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Analysis of Dynamic Tension in Belt During Transient Condition of Belt Conveyor System by Lagrange's Approach

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Abstract— In belt conveyor system, belt is the key component contributing 25% to 50% of total cost of the system. This paper presents a simulation study of dynamic tension in the belt. Conveyor belt is a traction component which transmits power and motion, and also carrying material load. Tension developed in the belt directly governs design and strength of structural support system, pulley assembly and the drive. Traditionally, belt tension is studied by static analysis and large factor of safety (8-10) considered for design. Conveyor belt consist of fabric carcass with a protective rubber cover, thus can be represented by a viscoeleastic model. Belt conveyor system is simplified into series of lump mass parameter and dynamic characteristic of the belt studied using Lagrange's approach. Simulation results indicates that during full load starting condition, dynamic tension suddenly rise 1.82 times more than steady state running tension value in the belt. Dynamic analysis data useful for safe and reliable running, lowering factor of safety, improve stability and reduced belt stresses during starting.

***Keywords*—**Belt Conveyor, Lump Mass, Lagrange, Dynamic Tension

I. Introduction

Belt conveyor is most widely preferred bulk handling system because of its versatility, high capacity and reliability for bulk material handling [1]. A troughed endless belt travels with a constant speed supported over the rotating roller and bulk material transfer from one end to other. Pulling force require to run system is to overcome bulk mass, belt mass, system inertia and altitude of discharge point. Initial tension requires preventing slipping. It is important to know belt tensions at various critical points in conveyor. Maximum tension occurring in the belt loop decides selection of belt and also main criteria of the design itself [2]. During transient phase of starting or stopping tension values also varies significantly. Static calculation of tension assume equilibrium cases of this condition and design based considering 8 to 10 factor of safety [3]. The belt carries bulk material and transmits the power to move load, is made up of synthetic fibers, rubber, and steel cables or combination of these materials. Belt shows properties as viscoelastic material and tension calculation can perform on viscoelastic model. Vogit model comprises of spring and damper in parallel gives much realistic solution for dynamic tension [4],[5]. In this paper a belt on rotating elements is studied based on lumped parameter element method. Belt is divided in number of continuous series of lumped mass, each unit is associated with its equivalent mass based on component and stiffness and damping constant based on the belt properties. Langrage approach used for equation of motion of each unit and whole belt line is then simulated for fully loaded starting condition. The comparison is made between result of static analysis and simulated result for the starting tension in a belt. Simulated result shows appropriate dynamic picks and variation of tension values at various critical point of belt line.

The paper is organized as follows, Section I contains the introduction of work carried out in the paper, Section II contain static analysis technique for calculation of minimum pull require to overcome inertial resistance of the system and tension in belt for steady state running, Section III contain traditional method to obtained starting tension developed in the belt to start fully loaded belt conveyor system, Section IV contain viscoelastic nature of belt material and essential model assumed for belt unit, section V explain the Lagrange approach consider for equation of motion of each unit, Section VI describes modeling and simulation of belt conveyor and initial condition used in to run simulation, Section VII contain a case study of existing system, tension at various section is compared , and Section VIII concludes research work with future directions.

II. Tractive Pull for Steady State Running

The total conveying distance of belt in the belt conveyor system comprises of the horizontal travel, inclined curve of both carrying and return side path and takes up winding. Bulk mass conveyed by the carrying side whose travel distance would be less than the total carrying side belt length.

