THE APPLICATION OF FLYWHEELS ON BELT CONVEYORS

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ABSTRACT

In practice, a differentiation can be made between an operational stop of a belt conveyor, where drives may be used to bring the belt to rest in a controlled way; and an emergency stop. In some cases it may be beneficial to extend the time it takes a belt to stop during an emergency stop. This holds true, for example, in a steep incline belt or for some very long overland systems. This paper explains how flywheels can extend the stopping time of belt conveyors and analyses the impact flywheels have on the operational performance and dynamics of belt conveyors. A practical example of an existing belt conveyor equipped with flywheels is given.

INTRODUCTION

Belt conveyors are commonly used for the continuous transportation of bulk solid materials. During the design of a belt conveyor, all the applicable ambient and operational conditions have to be analysed.

Ambient conditions are primarily about the ambient temperature and the moisture content of the air. The ambient temperature affects the behaviour of the rubber compound used in the belt's covers and the rolling resistance of idler rolls (Lodewijks, 2004). The moisture content affects the friction coefficient between the conveyor's pulleys and the belt and thus may affect the power transmission from the drive train into the belt.

When considering the operational conditions, the stationary operation and the transient operation have to be distinguished. The stationary operation includes both the case where the belt is not moving at all, which of course has little practical significance, and the case where the belt is running at full design speed. Whether full speed is always the design speed depends on how the belt is driven. If an uncontrolled fluid coupling is used, then the belt speed changes with the bulk solid material load on the belt. If a speed controlled Variable Speed Drive (VSD) is used, then full speed is the design speed. The transient operation normally includes the following situations:

— *normal operational start*; a normal operational start is a start where the belt is started in a planned manner. This may be a controlled manner if VSDs or controlled fluid couplings are used, or an uncontrolled manner if a conveyor starts direct on line.

— *aborted start*; an aborted start is a normal operational start that is aborted before the start-up is completed. Abortion can be caused by thermal overload of the drives, serious deviation from the planned belt speed start-up profile caused by overload of the belt, serious misalignment of the belt triggering a misalignment switch, or an operator pulling the pull cord.

— *normal operational stop*; a normal operational stop is a stop where the belt is stopped in a planned manner. This may be a controlled ramp-down of the belt if VSDs are used, or the belt can drift to rest. In the latter case, the stopping or drift time depends on the load of the bulk solid material on the belt. In some cases brakes are used to limit the stopping time. Normally the brake settings are pre-set for a normal operational stop.

— *emergency stop*; an emergency stop is when the belt has to be stopped in a short period of time because an emergency condition occurs. Emergency conditions can be similar to the conditions described earlier under the aborted start. In any case, the goal of an emergency stop is to bring the belt to a stop as soon as possible. What the shortest stopping time is in practice depends totally on the system under consideration and the application. An emergency stop of a man-carrying conveyor is obviously necessarily much faster than an emergency stop of an overland system hauling ore. In practice, stopping times around 30–40 seconds are used for belt conveyors. However, stopping a 20 km overland system in 30 seconds in a controlled manner, and such that the belt tensions remain within limits and the dynamic behavior is still acceptable, may be a challenge!

An overview of dynamic analyses of belt conveyors by Lodewijks can be found in (Lodewijks, 2002).

FLYWHEELS

Flywheels have been in use on a large scale since the beginning of the industrial revolution. In essence, a flywheel is a rotating mechanical device that is used to store rotational energy. Flywheels in belt conveyors are typically disks made of steel that are mounted on a shaft of the drive system. Flywheels can be installed on the high speed shaft, between the drive and the gearbox, as well as on the low speed shaft, on a shaft after the gearbox. In some cases flywheels can be installed inside the gearbox. However, this is only possible if the inertia of the flywheel is limited compared to the inertia of the gearbox and drive train.

Figure 1. Belt conveyor drive with flywheel
(courtesy Hansen)

In general, a flywheel can:

1. Provide continuous energy when the energy source is discontinuous
2. Deliver energy at rates beyond the ability of a continuous energy source
3. Control the orientation of a mechanical system. In the belt conveyor application, flywheels are primarily used for the storage of energy that is required when the energy source is not able to provide enough energy, normally because of drive failure or a shut down.

