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Platform Motion at Lower Loading Station in Trucklift Slope Hoisting System with Varying Profile of Track

Kwang Hyok Kim[1], Tok Hyong Han[1], Un Chol Han[2]*, and Ryo Myong Hong[1]

1. Faculty of Mining Engineering, Kim Chaek University of Technology, Pyongyang, Democratic People's Republic of Korea
2. School of Science and Engineering, Kim Chaek University of Technology, Pyongyang, Democratic People's Republic of Korea

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Abstract

This paper focuses on a study concerned with estimation of the platform motion at the lower loading station in the Trucklift slope hoisting system with varying profile of track. The TruckLift slope hoisting system is an innovative transport technology for open-pit mines, and considerably accelerates and cheapens transport from mine. When a truck drives onto or drives off the platform at the lower loading station in the Trucklift slope hoisting system with varying profile of track, the platform motion influences the operation of the Trucklift slope hoisting system, and the configuration of inclined rope hitched to the platform is varied. The simulation result by using the ADAMS (Automatic Dynamic Analysis of Mechanical Systems) software shows that the horizontal distance between lower loading station and platform varies when a truck drives onto or off the platform and the initial horizontal distance that is the distance between lower loading station and platform when the winder is applied the brake, can be an important factor in operation of the Trucklift slope hoisting system with varying profile track.

1. Introduction

The TruckLift slope hoisting system is an innovative transport technology for deep open-pit mines, and considerably accelerates and cheapens transport from mines [1]. In order to accelerate and cheapen transport while maintaining flexibility offered by truck transport, the Trucklift systems were developed, which also have other names. When the mining penetrates increasingly deeper, the mine takes some kind of funnel shape. The deeper the funnel, the greater the expense for transport. While the roads hardly change deep down in the mine as well as at the top, expenditure on the haulage incline increases drastically. On the one hand, the driving time is prolonged by the increasingly longer incline road and the relatively low driving speed of the trucks. On the other hand, fuel consumption increases considerably, just as, in particular, does vehicle wear. In the TruckLift slope hoisting system, the advantages are of the transport time being curtailed by the difference in height being rapidly overcome and of the reduction of the truck fleet.

This paper covers the Trucklift slope hoisting system, where trucks are hoisted on the platform by the power of winder. These systems are generally similar to structure and operating principle, and consist of a slope hoisting plant, platforms, tracks, and loading stations. In the Trucklift slope hoisting system with a single track, as shown in Figure 1(a), there are a platform and a counterweight. An empty truck drives off a platform, and a laden truck drives onto the platform via the lower loading station after the platform reaches it. After the platform reaches the upper loading station, the laden truck drives off, and the empty drives onto the platform. In the system with double track, as shown in Figure 1(b), there are two platforms and two tracks whereby the platforms move simultaneously but in the opposite

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Corresponding author: huch8272@star-co.net.kp *(U.C. Han)*

directions. The platform with laden truck moves up on a track, and the one with empty truck moves down on the other track.

In order to estimate the movement of platform at the lower loading station when a truck drives off or onto the platform, the movement of the truck on the platform and the lower loading station and the effect of sagged inclined rope hitched to platform should be considered simultaneously. The platform motion is related to not only the profile of track and parameters of truck and platform, but also the parameters of sagged inclined rope hitched to platform.

Ropes have a range of applications in civil engineering and marine engineering. Linear and non-linear dynamics of inclined rope have attracted a considerable interest over the last few decades.

It is well-known since a long time ago that the equilibrium profile assumed by a rope under its own weight is represented by a catenary. Many studies on sagged ropes have focused on the vibration of inclined rope with two immovable pinned-supports.