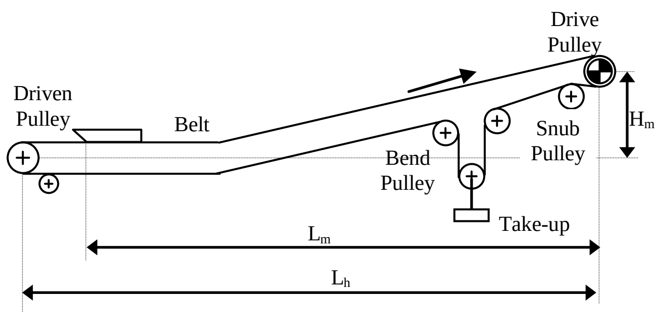

Fig.1 Belt conveyor layout

Calculation of tension in the belt is based on steady state fully loaded condition, as its starting is refers as maximum stress condition of the operation [6]. Horizontal centre to centre distance between material discharge end and tail end is considered for load calculation. Equation (1) is stated total tractive pull require to pull bulk mass, belt mass, to overcome rolling resistances on carrying and return side and to lift the total load at altitude gradient [7]. The mass quantity is taken for unit length of belt.

$$P = CfgL_h(m_C + m_r + m_m + 2m_b) + m_m H_m g \quad (1)$$

Where,

C = Conveyor length coefficient (.)
f = Conveying friction coefficient (.)
L_h = Belt Horizontal run distance (m)
m_C = Carrying idler rotating mass (kg/m)
m_r = Return idler rotating mass (kg/m)
m_m = Bulk material mass (kg/m)
m_b = Belt mass (kg/m)
H_m = Total vertical lift of belt conveyor (m)

Maximum belt tension at the entry of driving pulley estimated on total frictional resistance offer by the system and physical parameter of the drive pulley, further that of on exit side of drive pulley is calculate by Euler's belt friction law, $T_1/T_2 = e^{\mu\theta}$. Where μ and θ represents coefficient of friction and angle of wrap at drive pulley. Subsequent tensions at various locations of return and carrying side such as take up, altitude change; driven pulley etc are based on the simple resistance rule.

$$T_{i+1} = T_i + (conveying\ resistance)_i^{i+1} \quad (2)$$

While calculating of belt tension around the belt conveyor system it should be taken care of sag tension. Minimum tension over the path during any phase of running should not less than the sag tension of carrying or return side [8]. And if it occurs then it should be adjusted with take up initial tension via take-up weight.

$$T_{sag\ (carry)} = (12.5 \times (m_b + m_m) \times g \times S_c) \div (sag\%) \quad (3)$$
$$T_{sag\ (return)} = (12.5 \times m_b \times g \times S_r) \div (sag\%) \quad (4)$$

Where S_c and S_r are spacing between adjutant idlers on carrying side and return side respectively. $sag\%$ is a numeric value limits 0.5 to 2 [9]. Conveyer equivalent linear moving mass include equivalent mass of total belt length, carrying and return idlers and material mass. Snub pulleys are introducing their mass as 3% to 2% of total mass of system excluding drive unit mass, on carrying and return side of belt respectively. Drive unit equivalent mass varies from 7.5% to 17.5% of previously calculated total mass accordance the altitude variation along the belt line [10]. Total equivalent mass is use for calculation of starting acceleration of the conveyor to reach desired velocity.

III. TRANSIENT STARTING OF BELT CONVEYOR

In static analysis of the belt, tension at various point along the path obtain with local friction resistance value. For theoretical condition, tractive pull which is equal to conveyor motional resistance, is require to attain steady state running of fully loaded belt conveyor; but due to self inertia of conveyor system during starting, applied tractive pull need to be more than calculated value (generally 1.4 to max 1.7) [2]. The excess amount of starting pull causes sudden rise in belt tension to a great level. Starting torque leads to starting transient condition which settles to steady state with due time. Best design of conveyer system must compromise between minimum starting time and minimising the starting tension in the belt. Higher Staring acceleration value also has limiting value so as to prevent relative motion of bulk material over the belt. Belt tension during starting phase comprises of inertial force in addition with frictional and altitude load at the unit. Subsequent tensions at various locations of return and carrying side such as take up, altitude change; driven pulley etc are based on the D'Alembert's principle.

$$T'_{i+1} = T'_i + (conveying\ resistance)_i^{i+1} + M_i a \quad (5)$$

Where M_i is equivalent mass of $i-th$ node and a is starting acceleration of the system.

