6] used Fourier transform dynamics analysis method to determine the dynamic mechanical properties of linear and nonlinear viscoelastic material. Based on the above analysis, the Vogit model or Maxwell models cannot descript the real viscoelastic of conveyor belt. According to the viscoelasticity theory, the conveyor belt can be simplified as a more complex viscoelastic model formed from more springs and dampers through series or parallel, and it can be more close to the real mechanical properties of the material, but the increased number of components and the complexity of model will cause the complexity of the mechanical equation of conveyor model. In addition, the programming and solving calculation was complex, the boundary conditions are complex and uncertain, and the application of complex model is limited, which is not conducive to solving and calculation of the conveyor belt model, but also greatly limits application of complex rheological model in engineering practice. These problems make that modeling, analysis and research of the conveyor Dynamic has been one hotspot content of conveyor technology and theoretical research.

Based on the above problems, viscoelastic properties of conveyor will be simplified into one-dimensional elastic rod, composite discrete element model will be built based on Vogit and Maxwell model. The kinetic equations of each discrete units was derived using kinetic energy, potential energy of driving segment, bearing segment and return segment and equation of energy dissipation and LaGrange equation. Based on Wilson-θ algorithm, the kinetic equation of DT1307-type ST2000's conveyor belt was solved by using Matlab to write computer programs. Research on the change rule of conveyor displacement, velocity, acceleration and dynamic tension during the boot process reveals the working mechanism of nonlinear viscoelastic, and controls dynamic tension peak of conveyor belt in the state of motion. It will lay the theoretical foundation for dynamic performance optimization of large belt conveyor and provide reliable design basis for the designers. It has certain theoretical and practical significance for designers to reduce design safety factor of rubber belt, prevent breaking, choose a reasonable rollers, reduce system power consumption and spare parts and save investment [7, 8].



(a) Vogit model



(b) Maxwell model

Fig. 1. Comparison of two viscoelastic model.

2. Discrete Modeling of Conveyor System

2.1. Discrete Modeling of Conveyor System

Dynamic characteristics of the conveyor belt has obvious viscoelastic characteristics, while it was in non-steady conditions, the speed, acceleration, displacement and dynamic tension of each point in the rubber belt have dynamic features, namely it was the function of time. Dynamic characteristics at low speed, short distance and a small volume of the conveyor belt is not obvious (even under certain conditions it can be ignored), it can be analyzed directly using rigid body dynamics method. For high-speed, long-distance and large-scale overloaded mining conveyor belt, this dynamic characteristic will be a very significant impact on the performance and reliability of the conveyor system, and it can be analyzed through the establishment of conveyor dynamics model.

Establishing Kinetic model is to build the appropriate viscoelastic model, but rubber belt systems including rubber belt, as well as loading and unloading manner of transported materials. The physical characteristics itself (such as elastic modulus and viscosity coefficient), the physical properties of materials (such as specific gravity, angle of repose, the distribution coefficient, etc.), and shock of loading and unloading position have an impact on dynamic characteristics of the conveyor, which cannot be accurately described by the model of the existing conveyor. The transmission and supporting rollers and conveyor idlers makes conveyor occurs complex deformation, which belongs to the category of shell deformation theory. Taking into account the engineering practical design and application, the conveyor belt was seen as a one-dimensional viscoelastic rod, it fully meets the engineering requirements.

Just as shown in Fig. 2, the conveyor belt in this study will be considered as one-dimensional viscoelastic conveyor rod, the coordinate system whose original position was seen as the origin and the dynamic model was established, and we assumed that the direction of the conveyor belt tension is positive, and contraction direction is negative. The continuous quality of endless conveyor belt was divided into several units, each other was connected with no quality viscous component and elastic component, namely uses discrete system to approximate the continuous system [9]. Meanwhile, the conveyor system is divided into typical three units, it was the drive roller head unit, bearing unit and return segment unit from right to left. Numbered was from the head of the original position, the number against the transport direction are 1, 2 ...... i, i +1, ... j, j +1 ...... n, so the total number of units was n = i + j. Considering the impact of tensioning device and vibration on the rubber belt, the displacement and velocity generated by tension force and vibration was distributed evenly to both sides of the tensioning rollers conveyor belt.