The rotational energy E_f stored in a flywheel with moment of inertia I_f and rotating with an angular velocity ω is equal to

$$E_f = \frac{1}{2} I_f \omega^2 \qquad 1$$

If the flywheel has a mass m_f and a radius r_f then the moment of inertia I_f of the flywheel is

$$I_f = \frac{m_f r_f^2}{2} \qquad 2$$

Energy is transferred to a flywheel by applying a drive torque to it, which increases its rotational speed. In a belt conveyor the angular velocity of a flywheel is increased together with the rest of the system. The energy of a flywheel is released if the drives are shut down and the belt drifts to rest.

APPLICATION IN BELT CONVEYORS

In belt conveyors, flywheels are used for one main reason: to slow down the momentum of the reduction in belt speed when the drives cannot be used to stop the belt in a controlled manner. Whether the decreasing belt speed during a stop needs to be slowed down or not depends primarily on two questions.

The first question is whether or not the belt conveyor is part of a series of belt conveyors, or feeding into a bunker. For example, if a long overland conveyor is part of a series of belt conveyors and feeding a small in-plant conveyor, then the stopping time of the in-plant conveyor might be considerably shorter than the stopping time of the overland conveyor. Assume that no significant bunker is available between the overland conveyor and the in-plant conveyor. In that case the stopping times of the two conveyors must be matched to prevent overloading the bunker in between the faster stopping in-plant conveyor and the overland conveyor. In principle, two options are available to achieve this – either using a brake to stop the overland conveyor faster or a flywheel to extend the stopping time of the in-plant conveyor.

The second question is whether or not the belt tensions are acceptable during a drift stop, in particular the minimum belt tensions. Some conveyors have a profile that makes them susceptible to low tension areas during an emergency stop when the drives cannot be used to stop the conveyor. Examples are incline shaft conveyors and conveyors with a “dip” in the profile. One way to control the development of low tension areas is to use flywheels to slow down the decrease of the belt speed of the conveyor. Other options are to increase the take-up tension or to use brakes and capstans to regulate the belt tension.

Stopping time

Since flywheels are applied to have an effect on the natural drift time of belt conveyors, assuming that no additional brakes are used, the drift stopping time needs to be calculated. It is not difficult to predict the drift stopping time of a belt conveyor. One major misunderstanding is that the stopping times of belt conveyors, particularly the long overland conveyors and the high powered belt conveyors, can only be calculated using a dynamic analysis. This is not true. The drift stopping time can be calculated using a quasi-static approach. The determination of the actual belt speed variation during the stop however, requires a dynamic analysis. The same holds for a prediction of the belt tension variation during a stop.

If the DIN 22101 design approach is used then the total mass of a belt conveyor with length L can be described as follows

$$M_c = L(m_r' + 2m_b' + m_l') \quad 3$$

where m'_r is the reduced mass of the carry and return idler rolls per metre of belt length; m'_b the mass of the belt per metre and m'_l the mass of the bulk solid material on the belt per metre. Note that in Equation 3, the drive train inertia Id is not included. With a fictive coefficient of friction f, a ratio between main and side resistances C, g the gravitational acceleration and an elevation change H between head and tail pulley the required drive force becomes

$$F_d = CfgM_c + m_l'gH \quad 4$$

In the above equation the effect of the inclination or declination of the belt conveyor on the friction, the tan(δ) term, has been neglected.

