ISSN: 2277-3754
ISO 9001:2008 Certified
International Journal of Engineering and Innovative Technology (IJEIT)
Volume 3, Issue 1, July 2013

Modelling a Nonlinear Conveyor Belt System Integrated on a Closed Loop Channel

Kenneth Obrien Mpho Mapoka, Keneilwe Zuva, Tranos Zuva
Botswana College of Agriculture, University of Botswana, Tshwane University of Technology

Abstract— This study provides an elite insight on how to model a simple nonlinear conveyor system. In the paper an explicit overview of the conveyor belt system and fair consideration of nonlinear friction was done. The mathematical model of the conveyor system was derived considering the nonlinear friction on the system.

***Index Terms*—Modeling, Conveyor, Nonlinear, Friction, Drive System, DC Motor**

I. INTRODUCTION

A typical conveyor system has diverse applications largely in industries, and the range of diversity depends on function, for example transportation of materials, workmanship, loading goods, passenger transportation i.e. at airport, luggage conveying and so on. Conveyor designs comes in variety of forms long or short horizontal conveying, inclined or declined conveying and vertical conveying, dependant much on the location or area of work.

II. PHYSICAL DESCRIPTION OF CONVEYOR BELT SYSTEM

A typical Conveyer Belt System (CBS) consists of the following elements electrical power supply, Belt Conveyor Drive (BCD) system, conveyor body, feedback channels, braking mechanism and the system controller. The closed loop control method is inherent on the system, as illustrated by a general schematic diagram in Fig. 1. This subsection provides a concise conveyor belt system description.

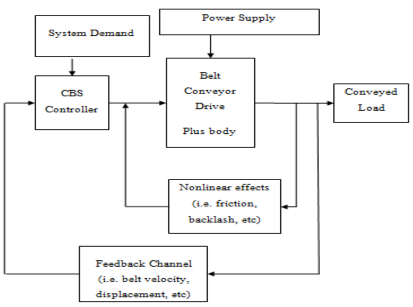

Fig. 1: Schematic Block Diagram of a Conveyor System

A. Controller and Feedback Channel

The aim of the controller and the feedback channel is to continuously monitor any deviations on the system output by comparing the reference signal with the signal being feedback to determine the velocity or displacement error. Therefore, the error signal is used as the command signal to drive the system. The controller ensures that the output tracks some changes in the reference signal to fulfill some control tasks and most importantly the controller ensures that the output converges towards the reference point and settles down as quickly as possible i.e. for these to happen the reference input signal has to be constant.

B. Drive System

There different types of BCD equipment with varying applications in mining industries. There are factors influencing the designs of the BCD system such as location, performance requirements, costs and installation. Generally the BCD equipment consists of the following elements DC motor, speed reduction mechanism (gears), sprockets, chains and drive shafts. Integration of this elements and powering them generates the torque needed to drive the CBS. BCD equipment has special – purpose units used to control the starting or stopping dynamics of the system, and speed control units to control the system velocity.

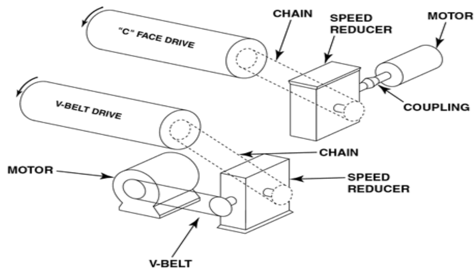

Fig. 2: Two Forms of the BCD System [1]

The speed reducer is a mechanism of high gear ratio converting high speed low torque to low speed high torque i.e. the DC motor generates low torque and the highest speed possible.

C. Power Supply

This is the energy source for the BCD. The BCD needs concise and constant electrical power supply to drive the DC motor system therefore, it is of this reason a more convenient transformer is used to provide the appropriate power to the BCD equipment. Literature [2] provides detailed insight on types and operation of transformers. A transformer has two different coils primary and secondary coil. This coils are used either to step up or down the voltage (or flux induced) and vice versa, depending on the system requirements. For instance, if the BCD requires higher voltage, number of secondary winding will be greater than primary winding and vice versa. The transformer is used to provide voltage signal for the DC motor (load). For more information about the transformer the following reference can helpful.

ISSN: 2277-3754
ISO 9001:2008 Certified
International Journal of Engineering and Innovative Technology (IJEIT)
Volume 3, Issue 1, July 2013

D. Belt Body

The belt component of the system loops around the drive roller and the rear roller with intermediate idlers at the top and beneath the conveyor floor. Intermediate idlers prevent belt sagging, minimizes friction and enhances material conveyance. Idlers beneath the conveyor floor support the belt, avoiding situations where the belt might hang and create problems such as slippage, uncontrollable belt movements (vibrations), sags, drive and rear rollers may lose grip. An example of securely designed conveyor belt system is shown in Fig. 3. The belt is a visco – elastic material therefore, it is practically impossible to keep the belt elasticity constant. The spring constant of the belt varies as operation time increases as well as changing loads. As loads volume change each time they add stresses and strains on the belt. This present control issues because the operator or engineer has to pay too much attention on aspects such as power distribution, belt speeds and loads volumes. Thus, constant adjustments have to be made to avoid loss of grip (rollers) and slippage.