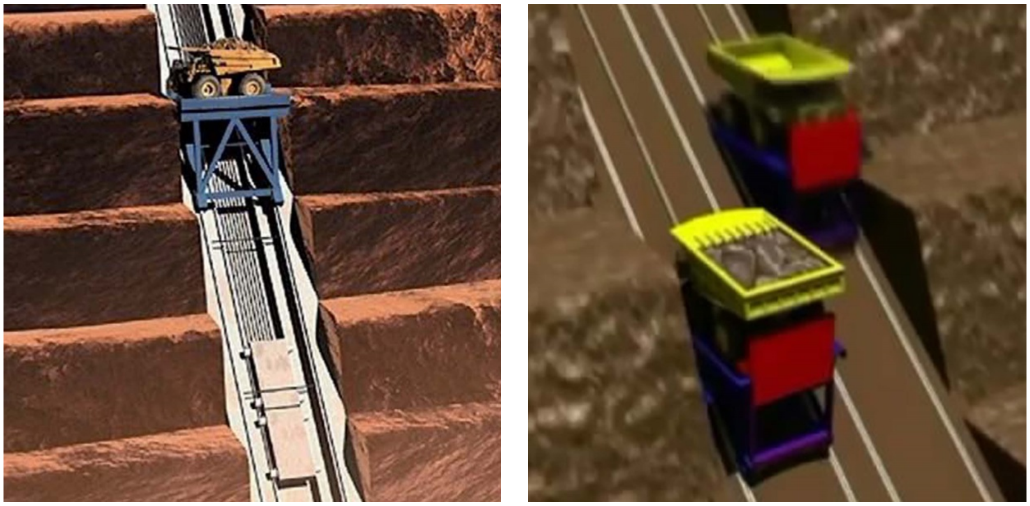

(a) (b)

Figure 1. Trucklift slope hoisting system (a) Trucklift slope hoisting system with single track, (b) Trucklift slope hoisting system with double tracks.

Linear models for in-plane free vibrations of inclined taut ropes have been proposed by Wu et al. [2] and Zhou et al. [3] based on a cubic approximation of the inextensible catenary solution and assumptions of the small ratio of sag to span and neglected longitudinal motion. A numerical model has been developed by Sorokin et al. [4] for linear vibrations of arbitrarily sagged extensible inclined ropes in a quiescent viscous fluid. An experimental study on the inclined rope has been proposed by Rega et al. [5]; it was aimed at experimental modeling and investigating the linear free and non-linear forced vibrations of sagged inclined ropes. Free undamped vibrations of ropes of arbitrary sag and inclination have been investigated according to the catenary theory by Mansour et al. [6].

Still, it should be noted that the analytical and numerical models mentioned previously are mainly addressed to purely stretchable ropes characterized by high pre-stressed configurations in which their bending stiffness is neglected. The three-node curved isoparametric finite element model has been investigated by Ni et al. [7]. Ricciardi et al. [8] have investigated a continuous model for dynamics of large-diameter sagged horizontal cables. Reduced-order model capable of analyzing the vortex-induced vibration of catenary riser in the ocean current has been developed by Srinil et al. based on exact hyperbolic solution of inclined inextensible catenary riser [9]. A geometrically exact mechanical formulation has been proposed by Arena et al. [10] for three-dimensional motions of flexible ropes.

A modelling method and an accurate numerical procedure have been investigated to simulate the dynamical responses of a multi-cable driven parallel suspension platform system by Wang et al.

[11]. By expressing the equations of motion and constraint equations at a velocity level, a non-smooth algorithm was used to numerically solve the equations. The numerical results were compared with the simulation data by using the ADAMS (Automatic Dynamic Analysis of Mechanical Systems) software, and the two results agreed well with each other.

In the light of previous investigations, the present work provides an alternative way to get the numerical solution of the motion of inclined rope by using flexible part in ADAMS and its application to analysis of the platform motion during truck changing in the Trucklift slope hoisting system.

This work focused on a study concerned with estimation of the platform motion at the lower loading station in the Trucklift slope hoisting system with varying profile of track. In order to properly explain the new approach, this paper is organized as what follows.

Section 2 is dedicated to static configuration of an extensible sagged inclined rope with the edges on the inclined tracks, and the simulation model to simulate the platform motion with consideration of stretching and bending of inclined rope by using a flexible body in ADAMS. Simulation in ADAMS provides the tension force in the inclined rope and position of platform during truck changing, and the result of it is presented in Section 3. Finally, the concluding remarks and some directions for further research works are drawn.

2. Simulation Model for Platform Motion at Lower Loading Station

A track of the Trucklift slope hoisting system is generally straight along the surface of open-pit mine, and it may consist of several tracks with different slopes, as shown in Figure 2.