IV. VISCOELASTIC PROPERTIES OF BELT

During starting and stopping process of belt conveyor system huge peak tension developed which may results belt rupture, belt slip on drive pulley, bulk vibration and uncontrolled running. These sudden peaks in tension can't be investigated by the static analysis method [11]. Therefore to fulfill requirement of real engineering, greater factor of safety is used in traditional conveyor designs. For long distance and large capacity, it not only has static characteristics, but also has complex dynamic characteristics for the start-up, operation and braking process. Belt of conveyor is composed by a rubber layer and the core wire or fabric rope and shows nonlinear characteristics of stress and strain, creep properties, relaxation properties during operation; therefore it has obvious features of dynamic viscoelastic properties. From the viscoelasticity theory, the conveyor belt can be represented as more number of complex viscoelastic model made from more springs and dampers through series or parallel, and it tends to be all the more near the real mechanical properties of the material. Springs represent a flexible linear part with restorative forces and damper represents a viscous linear component with damping forces. Spring and a dashpot in series arrangement yields the Maxwell model, while associating a spring and dashpot in parallel yields the Kelvin– Voigt model. Kelvin– Voigt model is used to analysis short-term transient condition of belt during operation and it is more close to realistic mechanical properties of the unit [11].

V. LAGRANGE'S EQUATIONS

For n degree of freedom system, the equation of motion for a vibrating system is derived by the use of Lagrange's equation. The conveyer system is segmented into number of lumped mass unit connected in series. Each unit having appropriate of motional resistance, inertial resistance, potential gradient due to the device and system part associated with the unit. Thus for a unit body, equation of kinetic energy T, potential energy U and energy dissipation D can written as in (6).

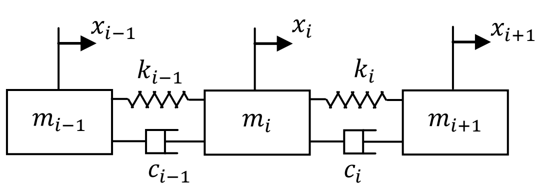

Fig.2 Lump Parameter model of unit

$$T = \frac{1}{2} m_{i-1}\dot{x}_{i-1}^2 + \frac{1}{2} m_i \dot{x}_i^2 + \frac{1}{2} m_{i+1}\dot{x}_{i+1}^2$$

$$U = \tfrac{1}{2} k_{i-1}(x_i - x_{i-1})^2 + \tfrac{1}{2} k_i (x_{i+1} - x_i)^2 \qquad (6)$$

$$D = \frac{1}{2} c_{i-1}(\dot{x}_i - \dot{x}_{i-1})^2 + \frac{1}{2} c_i (\dot{x}_{i+1} - \dot{x}_i)^2$$

Solving partial derivatives of equation (6) and substituting in Lagrange equation (7) to obtain equation of motion for the unit body as in (8) [12].

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{q}_i}\right) - \frac{\partial T}{\partial q_i} + \frac{\partial U}{\partial q_i} + \frac{\partial D}{\partial \dot{q}_i} = Q_i \qquad (7)$$

$$m_i\ddot{x}_i - c_{i-1}\dot{x}_{i-1} + (c_{i-1} + c_i + w_i)\dot{x}_i - c_i\dot{x}_{i+1}$$
$$-k_{i-1}x_{i-1} + (k_{i-1} + k_i)x_i - k_i x_{i+1} = F(t) \qquad (8)$$

Where w_i is the suffered resistance at $i - th$ unit, and taken as additional damping, $F(t)$ repreent external force to the unit.