If it is assumed that the belt conveyor acts like a rigid body, as is the assumption in DIN 22101, then Newton's second law can be applied to calculate the stopping time of a belt conveyor. If the radius of the drive pulley is r_d, then the inertia of the (mass of the) belt conveyor can be calculated

$$I_c = M_c r_d^2 \qquad 5$$

To convert the conveyor's inertia to the high speed side of the drive train, the inertia calculated in Equation 5 has to be divided by i^2 where i is the gearbox ratio. Assume that the inertia of the drive train is equal to I_d. The total belt conveyor inertia then is equal to

$$I_t = I_c + I_d \qquad 6$$

With the required drive force F_d the drive torque applied on the drive pulley is equal to

$$T_d = F_d r_d \qquad 7$$

Using Newton's second law, the angular acceleration α of the drive train, on the low speed side, can be found

$$\alpha = \frac{T_d}{I_t} \qquad 8$$

The belt's deceleration a can be related to the angular acceleration α

$$a = r_d \alpha \qquad 9$$

If the belt conveyor is running at a speed V and the conveyor drifts to rest linearly (with constant deceleration) then the deceleration a can also be described as

$$a = \frac{\Delta V}{\Delta t} \qquad 10$$

In Equation 10, ΔV is the difference between the stationary running belt speed and the stopped belt speed, in this case ΔV is equal to V, and Δt the difference between the time where the stop was initiated and the time the belt stopped, which is equal to the stopping time. If the Equations 3 to 10 are combined, then the stopping time Δt can be calculated

$$\Delta t = \frac{\Delta V\left(\frac{I_d}{r_d^2} + M_c\right)}{CfgM_c + m_l' gH} \qquad 11$$

If the stopping time found with Equation 11 is too short and needs to be extended, for reasons discussed earlier, then measures have to be taken. From Equation 11 it can be learned that basically the only variable that is available to change Δt is the inertia I_d. This is where a flywheel comes in. With the application of a flywheel the inertia I_d can be increased which (linearly) increases the stopping time Δt.

Flywheel dimensions

With Equation 2 the required dimensions of the flywheel can be calculated. Assume that the flywheel has a thickness d_f, a radius r_f and a density ρ. Including the dimensions of the flywheel shaft made of the same material, the inertia I_f depends as follows on the flywheel's dimensions

$$I_f = \pi \rho d_f r_f^4 \qquad 12$$

From Equation 12 it can be learned that the radius of the flywheel contributes the most to its inertia.

CASE STUDY

In 2001 the first author of this paper was involved in a South African project called Maandagshoek, which was an Amplats/ETS project. One of the conveyors, the so-called North Shaft Decline Conveyor was typical of a conveyor that might require flywheels. The conveyor had an overall length of 1 350 m and a lift of 219 m. In fact, although called a decline conveyor, it was an incline shaft conveyor. The conveyor hauled 600 MTPH of platinum ore on a 1 050 mm-wide belt running at 2.25 m/s. The conveyor had two 335 kW drives at the head that both had an inertia of 27.0 kg/m^2.

Figure 2 shows belt speed during a drift stop of the conveyor as a function of the extra inertia at the head drives (per drive). The results were obtained using a commercial dynamic analysis package. As can be seen, the belt stops very fast with no additional inertia. In addition it can be observed that the belt reverses temporarily (belt speed below zero), which for this conveyor is not an acceptable dynamic condition. With an increase in head drive inertia the stopping of the belt smooth's out. However, it takes 89.5 kg/m^2 extra inertia to prevent reverse belt motion.