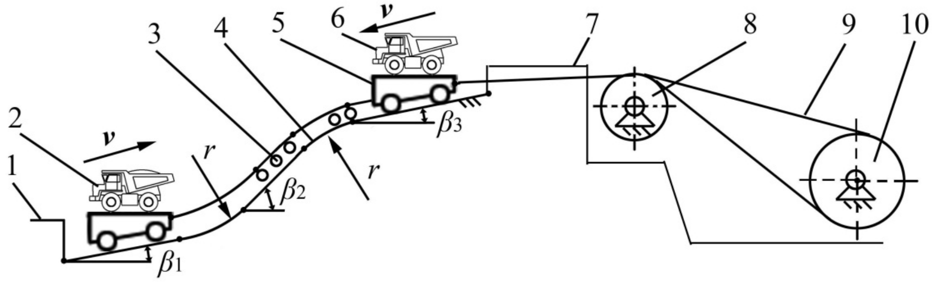


Figure 2. Schematic diagram of Trucklift slop hoisting system 1– lower loading station, 2– laden truck, 3– guide pulley, 4– track, 5– platform, 6– empty truck, 7– upper loading station, 8– sheave, 9– rope, 10– winder.

If the track of Trucklift slope hosting system consists of several tracks with different slopes, there is the sagged inclined rope hitched to platform when that moves on the lower loading station, as shown in Figure 3.

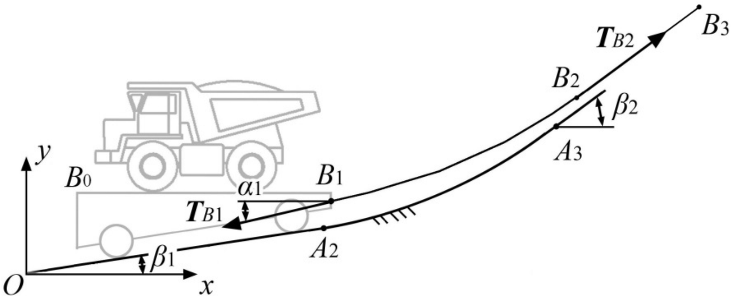


Figure 3. Sagged inclined rope in Trucklift slope hoisting system.

Keeping the elastic material assumption and considering only the axial rigidity, the rope's initial static configuration is expressed in a fixed Cartesian coordinate system Oxy, as follows [4]:

$$\begin{cases} x = \dfrac{H}{q_0}\left(\chi + \dfrac{H}{EA}\sinh\chi\right) + C_1 \\ y = \dfrac{H}{q_0}\left(\cosh\chi + \dfrac{H}{EA}\cosh^2\chi\right) + C_2 \\ \chi = \ln\tan\left(\dfrac{\pi}{4} + \dfrac{\alpha}{2}\right) \end{cases} \tag{1}$$

where q0 = ρgA is the gravitational force per unit rope length before stretching, E, ρ, and A are the Young modulus, the rope mass density, and the area of the cross-section, respectively, H is the horizontal component of the tension force T, and α is the local slope of sagged inclined rope.

The parameters C1 and C2 are defined by the suspension conditions at the left edge of the sagged inclined rope (χ = χ1 at point B1), whereas the suspension condition at the right edge (χ = χ2 at point B2) yields [4].

$$\begin{cases} \chi_2 - \chi_1 + \dfrac{H}{EA}(\sinh\chi_2 - \sinh\chi_1) = \dfrac{q_0 l}{H} \\ \cosh\chi_2 - \cosh\chi_1 + \dfrac{H}{2EA}(\cosh^2\chi_2 - \cosh^2\chi_1) = \dfrac{q_0 h}{H} \\ \sinh\chi_2 - \sinh\chi_1 = \dfrac{q_0 L_0}{H} \end{cases} \tag{2}$$

where l is the horizontal span of sagged inclined rope, and h is the height difference between edges of it.

Generally, L0, l, and h of sagged inclined rope are given because edges of it are fixed but L0, l, h, H, and χ1 are unknown, and only χ2 and E, A, q0 of sagged inclined rope are given in our study. By the coordinates of edges, as shown in Figure 2, the horizontal span and height difference between edges of sagged inclined rope are determined as follows:

$$l = x_{B2} - x_{B1},\ h = y_{B2} - y_{B1} \tag{3}$$

The length of rope on the straight track with slope β2 is determined as follows:

$$l_{B2B3} = (L_1 - L_0)\left(1 + \frac{T_2}{EA}\right) \tag{4}$$

where L1 is the undeformed length of rope on the track (between the point B1 and B3 in Figure 2), and T2 is the tension force at point B2. In addition, coordinates of point B2 could be expressed by coordinates of points B3, and length of rope on the straight track with slope β2.

$$\begin{cases} x_{B2} = x_{B3} - (L_1 - L_0)\left(1 + \dfrac{T_2}{EA}\right)\cos\beta_2 \\ y_{B2} = y_{B3} - (L_1 - L_0)\left(1 + \dfrac{T_2}{EA}\right)\sin\beta_2 \end{cases} \tag{5}$$