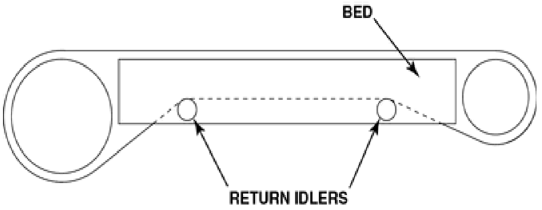

Fig. 3: Underneath belt supported by Return Idlers [1]

III. SYSTEM MODELLING

The main objective of this paper is to develop an adequate conveyor model that mimics the behavior of a real system. The model is developed using relative differential equations and constants parameters. It is crucial to develop a model that captures the features that we are interested to control or investigate. As several subsystems are discussed above, each subsystem is modelled independently and later combined to form one complete system.

A. Mathematical Modelling

CBS block diagram in Fig. 1 presents the conveyor drive, load and the belt subjected to nonlinear friction specifically coulomb and viscous friction. These multi-mass components depend entirely on velocity forces to traverse. Furthermore, these velocity forces are likely to exhibit nonlinear behavior of the CBS in certain regions during operations. Thus, the following assumptions are proposed to support basic idea and simplicity of the models:

- The motor provides a higher – dynamic speed with small time delay
- Connection between motor shaft, and gear drive is rigid and short,
- Connection between gear drive shaft, and driving pulley is finite stiffness,
- The belt modelled by linear springs with load plus constant belt elasticity,
- Nonlinear friction is concentrated on the drive system

B. CBS Dynamics – Electrical Modelling of the DC Motor

In modeling the DC motor, the aim is to express the motor characteristics using differential equations and relation of the applied voltage to the torque produced by the rotor. The equations that describe the electrical components of the DC motor are as follows:

$$e_b = K_b w_m \qquad - \qquad (1)$$
$$V = R.I + L\frac{dI}{dt} + e_b \qquad - \qquad (2) \qquad [3]$$
$$\tau_m = K_m I \qquad - \qquad (3)$$

Where V is the motor armature voltage, R is the armature coil resistance, L is the armature coil inductance, I is the armature current, e_b is the back electromotive force, K_m is the motors torque constant, τ_m is the torque developed by the motor and w_m (rad/s) is the rotational speed of the motor

C. Electro – Mechanical Modelling of the BCD

Considering speed dependent friction, backlash, time delays and dead zones nonlinearities, a nonlinear model for the two mass BCD system schematically represented in Fig. 2 can be obtained using torque balance rule:

Where J_m, J_L, B_m and B_L represent the motor, load inertia and friction respectively, τ_1, τ_2 generated torques, w_m, w_L generated angular speed of the motor and load and θ_m, θ_L motor and load displacement. Supposing the operation requires the systems to run continuously in one direction, some of the nonlinear effects reduce to zero including friction, backlash (i.e. will have no significant impact on the system performance except for instances where the BCD has to start/stop). Therefore the system can then be simply approximated by linear models. However, the BCD in Fig. 4 is bi – directional implying that all or most of the nonlinear effects such as friction, backlash and dead zone etc have significant impact on the system performance and stability. Thus, the system is approximated using nonlinear model. Dynamics of a nonlinear system are extremely complex and also yield complex solutions. Integrating all possible nonlinearities would not be the most effective approach in modelling and control. Therefore, it's mandatory to isolate adversities when modelling and analyzing system behavior. However, the inspiration of this paper is to model a nonlinear dynamical system incorporating friction phenomenon. The Coulomb and viscous friction phenomenon is highly present in the drive system when static and moving, it also induces damping, as well as imposing limitations on the system bandwidth. When modelling a system with nonlinear friction laws of friction are used.

- ***Laws of Friction***

Leonard da Vinci (1452 - 1519) from his experiments of friction observed that friction is entirely independent of the contact area and directly proportional to the load [4, 5]. The theory dwells much on the concept of static friction, while Coulombs distinguishes between static and kinetic friction. In 1781 Coulombs realized that for a body to start moving

ISSN: 2277-3754
ISO 9001:2008 Certified
International Journal of Engineering and Innovative Technology (IJEIT)
Volume 3, Issue 1, July 2013

applied force must be greater than static friction or opposing force. Newton's third law infers Leonard da Vinci (1452 - 1519) and Coulombs laws of friction.