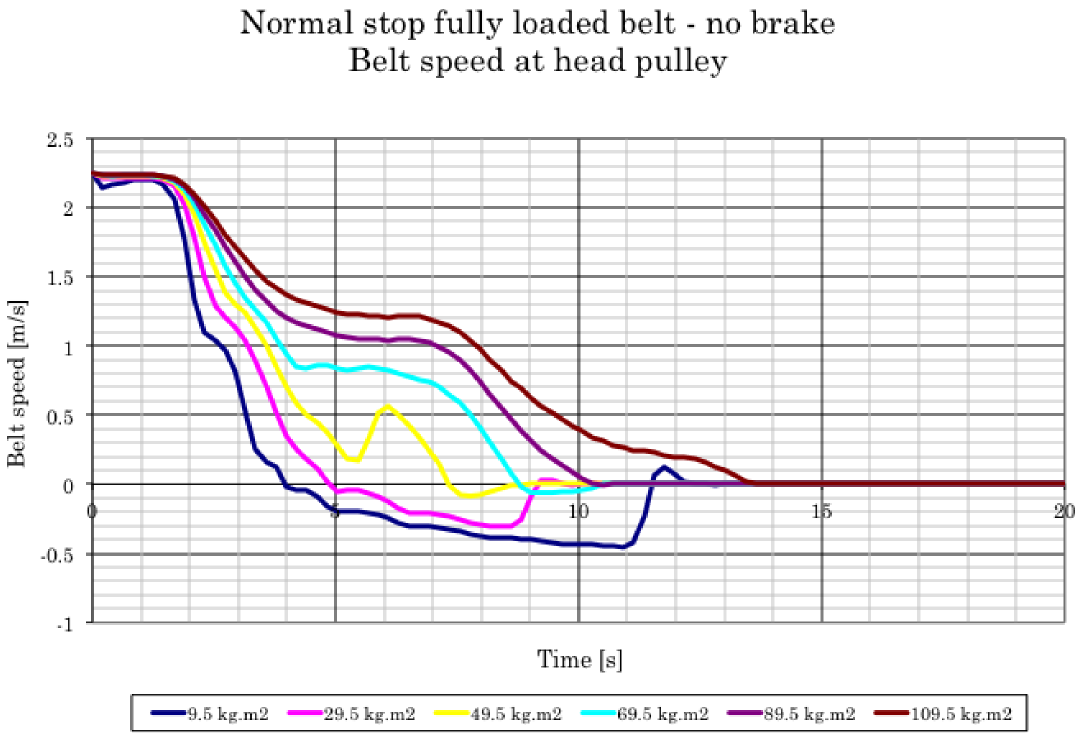

Figure 2**.** Belt speed as a function of time for different additional head drive inertias

Figure 3 shows the minimum belt tension in the belt during the same drift stops as presented in Figure 2. From Figure 3 it is learned that unless the additional head drive inertia is over 89.5 kg/m^2 the belt tension goes to zero during the stop. A belt tension that low means that the belt may literally be on the floor, which is an unacceptable situation. From Figures 2 and 3 it is shown that in order to achieve acceptable belt tensions, the additional head drive inertia should be at least 89.5 kg/m^2 which leads to a minimum stopping time of ten seconds. This stopping time is acceptable. However, to allow for a slightly smaller flywheel, the option of using a small 5 kNm brake at the low speed side of the tail was investigated.