Substituting Equations (3) and (5) into Equation (2) with considering T2 = H/cosβ2, tanβ1 = yB1/xB1:

$$\begin{cases} \chi_2 - \chi_1 + \dfrac{H}{EA}(\sinh\chi_2 - \sinh\chi_1) = \dfrac{q_0}{H}\left[x_{B3} - (L_1 - L_0)\left(\cos\beta_2 + \dfrac{H}{EA}\right) - x_{B1}\right] \\ \cosh\chi_2 - \cosh\chi_1 + \dfrac{H}{2EA}(\cosh^2\chi_2 - \cosh^2\chi_1) = \dfrac{q_0}{H}\left[y_{B3} - (L_1 - L_0)\left(\sin\beta_2 + \dfrac{H}{EA}\tan\beta_2\right) - x_{B1}\tan\beta_1\right] \\ \sinh\chi_2 - \sinh\chi_1 = \dfrac{q_0 L_0}{H} \end{cases} \tag{6}$$

From equilibrium of platform straight track with slope β1, the equation with horizontal component of tension force and mass of platform could be written as follows:

$$\frac{H}{\cos^2\alpha_1}\left(\tan\alpha_1 + \frac{\cos\beta_1 + f\sin\beta_1}{\sin\beta_1 - f\cos\beta_1}\right) - mg = 0 \tag{7}$$

where f is the resistant coefficient of platform, and m is the mass of platform including a truck.

The system of non-linear Equations (6) and (7) with respect to H, χ1, xB1, and L0 are solved numerically for any combination of parameters, furnishing the explicit solution of the extensible inclined rope in the parametric form (1). The position of platform and static configuration of rope are given from the above equations when the platform stays at the lower loading station.

The platform on the track could be shook when a laden truck drives onto platform or an empty one drives off at the lower loading station. When a laden truck drives onto the platform or an empty one drives off, two ends of catenary move because the platform moves, and length of catenary varies too. However, equations of catenary profile will be complex by accounting for stretching and bending.

The ADAMS simulation could be used to analyze the platform motion with consideration of stretching and bending stiffness of sagged inclined rope in the Trucklift slope hoisting system. The ADAMS simulation is an alternative way in investigating the sagged inclined rope. ADAMS lets us build models of mechanical systems, and simulate the full-motion behavior of the models. We can also use ADAMS to quickly analyze multiple design variations until we find the optimal design.

The FE Part (Finite Element Part in ADAMS software) is a wholly Adams-native modeling object with inertia properties, and is accurate for very large deformation cases. In ADAMS, the FE Part is composed of small pieces, known as finite elements. The behavior of each element is well-known under all possible support and load scenarios. The elements share common points called nodes, section properties are assigned on each node. To analyze the vibration of a sagged inclined rope by using FE part, it is necessary to specify material, beam type, damping ratio, faceting tolerance, and section properties of rope. Beam Type specifies the specific type of FE Part to be modeled. There are 4 kinds of beam including 3D Beam, 2D Beam XY, 2D Beam YZ, and 2D Beam ZX. 3D Beam is a three-dimensional fully geometrically non-linear representation useful for beam-like structures, and accounts for stretching, shearing, bending, and torsion. 2D Beam such as 2D Beam XY, 2D Beam YZ, and 2D Beam ZX is two-dimensional geometrically non-linear representations useful for beam-like structures, whereby the centerline of the beam can be assumed constrained to a plane parallel to the model's global plane. 2D Beam can stretch or bend in plane. 2D Beam will solve faster than the 3D Beam. Material defines a collection of constants required to define the stress-strain relationship for a given physical material. Faceting Tolerance specifies a real value to control the mesh density for visualizing the FE Part. The default Faceting Tolerance is 300.0. Increasing this value will result in a finer mesh of triangles, which gives a more accurate representation of curved surfaces. Section properties define the cross-sectional property values for each node specifying area and area moments of inertia (Iyy, Izz, and Iyz) of the beam. ADAMS offers some standard cross-section types such as Solid Circular, Solid Elliptical, Solid Rectangular, Solid I Beam, and General Section.

In order to simulate the platform motion by using ADAMS, we can use the following assumptions:

(i) The winder is in the rest because the winder is applied to the brake when a truck drives onto or off the platform at the loading station in Trucklift slope hoisting system.