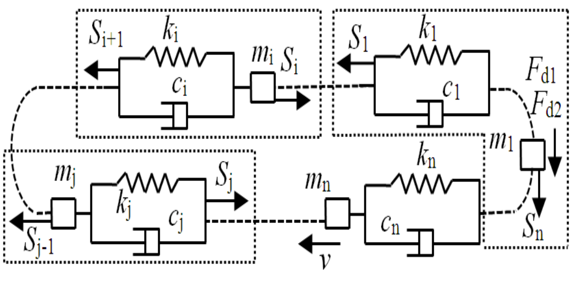


Fig. 2. Conveyor system discrete element model.

2.2. Kinetic Equation of Conveyor Unit

Taking bearing section as isolation, the equations of kinetic energy T, the potential energy U and energy dissipation D of the unit body can be written, which is composed an equation system (1).

$$\begin{cases} T = \frac{1}{2} m_{i\text{-}1}\dot{x}_{i\text{-}1}^2 + \frac{1}{2} m_i \dot{x}_i^2 + \frac{1}{2} m_{i+1}\dot{x}_{i+1}^2 \\ U = \frac{1}{2} k_{i\text{-}1}\left(x_i - x_{i\text{-}1}\right)^2 + \frac{1}{2} k_i \left(x_{i+1} - x_i\right)^2 \\ D = \frac{1}{2} c_{i\text{-}1}\left(\dot{x}_i - \dot{x}_{i\text{-}1}\right)^2 + \frac{1}{2} c_i \left(\dot{x}_{i+1} - \dot{x}_i\right)^2 \end{cases}, \quad (1)$$

where m_i is the i-th unit mass; k_i is the stiffness coefficient of i-th unit; c_i is the damping coefficient of i-th unit; x_i is the displacement of i-th unit. According to Lagrange equation [7], the formula (1) can be obtained.

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{q}_i}\right) - \frac{\partial T}{\partial q_i} + \frac{\partial U}{\partial q_i} + \frac{\partial D}{\partial \dot{q}_i} = Q_i, \quad (2)$$

where (i=1,2,…)

The corresponding partial derivative was conducted for equations (1), and the result was substituted into equation (2), the formula (3) was obtained.

$$\begin{gathered} m_i \ddot{x}_i - k_{i-1}x_{i-1} + \left(k_{i-1} + k_i\right) x_i - k_i x_{i+1} - \\ - c_{i-1}\dot{x}_{i-1} + \left(c_{i-1} + c_i\right)\dot{x}_i - c_i \dot{x}_{i+1} = -w_i \end{gathered}, \quad (3)$$

where w_i is the suffered resistance of i-th unit.

Similarly, the equation of driving drum head unit and return segment unit can be written as formula (4).

$$\begin{gathered} \left(m_1 + \frac{J_1}{R_1^2}\right)_1 \ddot{x}_i - k_n x_n + \left(k_1 + k_n\right) x_1 - k_1 x_2 - \\ - c_n \dot{x}_n + \left(c_n + c_1\right)\dot{x}_i - c_1 \dot{x}_2 = F_{d1} + F_{d2} - w_1 \end{gathered}, \quad (4)$$

where F_{d1}, F_{d2} are the driving forces of the driving drum, respectively; J_1 is the rotation inertia of driving drum; R_1 is the radius of driving drum.

$$\begin{gathered} m_j \ddot{x}_j - k_{j-1}x_{j-1} + \left(k_{j-1} + k_j\right) x_j - k_j x_{j+1} - \\ - c_{j-1}\dot{x}_{i-1} + \left(c_{j-1} + c_j\right)\dot{x}_i - c_j \dot{x}_{j+1} = -w_j \end{gathered}, \quad (5)$$

According to the above derivation, the dynamic equation group for each divided unit was built (6).

$$\begin{cases} \left(m_1+\frac{J_1}{R_1^2}\right)_1 \ddot{x}_i - k_n x_n + (k_1+k_n)x_1 - k_1 x_2 - c_n\dot{x}_n + (c_n+c_1)\dot{x}_i - c_1\dot{x}_2 = F_{d1}+F_{d2}-w_1 \\ \vdots \\ m_i\ddot{x}_i - k_{i-1}x_{i-1} + (k_{i-1}+k_i)x_i - k_i x_{i+1} - c_{i-1}\dot{x}_{i-1} + (c_{i-1}+c_i)\dot{x}_i - c_i\dot{x}_{i+1} = -w_i \\ \vdots \\ m_j\ddot{x}_j - k_{j-1}x_{j-1} + (k_{j-1}+k_j)x_j - k_j x_{j+1} - c_{j-1}\dot{x}_{i-1} + (c_{j-1}+c_j)\dot{x}_i - c_j\dot{x}_{j+1} = -w_j \\ \vdots \\ m_n\ddot{x}_n - k_{n-1}x_{n-1} + (k_{n-1}+k_n)x_n - k_n x_1 - c_{n-1}\dot{x}_{n-1} + (c_{n-1}+c_n)\dot{x}_n - c_n\dot{x}_1 = -w_n \end{cases}, \quad (6)$$