VI. MODELLING AND SIMULATION OF BELT CONVEYOR SYSTEM

The belt conveyor system is divided in to five sub-units, two on carrying side and three on return side of the system. The numbering of units is in opposite direction of the motion of the belt. m_i represent equivalent mass of the unit. Stiffness constant k_i of each element is based on Young's modulus and length of unit. Damping constant c_i of each element evaluated as dependant value of element mass and stiffness considering critical damping as 0.1. For continuous lump parameter model when $i = 1, x_{i-1} = x_n$ and $i = n, x_{i+1} = x_i$ .Matrix form of equation of motion thus obtained.

$$M.\ddot{x}(t) + C.\dot{x}(t) + K.x(t) = F$$

$$\ddot{x}(t) = \frac{F - C.\dot{x}(t) - K.x(t)}{M} \qquad (9)$$

Where M is reduced mass matrix; C is damping coefficient matrix; K is stiffness matrix of n units. F is external force matrix and $x(t)$ is dislocation matrix. Resistance offered by each unit is sufficiently added as damping phenomenon at each unit. 1.4 times higher starting pull is applied to drive unit as a ramp function decreases linearly to steady state tractive pull over a time period till reach desired velocity. Simulation model for the two degree differential equation was prepared in mathematical solver simulink [13]. Gravity take-up mass is divided equally to adjacent units [14]. Initial condition at conveyor started, $t = 0, x_i = 0, \dot{x}_i = 0$ spring and damping constants are formulated based on the belt properties for each unit. The simulation runs for a sufficient time to settle the responses at steady state level.

VII. ANALYSIS OF COMPUTING RESULT

Belt conveyer chosen is one of the parts of Koradi Thermal Power Station (KTPS), Nagpur, (M.S.) India. It is situated in coal handling plant number 106. Conveyor system runs horizontal for 155.4 m and lift of 25 m for remaining 323.07 m. Drive pulley is at discharge end and takes up is gravity type located at 112.46 m return side from drive end.

Material conveyed is coal	
Length of belt (centre to centre distance)	478.48 m
Types of idlers -Impact idlers	15 no.
Carrying idlers	359 no.

Self aligning carrying idler	38 no.
Self aligning return idler	15 no.
Return idlers	144 no.
Weight carrying capacity	750 t/hr.
Designed capacity	1000 t/hr.
Belt velocity	3 m/sec
Belt width	1.2 m
Thickness	0.012 m
Open belt length	1000 m
Head pulley diameter	0.6 m
Tail pulley diameter	0.5 m
Bend pulley diameter	0.5 m
Snub pulley diameter	0.5 m
Take up pulley diameter	0.5 m
Motor power (kW)	200 KW

Static analysis of the belt conveyor was done and findings of tension values across the belt loop are drawn graphically as in Fig.3. In actual design take up tension is to maintain same in all running condition of system. Fully loaded steady state analysis shows that maximum tension 66.4 KN in the belt loop occurs at entry of drive pulley would increase to a value of 82.3KN during the starting. This path of this reduction in Fig. 4 is not clear with static analysis and assumed to be settled in 12.55 seconds with initial acceleration of 0.239 m/s^2. At the event of starting, tension at overall places rises except at exit point of drive pulley.