(ii) The rope hitched to platform is extensible, and has bending stiffness

(iii) The rope between B2B3 (Figure 4 (a) and (c)) is not sagged because there is enough rollers on straight track and the rope between B2B3 is on the rollers

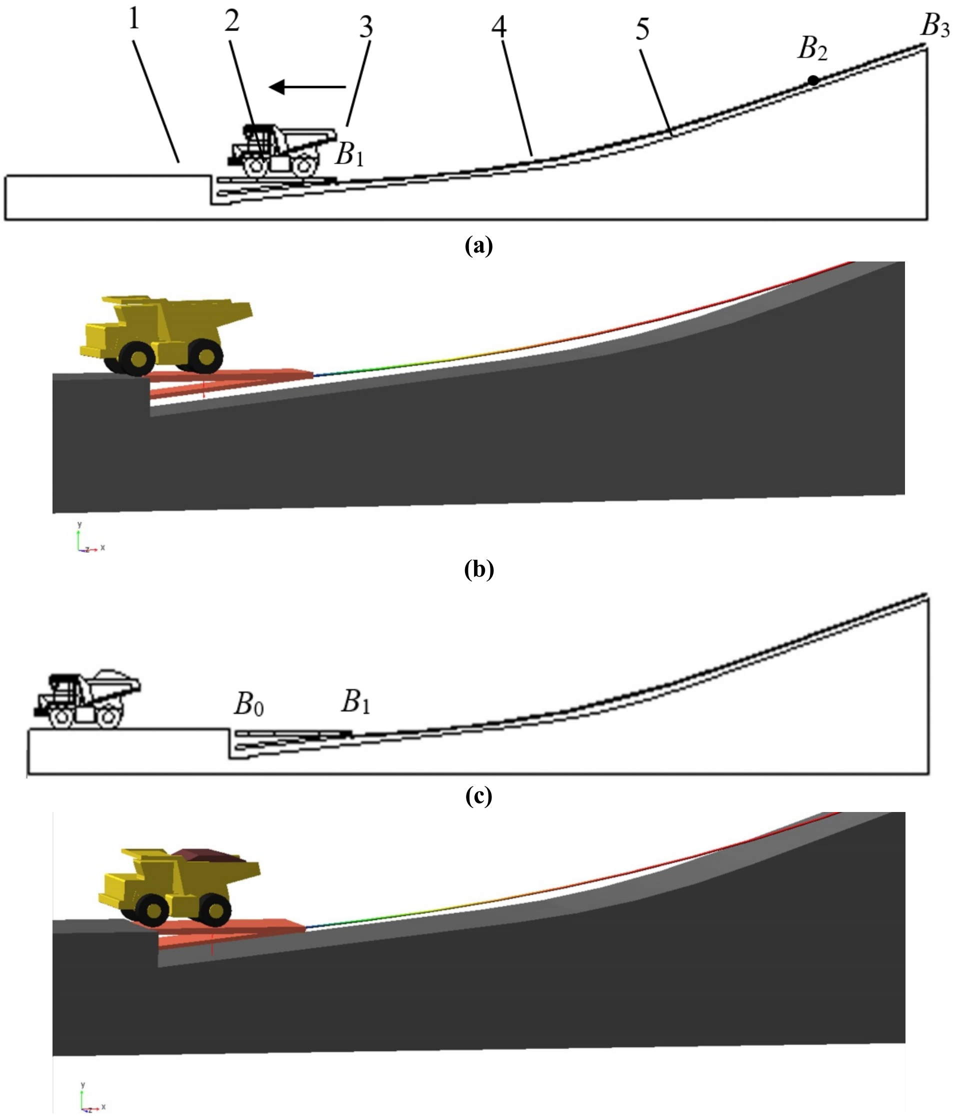
The simulation model consists of a platform and an empty truck on it, a track, and a rope, as shown in Figure 4(a). The track consists of two straight tracks with slope β1 and β2, respectively, and a curved track between them. The mass of the empty truck is equal to 19t, and the slope β1 is 10°, slope β2 is equal to 19°, and an end of rope is fixed at the point B3.

The steps of constructing the simulation model are as follows:

Firstly, only geometries of truck, platform, and trace were created in Solidworks, and imported individually into the ADAMS software.

Secondly, geometries were located in the ADAMS software

When an empty truck drives off the platform, the truck locates on the platform at the beginning of simulation, as shown in Figure 4(a).



(a)

(b)

(c)

(d)

Figure 4. Simulation model to analyze the movement of the platform at the lower loading station (a), (b) when an empty truck drives off the platform, (c), (d) when a laden truck dives onto the platform; 1– lower loading station, 2– platform, 3– empty truck, 4– rope, 5– track, 6– laden truck.