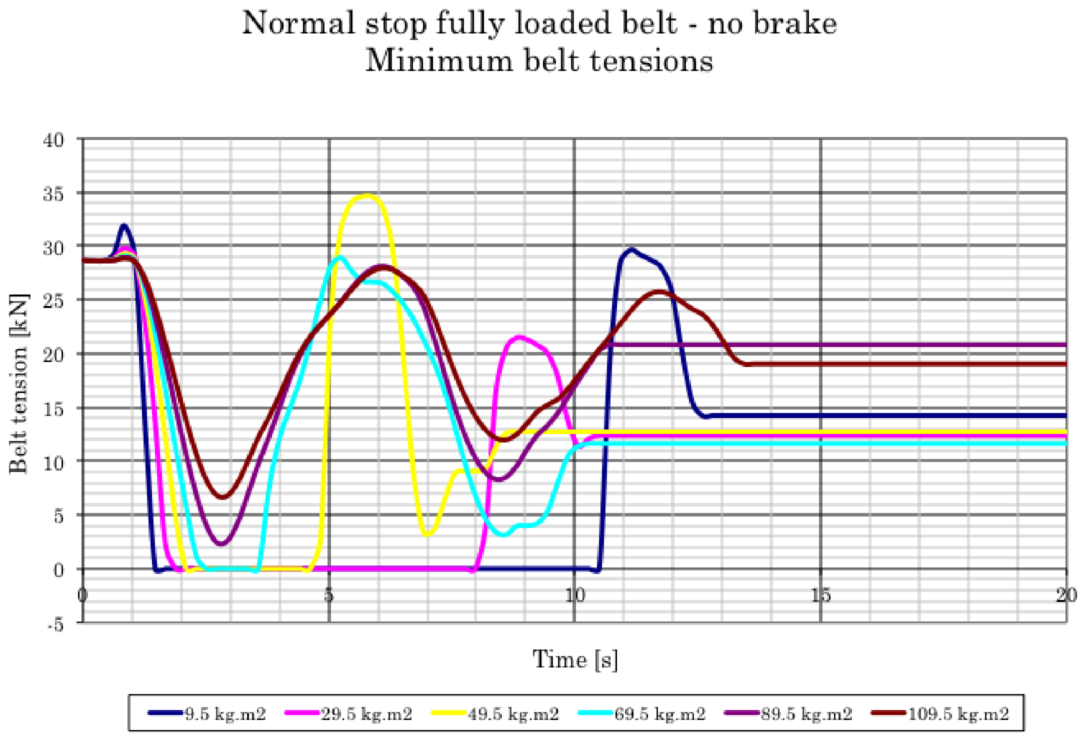

Figure 3. Belt tension as a function of time for different additional head drive inertias

Figure 4 shows the effect of the brake on the belt speed development during the stop. It can be seen that the stopping times are slightly reduced, but not unacceptably. However, what is more important is that the development of the belt speed during stop is much more regular; only for the two lowest inertias does the belt speed slightly show some signs of a reverse motion. Figure 5 then shows the development of the minimum belt tension during the braked stop. Here it can also be seen that the brake has a significant effect on the stop. There are still some unacceptably low tension areas, but they are much smaller compared to the situation where no brake is used. Without a brake the minimum head drive inertia was 89.5 kg/m^2, with brake it is 49.5 kg/m^2. Since this is a substantial difference over the penalty of having to use a brake, it was decided to install 50 kg/m^2 flywheels on both drives.

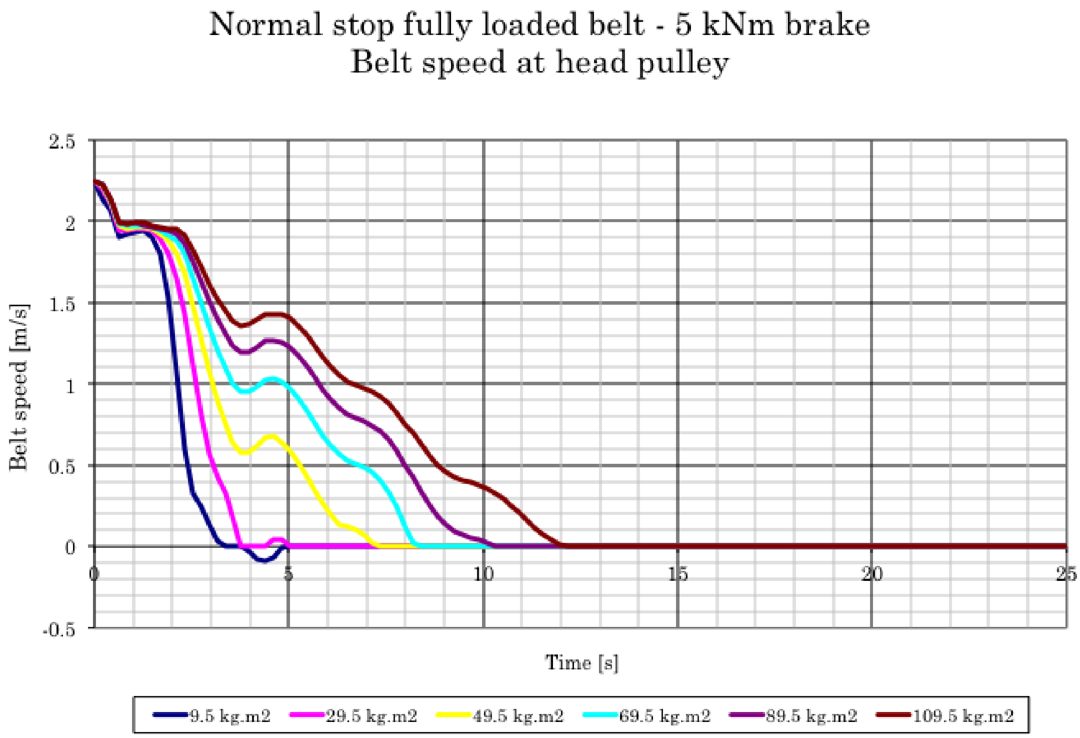

Figure 4. Belt speed as a function of time for different additional head drive inertias using a brake