Solving equations group (6) was converted into a matrix form:

$$[\mathrm{M}]\{\ddot{X}\}+[C]\{\dot{X}\}+[K]\{X\}=\{F(t)\}, \quad (7)$$

where $[\mathrm{M}]$ is the mass matrix of n units; $[C]$ is the damping coefficient of N units; $[K]$ is the stiffness coefficient matrix of N units; $\{\ddot{X}\}$ $\{\dot{X}\}$ is the acceleration column vector; $\{\dot{X}\}$ is the speed column vector; $\{X\}$ is the displacement column vector; $\{F(t)\}$ is the external force column vector.

Meanwhile, the dynamic tension equation of any $i \in n$ unit is as follows:

$$F_i(t)=k_i\left[x_{i+1}(t)-x_i(t)\right]+c_i\left[\dot{x}_{i+1}(t)-\dot{x}_i(t)\right] \quad (8)$$

Solving equations group (7) and (8), the displacement x, the speed $\dot{x}$, the acceleration $\ddot{x}$ and the dynamic tension $F(t)$ of a unit at any time can be obtained.

3. Kinetic Equation Algorithm

3.1. Boundary Conditions and Initial Conditions

Before solving the dynamic equations of conveyor belt, the boundary conditions and initial work conditions also need to be determined. Taking DT1307 type as an example, it uses a hammer-type tensioning device. For x_{lj} is hammer displacement, x_{r1}, x_{r2} are the displacement of separation point, chemotaxis point of tension roller, respectively, S_i, S_{i+1} are tension of both sides of the drum, G_{lj} is gravity of hammer, g is gravitational acceleration, then the boundary conditions between hammer, rollers and conveyor can be obtained:

$$\begin{cases} x_{lj}=\left[x_{r2}(t)-x_{r1}(t)\right]/2 \\ \dot{x}_{lj}=\left[\dot{x}_{r2}(t)-\dot{x}_{r1}(t)\right]/2 \\ S_i+S_{i+1}=G_{lj}\left[1+\ddot{x}_{r2}(t)-\ddot{x}_{r1}(t)/g\right] \end{cases}, \quad (9)$$

When $i=1$, $x_{i-1}(t)=x_n(t)$, $\dot{x}_{i-1}(t)=\dot{x}_n(t)$; When $i=n$, $x_{i+1}(t)=x_1(t)$, $\dot{x}_{i+1}(t)=\dot{x}_1(t)$. When the conveyor startup, the initial tension is F_{0i}, for $i=1,2,\cdots,n$.

Initial conditions: when the conveyor startup, $\mathrm{t}=0$, $x_i(0)=0$, $\dot{x}_i(0)=0$; At the end of braking, $\dot{x}_i(t)=0$, $\ddot{x}_i(t)=0$, where $i=1,2,\cdots,n$.

In addition, corporate engineer provided reasonable boundary conditions for the running resistance, roller, loading and unloading and pre-tension according to the conveyor working conditions, so that the conveyor belt was close to the actual working conditions.

3.2. Kinetic Equation Algorithm

Using step-by-step integration method, above theoretical derivation can be calculated by the program. The main idea of step-by-step integration method is to discrete response time history in the time domain, and differential equation will be discrete into equation for the moment, and the speed and acceleration at any a moment is linear combination with all the displacement at adjacent time, then motion differential equation of system can be converted to a discrete-time algebraic equation group consisted of displacement. Stepwise numerical integration for the differential equations of coupled system can obtain any response on the discrete time. Wilson-θ method is an implicit integration method widely used to conduct discrete process, and as long as θ is greater than 1.37, no matter what value the step Δt is, the algorithm is unconditionally stable. During the startup and braking process, the equivalent elastic modulus changes with tension of the conveyor belt, so that running resistance has directional, which make dynamic equations of the conveyor belt to be a nonlinear equation of a variable damping, variable stiffness and variable load, so its numerical calculation can be used with unconditionally stable Wilson-θ method.