When a laden truck with payload 25t drives onto the platform, the truck locates on the lower loading station at the beginning of simulation, as shown in Figure 4(c).

Thirdly, rope was added into the simulation model in the ADAMS software.

A rope is modeled by using FE Part as flexible body, and the other end of it is connected to the platform by using revolute joint. A contact is defined between rope and straight track with slope β2 so that the rope is on the straight track with slope β2. Mass per unit length of rope is equal to 9.6 kg/m, and net cross-section area equal to 2.46 × 10−3 m2. The material is theoretically assumed to be homogeneous and linearly elastic with estimated Young's modulus equal to 108 MPa.

Fourthly, constraints were added to the ADAMS software.

At the lower loading station, a translational joint with frictional coefficient of 0.02 is added between platform and straight track of track with slope β1 because the platform moves on the straight track with slope β1 when a truck drives off and onto the platform. The truck consists of the main body and 4 tires with diameter 1.6 m, and revolute joints are added between them, and a revolute motor is added to the revolute joint between main body and rear tire so that the truck moves at 1.2 m/s and 0.5 m/s2 when starting. Two contacts are added between tires and platform, tires, and the lower loading station, respectively.

3. Result and Discussion

3.1. Result of simulation

From the ADAMS simulation, the static configration of the sagged inclined rope hitched to the platform with an empty truck could be obtained when the platform is in the rest (t = 5 s), and it is shown in Figure 5. Static configration of the inclined extensible rope could be obtained from the above equations by using MATLAB.

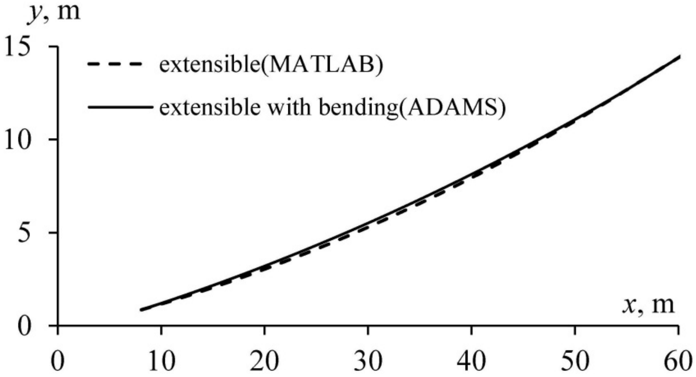
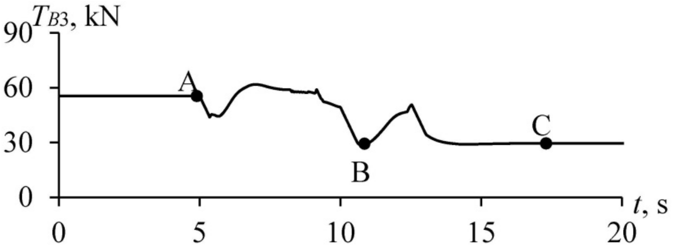
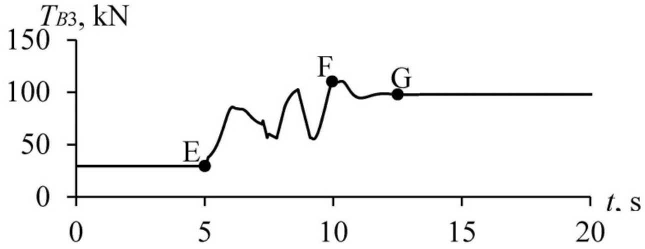


Figure 5. Static configuration of the sagged inclined rope hitched to the platform.

In Figure 4, the point B1 is the connection of rope to the platform. In Figure 5, x components of B1 for extensible rope, and extensible rope with bending are 8.077 and 8.06, respectively. As shown in Figure 6(a), the tension force of rope decreases when an empty truck drives off the platform, and the minimum tension force may be smaller than the tension force in the rope hithed to the stopped empty platform.