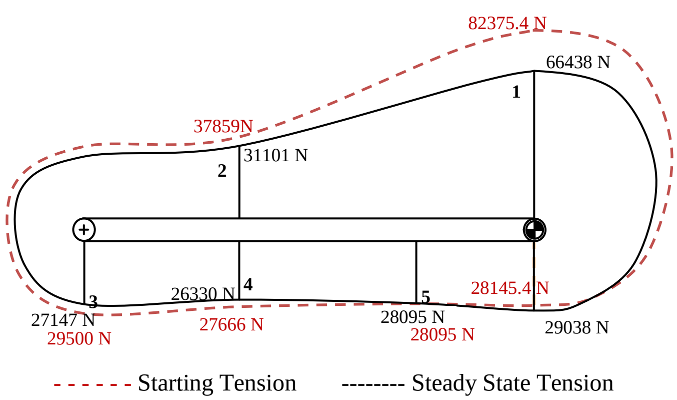

Fig.3 Tension variation along belt line

While in Fig. 5, result obtained from simulation clears that the dynamic variation of tension over the various critical points. Sudden pick of 115 KN tension observed at drive pulley unit which reduces steadily to a value of 62.3 KN. During fully loaded starting of belt conveyor, transient condition last about 30 sec which is higher than the time obtained in static analysis. Dynamic tensions in the subsequent units after drive unit are much lower than it.
Initial tension observed in take-up unit shows initial negative trend, represent contraction in the belt. This contraction is balanced physically by downward movement of gravity take-up assembly, so as to maintain initial tension in the belt. Major belt stresses developed in the starting phase can causes sudden failure of conveyor system.

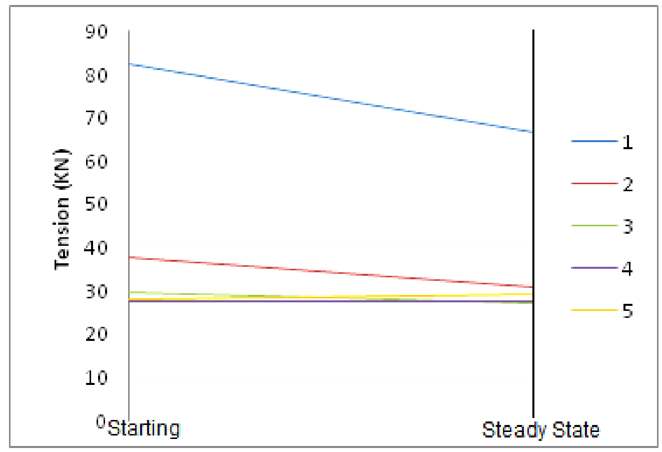

Fig 4. Tension change at critical points

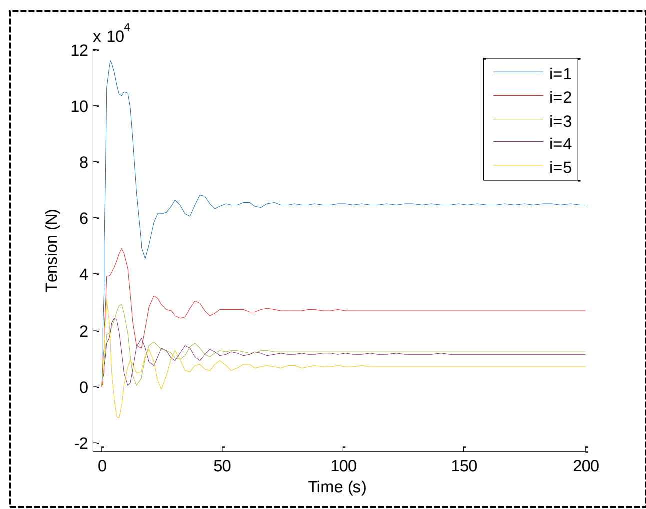

Fig 5. Dynamic Tension variation at critical points

VIII. CONCLUSION

Dynamical equation of conveyer system was built considering viscoelastic properties of the belt material and starting tension in the conveyor belt is compared with established numerical technique. It is not possible to find variation of tension directly from running belt, therefore simulation technique approaches to real results. The result shows significant peaks in tension during booting process. Transient tension value is more severe near drive pulley on the carrying side. Dynamic analysis of belt tension with lump parameter method helps to improve reliability of the system and to lower down the factor of safety used in conveyor system. Dynamic variation in tension in adjacent units also focused on the variation of belt stretch at starting phase. Higher tension at drive pulley unit during starting phase can be lower down by selecting particular angle of wrap and coefficient of friction at drive pulley. Tractive pull as a function of output torque characteristic of driving motor further can refine dynamic solution.

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