Wilson-θ method assumed that the change of acceleration is linearly in [t,] () within the [t, $t+\theta\Delta t$]($\theta \geq 1$) time interval.

If τ is the time variable since t time, then $0 \le \tau \le \theta\Delta t$, the acceleration can be obtained within this range under the assumption of linear acceleration, it was shown in Formula 10.

$$\{\ddot{x}\}_{t+\tau} = \{\ddot{x}\}_t + \frac{\tau}{\theta\Delta t}\left(\{\ddot{x}\}_{t+\theta\Delta t} - \{\ddot{x}\}_t\right), \quad (10)$$

After two integral, the formula (11) and (12) can be obtained:

$$\{\dot{x}\}_{t+\tau} = \{\dot{x}\}_t + \{\ddot{x}\}_t\tau + \frac{\tau^2}{2\theta\Delta t}\left(\{\ddot{x}\}_{t+\theta\Delta t} - \{\ddot{x}\}_t\right), \quad (11)$$

$$\{x\}_{t+\tau} = \{x\}_t + \{\dot{x}\}_t\tau + \frac{1}{2}\{\ddot{x}\}_t\tau^2 + \frac{\tau^3}{6\theta\Delta t}\left(\{\ddot{x}\}_{t+\theta\Delta t} - \{\ddot{x}\}_t\right) \quad (12)$$

If $\tau = \theta\Delta t$, the instantaneous speed (13) and displacement (14) at $t+\theta\Delta t$ time can be obtained from the above two equations.

$$\{\dot{x}\}_{t+\theta\Delta t} = \{\dot{x}\}_t + \frac{\theta\Delta t}{2}\left(\{\ddot{x}\}_{t+\theta\Delta t} - \{\ddot{x}\}_t\right), \quad (13)$$

$$\{x\}_{t+\theta\Delta t} = \{x\}_t + \theta\Delta t\{\dot{x}\}_t + \frac{\theta\Delta t^2}{6}\left(\{\ddot{x}\}_{t+\theta\Delta t} - 2\{\ddot{x}\}_t\right) \quad (14)$$

According to the above two formulas, the acceleration formula (15) and velocity formula (16) at $t+\theta\Delta t$ time can be expressed by displacement means.

$$\{\ddot{x}\}_{t+\theta\Delta t} = \frac{6}{\theta^2\Delta t^2}\left(\{x\}_{t+\theta\Delta t} - \{x\}_t\right) - \frac{6}{\theta\Delta t}\{\dot{x}\}_t - 2\{\ddot{x}\}_t \quad (15)$$

$$\{\dot{x}\}_{t+\theta\Delta t} = \frac{3}{\theta\Delta t}\left(\{x\}_{t+\theta\Delta t} - \{x\}_t\right) - 2\{\dot{x}\}_t - \frac{\theta\Delta t}{2}\{\ddot{x}\}_t \quad (16)$$

So, the momentum equation at $t+\theta\Delta t$ time is formula (17):

$$[M]\{\ddot{x}\}_{t+\theta\Delta t} = [C]\{\dot{x}\}_{t+\theta\Delta t} + [K]\{x\}_{t+\theta\Delta t} = \{F\}_{t+\theta\Delta t}, \quad (17)$$

where the meanings of $[M]$, $[C]$, $[K]$ are the same as in the formula (7), $\{F\}_{t+\theta\Delta t}$ is external force column vector, it can be expressed using formula (18).

$$\{F\}_{t+\theta\Delta t} = \{F\}_t + \theta\left(\{F\}_{t+\Delta t} - \{F\}_t\right), \quad (18)$$

Combined the formula (15), (16), (17) and (18) to solve, the solving equation of $\{x\}_{t+\theta\Delta t}$ can be obtained (19).