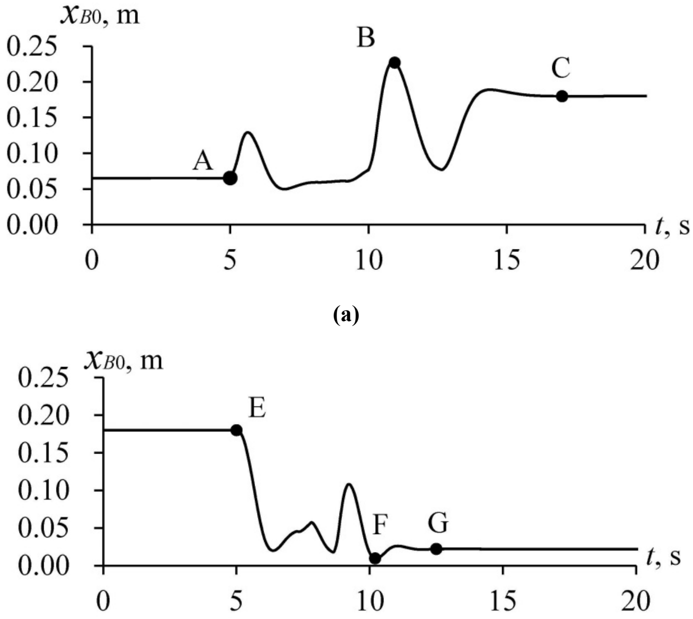
(a)



(b)

Figure 6. Tension force of rope hitched to the platform at the lower loading station (a) when an empty truck drives off the platform, (b) when a laden truck drives onto the platform.

As shown in Figure 6(b), the tension force of rope increases when a laden truck drives onto the platform, and the maximum tension force may be larger than the tension force in the rope hithed to stoped platform with a laden truck. When an empty truck drives off platform, the displacement of platform varies, as shown in Figure 7.



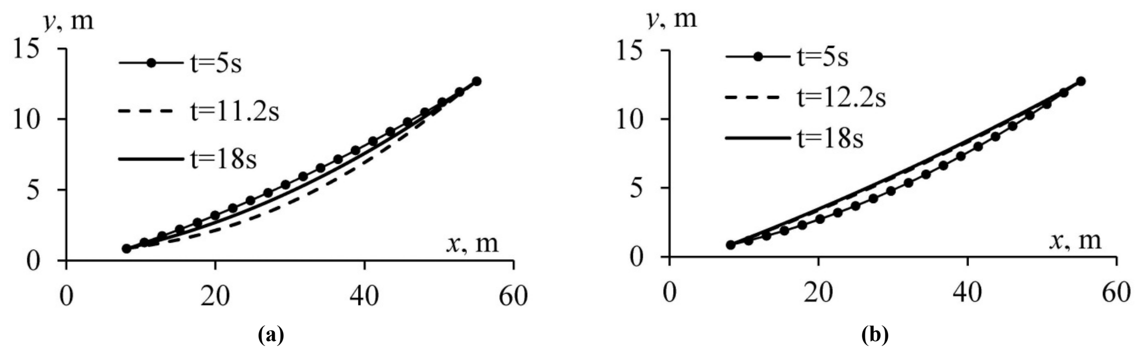
(a)

(b)

Figure 7. Displacement of platform at the lower loading station (a) when an empty truck drives off the platform, (b) when a laden truck drives onto the platform.

When an empty truck drives off the platform, the platform locates at the position with horizontal distance of 0.06 m from the lower loading station at the beginning of simulation. After 5 s (point A in Figure 7(a)), the platform moves because an empty truck moves on it and the distance between the platform and the lower loading station has the maximum value of 0.23 m at t = 12.2 s (point B). When an empty truck drives on the lower loading station, the platform stops at position with the distance of 0.18 m (point C) from the lower loading station. When a laden truck drives onto the platform, the platform locates at the position with the horizontal distance of 0.18 m from the lower loading station at the beginning of simulation. After 5 s (point E in Figure 7(b)), the platform moves because a laden truck begins to drive onto it and the distance between platform and the lower loading station has the minimum value of 0.01 m at t = 11.2 s (point F). After stopping of laden truck on the platform, the platform stops at the position with the distance of 0.03 m (point G) from the lower loading station.

The configuration of sagged inclined rope changes, as shown in Figure 8, because the platform moves on the track with slope β1 when a truck drives on the platform.



(a) (b)

Figure 8. Configruation of sagged inclined rope (a) when an empty truck drives off the platform, (b) when a laden truck drives onto the platform.

When an empty truck drives off the platform, the sag of sagged inclined rope is largest at t = 11.2 s, and it corresponds to point B in Figure 7(a). When a laden truck drives onto the platform, the sag is largest at t = 5 s, and it corresponds to point E in Figure 7(b).