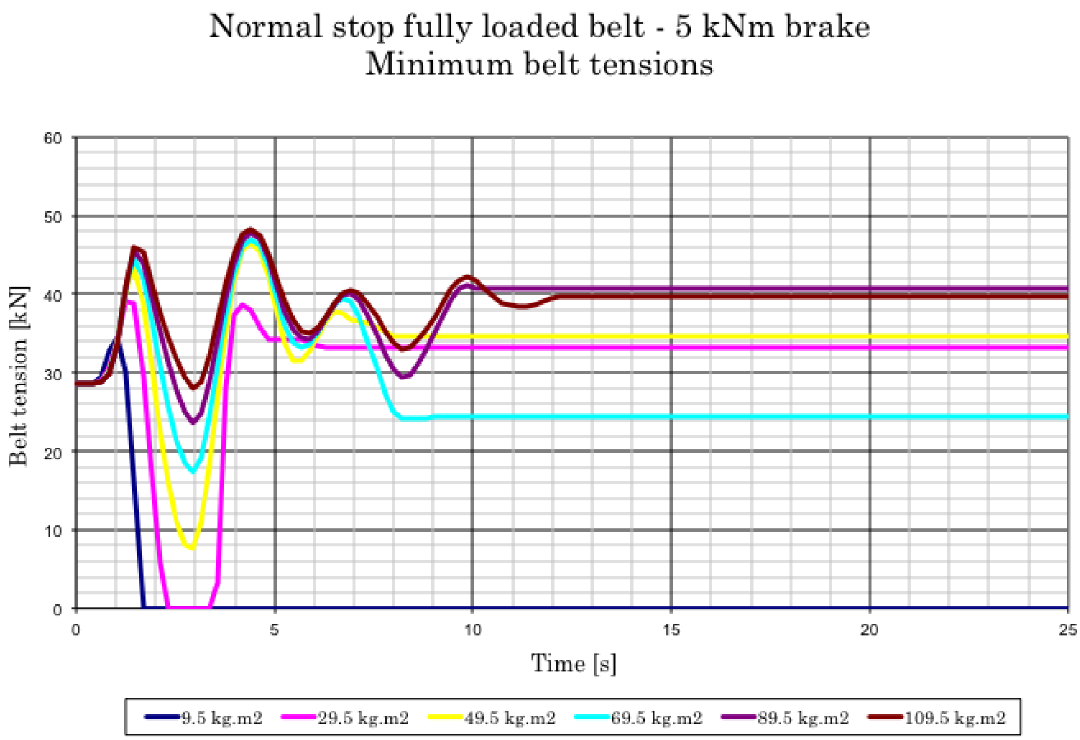

Figure 5. Belt tension as a function of time for different additional head drive inertias using a brake

SUMMARY

This paper explains the physics behind the application of flywheels on belt conveyors and shows the effect of the inertia of flywheels on the stopping time of belt conveyors. It also gives a tool to dimension a flywheel assuming that its inertia is known. An example of the application of flywheels on the minimum belt tensions of an incline shaft conveyor is given. In any case, even though the stopping time can be calculated using a quasi-static design approach, dynamic analyses are required to investigate the exact effect of the application of flywheels.

REFERENCES

1 Lodewijks, G. (2002), “Two Decades Dynamics of Belt Conveyor Systems”, *Bulk Solids Handling* ***22***, pp. 124-132.

2 Lodewijks, G. (2004), “Determination of rolling resistance of belt conveyors using rubber data: fact or fiction?”, *Bulk Solids Handling* ***23***, pp. 384-391.

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