$$[\hat{K}]\{x\}_{t+\theta\Delta t} = \{\hat{F}\}_{t+\theta\Delta t}, \quad (19)$$

where

$$[\hat{K}] = [K] + \frac{3}{\theta\Delta t}[C] + \frac{6}{\theta^2\Delta t^2}[M], \quad (20)$$

$$\{\hat{F}\}_{t+\theta\Delta t} = \{F\}_t + \theta\left(\{F\}_{t+\Delta t} - \{F\}_t\right) + [M]\left(\frac{6}{\theta^2\Delta t^2}\{x\}_t + \frac{6}{\theta\Delta t}\{\dot{x}\}_t + 2\{\ddot{x}\}_t\right) + [C]\left(\frac{3}{\theta\Delta t}\{x\}_t + 2\{\dot{x}\}_t + \frac{\theta\Delta t}{2}\{\ddot{x}\}_t\right) \quad (21)$$

After obtaining the instantaneous displacement $\{x\}_{t+\theta\Delta t}$ at time of $t+\theta\Delta t$, $\{\ddot{x}\}_{t+\theta\Delta t}$ can be obtained combining formula (15). If $\tau = \Delta t$ in formula (10), then formula (22) can be obtained combining formula (19).

$$\{\ddot{x}\}_{t+\theta\Delta t} = \frac{6}{\theta^3\Delta t^2}\left(\{x\}_{t+\theta\Delta t} - \{x\}_t\right) - \frac{6}{\theta^2\Delta t}\{\dot{x}\}_t + \left(1 - \frac{3}{\theta}\right)\{\ddot{x}\}_t \quad (22)$$

Similarly, $\tau = \Delta t$, combined formula (10) with formula (11) and (12), then

$$\{\dot{x}\}_{t+\tau} = \{\dot{x}\}_t + \frac{\Delta t}{2}\left(\{\ddot{x}\}_{t+\theta\Delta t} - \{\ddot{x}\}_t\right), \quad (23)$$

$$\{x\}_{t+\theta\Delta t} = \{x\}_t + \Delta t\{\dot{x}\}_t + \frac{\Delta t^2}{6}\left(\{\ddot{x}\}_{t+\theta\Delta t} - 2\{\ddot{x}\}_t\right) \quad (24)$$

So, one-step integration is completed.

3.3. Computer Solving of Kinetic Equation

Based on theoretical analysis in section 3.2 and Wilson-θ gradual integration method provided in the literature [10], the steps and procedures for solving kinetic equations of discrete element model are shown in Table 1.

The computer program box of Wilson-θ method was showed in Fig. 3, the corresponding computer program can be written to calculate the dynamic characteristics of the conveyor belt in kinetic model at any time, which lay the foundation for subsequent analysis.

Table 1. Computer solving procedures of Wilson-θ gradual integration method.

No.	Solving procedures
1	Initial calculation
1.1	Form mass matrix [*M*], damping matrix [*C*] and stiffness matrix [*K*]
1.2	Input $\{x_0\}$, $\{\dot{x}_0\}$, $\{\ddot{x}_0\}$
1.3	Select time step Δt, for $\theta = 1.4$, Calculate integration constant: $a_0 = 6/(\theta\Delta t)^2$, $a_1 = 3/\theta\Delta t$, $a_2 = 2a_1$, $a_3 = \theta\Delta t/2$, $a_4 = a_0/\theta$, $a_5 = -a_2/\theta$, $a_6 = 1-3/\theta$, $a_7 = \Delta t/2$, $a_8 = \Delta t^2/6$
1.4	Form effective stiffness matrix $[\hat{K}]$: $[\hat{K}] = a_0[M] + a_1[C] + [K]$
1.5	Put $[\hat{K}]$ as a triangle decomposition: $[\hat{K}] = [L][D][L]^T$
2	Calculate for increment of each time
2.1	Calculate payload at $t+\theta\Delta t$: $\{\hat{F}\}_{t+\theta\Delta t} = \{F\}_t + \theta\left(\{F\}_{t+\theta\Delta t} - \{F\}_t\right) + [M](a_0\{x\}_t + a_2\{\dot{x}\}_t + 2\{\ddot{x}\}_t) + [C]\left(a_1\{x\}_t + 2\{\dot{x}\}_t + a_3\{\ddot{x}\}_t\right)$
2.2	Calculate displacement at $t+\theta\Delta t$: $[\hat{K}]\{x\}_{t+\theta\Delta t} = \{\hat{F}\}_{t+\theta\Delta t}$
2.3	Calculate acceleration, velocity and displacement at $t+\theta\Delta t$ time $\{\ddot{x}\}_{t+\theta\Delta t} = a_4\left(\{x\}_{t+\theta\Delta t} - \{x\}_t\right) + a_5\{\dot{x}\}_t + a_6\{\ddot{x}\}_t$ $\{\dot{x}\}_{t+\theta\Delta t} = \{\dot{x}\}_t + a_7(\{\ddot{x}\}_{t+\theta\Delta t} + \{\ddot{x}\}_t)$ $\{x\}_{t+\theta\Delta t} = \{x\}_t + \Delta t\{\dot{x}\}_t + a_8(\{\ddot{x}\}_{t+\theta\Delta t} + 2\{\ddot{x}\}_t)$