3.2. Discussion

The distance between the lower loading station and the platform increases when an empty truck drives off platform, and decreases when a laden truck drives onto platform. The displacement of platform could be determined by the difference between the maximum and the minimum values of the distance, and is about 0.22 m in this simulation. As it is seen from the above simulation results, when a truck drives off and onto the platform, the distance between the lower loading station and the platform has the maximum value of 0.23 m, and it may be not considerable in comparison with the diameter of tire. As shown in Figure 7(a), the initial distance between the lower loading station and the platform is 0.06 m but it is not constant in the operation of the Trucklift slope hoisting system. Due to influence of sagged inclined rope, the initial distance is different for every braking of winder in the end of hoisting period. If the initial distance is larger considerably, tires of truck may be fallen into the space between them when a truck drives off or onto the platform at the lower loading station. The tension of rope increase with increasing of distance between the lower loading station and the platform, and it seems that the simulation result agrees with the mechanical principle.

4. Conclusions

This work focused on the estimation of platform motion with consideration of sagged inclined rope when a truck drives off or onto a platform at the lower loading station in the Trucklift slope hoisting system with varying profile of track. The system of non-linear equations to furnish explicit solution was proposed for extensible sagged inclined rope with the edges on the inclined track, and platform motion was simulated by using the ADAMS software, and the sagged inclined rope hitched to platform was modeled by flexible body with consideration of elasticity and bend. The maximum distance between the lower loading station and the platform was estimated by simulation in ADAMS under the given operational condition. In addition, we could obtain the displacement of the platform and the tension force of rope in the simulation.

The simulation result shows that the horizontal distance between lower loading station and platform varies when a truck drives onto or off the platform and Initial horizontal distance that is the distance between lower loading station and platform when the winder is applied the brake, could be an important factor in operation of the Trucklift slope hoisting system with varying profile track. If the initial horizontal distance is too small, the platform could impact against lower loading station during a truck drives onto the platform. If the initial horizontal distance is too large, a truck could not drive off the platform because a tire could fall in the space between lower loading space and platform.

Finally, the result may give a chance to design the platform and the lower loading station without special apparatuses to arrest a platform when a truck drives onto or off it.

Data Availability

The data used to support the findings of this study is available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

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حرکت پلت فرم در ایستگاه بارگیری پایین در سیستم بالابر شیب کامیون با مشخصات مسیر متغیر

کوانگ هیوک کیم[۱]، توک هیونگ هان[۱]، اون چول هان[۲]* و ریو میونگ هونگ[۱]

۱. دانشکده مهندسی معدن، دانشگاه صنعتی کیم چاک، پیونگ یانگ، جمهوری دموکراتیک خلق کره
۲. دانشکده علوم و مهندسی، دانشگاه صنعتی کیم چاک، پیونگ یانگ، جمهوری دموکراتیک خلق کره

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* نویسنده مسئول مکاتبات: huch8272@star-co.net.kp

چکیده:

این مقاله بر روی یک مطالعه مربوط به تخمین حرکت سکو در ایستگاه بارگیری پایین‌تر در سیستم بالابر شیب کامیون با مشخصات مسیر متفاوت تمرکز دارد. سیستم بالابر شیب TruckLift یک فناوری حمل و نقل نوآورانه برای معادن روباز است و به طور قابل توجهی حمل و نقل از معدن را تسریع و ارزان می‌کند. هنگامی که یک کامیون بر روی سکو در ایستگاه بارگیری پایین‌تر در سیستم بالابر شیب تراک لیفت با مشخصات مسیر متفاوت می‌راند یا از آن خارج می شود، حرکت سکو بر عملکرد سیستم بالابر شیب تراک لیفت و پیکربندی طناب شیبدار متصل به سکو تأثیر متفاوتی می‌گذارد. نتیجه شبیه‌سازی با استفاده از نرم‌افزار ADAMS (Automatic Dynamic Analysis of Mechanical Systems) نشان می‌دهد که فاصله افقی بین ایستگاه بارگیری پایینی و سکو زمانی که کامیون بر روی سکو حرکت می‌کند یا از آن خارج می شود و فاصله افقی اولیه که فاصله بین ایستگاه بارگیری پایین‌تر است، متفاوت است. و پلت فرم هنگامی که سیم پیچ ترمز اعمال می‌شود، می‌تواند یک عامل مهم در عملکرد سیستم بالابر شیب تراک لیفت با مسیر پروفیل متفاوت ایجاد کند.

کلمات کلیدی: سیستم بالابرنده شیب کامیون، ADAMS، طناب شیبدار آویزان، سکو.