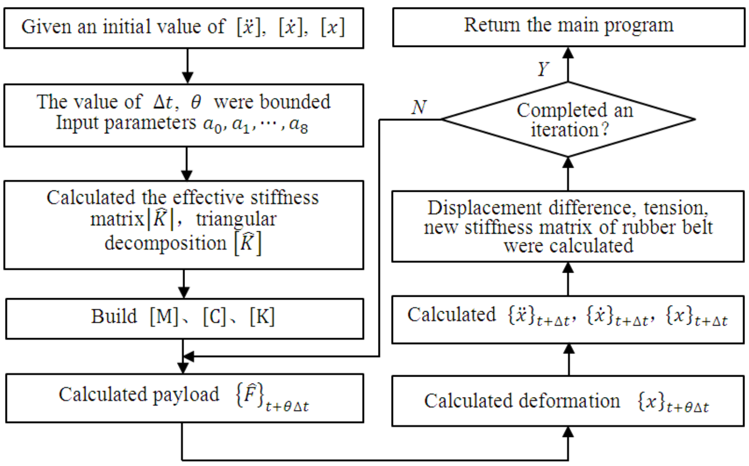


Fig. 3. Computer program box of Wilson-*θ* method.

4. Analysis of Computing Result

Taking flame-retardant steel cord conveyor belt ST2000 of DT1307-type conveyor belt designed and produced by Ningxia Tiandi Northwest Coal Machinery Co., Ltd as an example, dynamic tension, displacement, velocity and acceleration curves of conveyor belt was calculated at any time using Wilson-*θ* program shown in Fig. 3.

Load startup process of large mining conveyor belt is a very unstable condition, the tension force of conveyor belt will reach a maximum in the startup process, the intensive dynamic research on startup process is very important. The curve in Fig. 4 is the tension force of the different position during the boot process. At the first 15 s, tension force of each position has dramatic fluctuations, and the fluctuation range of the drive unit is greater than the bearing unit, return unit has a small fluctuation range and minimum tension force. In instant startup, the dynamic tension of drive unit can be up to 467.85 KN, after 50 s, the tension tends to drive around 378.61 KN in a stable state. The reason for tension of drive unit rising faster is mainly due to unreasonable start-up mode, a shorter start-up time and other factors caused a greater tension peaks. Setting a sufficiently long time, selecting controllable way to start, optimizing startup curve and increasing the pre-start delay can reduce the acceleration peak, smooth acceleration changes, to effectively reduce starter tension of the conveyor and increase running smooth of the belt. The speed of conveyor in the 20 s rise rapidly, then gradually approach to design speed 5 m/s, and continue to fluctuate in the vicinity, then it reached the design speed after 60 s. From the velocity curve Fig. 5, the speed change between drive unit, the bearing unit and return unit has a time lag, which showed that the stress wave gradually transfer from the drive unit to return unit, and the change is nonlinear.

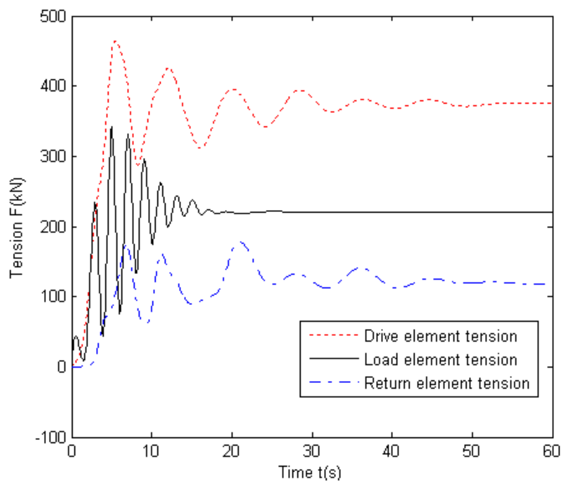


Fig. 4. Tension curve of conveyor belt.

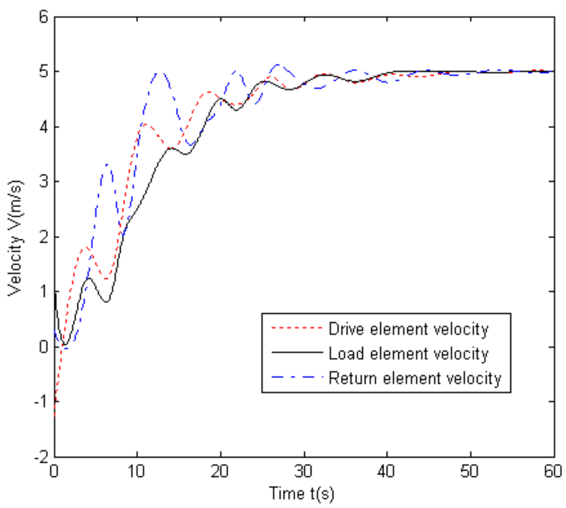


Fig. 5. Speed of conveyor belt.

Within the 20 s after starting, the acceleration change of conveyor is more severe Fig. 6, but with the increase of start time, the acceleration peak decreases, when it was about 50 s, the acceleration fluctuation tends to zero, and then the tension of the belt will reach a stable value. In the actual design and use, it should be possible to ensure that the starting process acceleration curve is gently and without mutation, the peak of acceleration is small in order to meet project needs. The displacement curve of different unit conveyor is showed in Fig. 7.

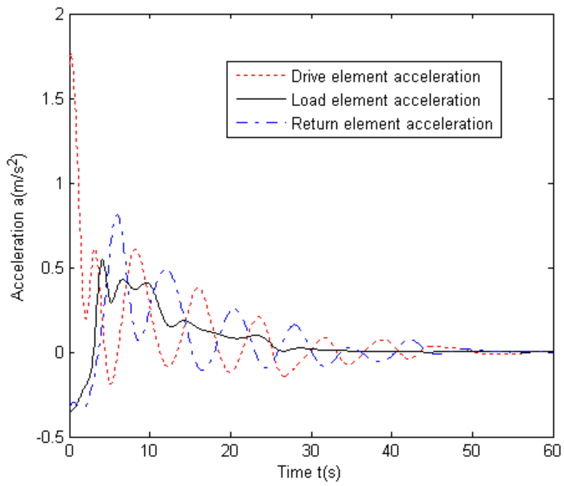


Fig. 6. The acceleration curve.

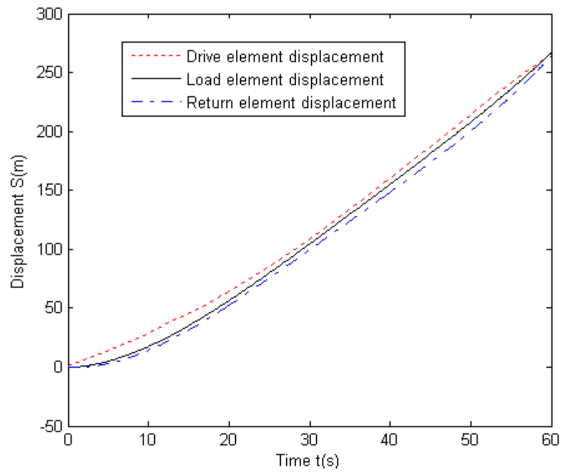


Fig. 7. The displacement curve.

In large capacity, high efficiency, long distance conveyor design and selection, the majority of domestic manufacturers use rigid theoretical to analysis conveyor belt, develop computational methods and design specifications. On this basis, the manufacturers always multiplies appropriate factor to meet the engineering requirements on the selected safety factor (usually about 10-15) according on their own design experience. This safety factor based on a static design is generally higher and the choice of conservative, because the driven tension of conveyor belt cannot accurately analyzed and calculated during startup and braking process. The above dynamic analysis shows that the speed, acceleration or dynamic tension have the most dramatic fluctuations in the former 20 s, and it has the greatest impact on the entire conveyor belt conveyor. Using a controlled soft-start technology and power equalization can effectively reduce motor starting power and tension, and reduce fluctuation caused by the speed and acceleration.

Application of the above results, inputting the maximum dynamic tension and design power parameters Fig. 8, the result can be calculated by the belt conveyor design calculation software programmed by Ningxia Tiandi Northwest Coal Machinery Co., Ltd. Fig. 8(a). A variety of logic was incorporated into the software, it not only can adapt to a variety of different types of pipe conveyor, and can automatically determine the arrangement of the belt conveyor, such as V type, anti-V type, N type and W type, which has some intelligence. The calculation can be completed in a short time basis, its reliability has been tested through a lot of engineering application, and it was accepted by the user. In addition, the software has the characteristic of user-friendly and simple operation, and inputting the initial design parameters can complete design, checking and other computing tasks. According to the results, the drawings, 3 D modeling, virtual assembly and simulation, interference checking, proofreading and other design work can be to completed by the designer Fig. 8(b), which greatly save design time of belt conveyor. Meanwhile, it can carry on the reliability optimization design for the key components of the conveyor, such as the rack, truss, rollers, etc., quality optimization design and vibration, modal, stress and strain analysis Fig. 8(c). If it meets the design goals, you can follow the appropriate procedures to produce component manufacturing and other work.

Ningxia Tiandi Northwest Coal Machinery Co., Ltd. optimized the design of DT1307-type belt conveyor and adjusted the dynamic control strategy, the initial design safety factor decreased from 11 to 7, and the cost of manufacturing machine reduced 5 %. Meanwhile it improves dynamic control precision of the control system, and the tension reduced by about 12 %, which make a considerable profit for manufacturing enterprises.

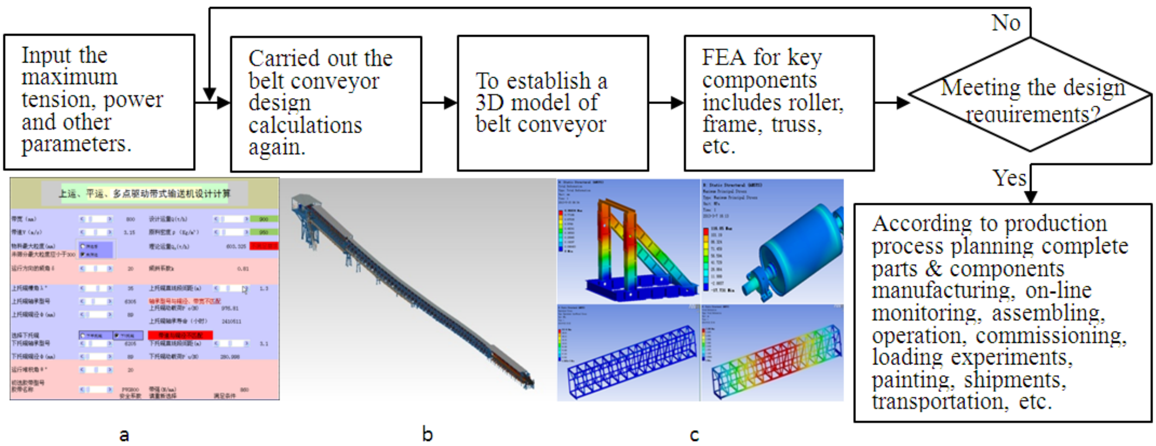


Fig. 8. Optimized design sketch of belt conveyor.

5. Conclusions

Application of driven viscous properties of conveyor belt, the discrete dynamic model and the corresponding dynamical equations of conveyor system was built. Then a computer integrating program was written in Wilson-θ method, and it was used to solve the kinetic of equation mine conveyor, and its dynamic analysis was carried out. Taking flame-retardant steel cord conveyor belt ST2000 an example look for solving dynamics to verify the reliability of theory, the result showed it objectively reflected the actual work of conveyor belt. The conveyor system was discrete into a number of units, and dynamic analysis is carried on at the different time domains, and the interaction mechanism of each unit in the movement and force the process was in-depth studied. The results show that the startup speed, acceleration had a big influence on dynamic tension of the rubber belt, and were closely related with time and size that the tension peaks appeared. The above findings provided the corresponding theoretical basis for the relevant people to design and optimize belt conveyor system. Under the conditions of meeting the actual needs of the project, transportation design tension is reduced by approximately 12 % than before, manufacturing cost of the DT1307-type conveyor machine saved about 5 %, which bring considerable profits for enterprises.

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