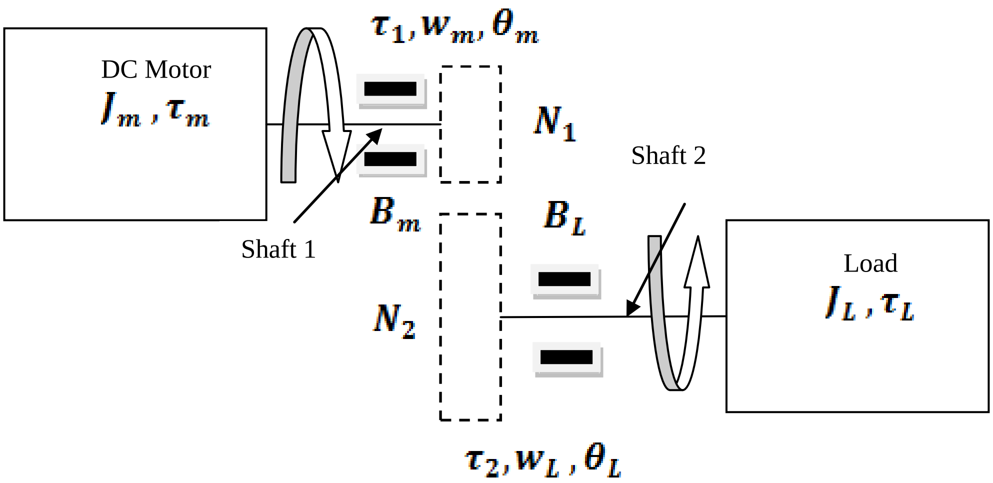

Fig. 4: Electro – Mechanical Model

Newton's third law states "for every action there is always an equal and opposite reaction [6]". These laws are useful when modelling systems with nonlinear friction.

Nonlinear models [3, 7, 8]:

$$J_m \dot{w}_m + b_m w_m + \tau_1 + \tau_f(w_m) = \tau_m \quad (4)$$

$$J_L \dot{w}_L + b_L w_L - \tau_2 + \tau_f(w_L) = \tau_L \quad (5)$$

The relationship between traversing gears in terms of torque, number of gears and displacement. The reader must also remember that for torque magnification and speed reduction for the mechanism number of the fed gear teeth must be smaller than receiving gears i.e. $N_1 \ll N_2$

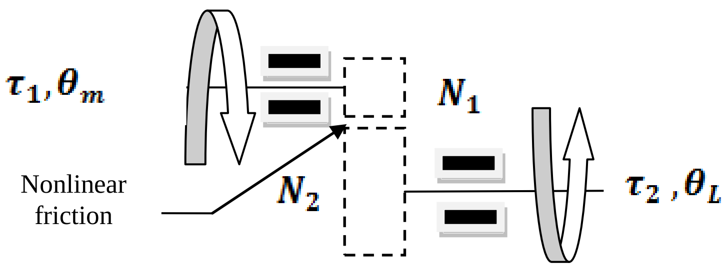

Fig. 5: Gear Reduction

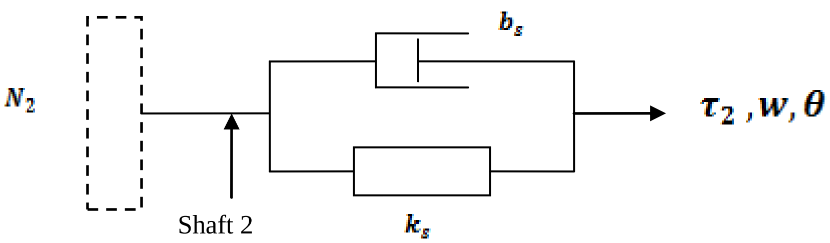

Fig. 6: Transmission Shaft linking the load and gear mechanism

$$O_L N_2 = O_m N_1 \;\; therefore \;\; \frac{O_L}{O_m} = \frac{N_1}{N_2} \leftrightarrow \frac{w_L}{w_m} = \frac{N_1}{N_2} \quad (6)$$

$$\tau_1 O_m = \tau_2 O_L ; \;\; \tau_1 = \frac{\tau_2 O_L}{O_m} = \tau_2 \frac{N_1}{N_2} = \tau_2 n \quad (7)$$

If $N_1 \ll N_2$, then the gear ratio in (6) reduces the speed and magnifies the torque

The shaft linking the motor and gear 1 (shaft 1 in Fig. 4) is shorter and has a finite stiffness as well as damping whilst shaft 2 (see Fig. 6) is assumed to be long exhibiting some level of dampness and stiffness.

Let

$$\theta = \theta_m - \theta_L \;\; and \;\; w = w_m - w_L$$

$$\tau_2 = k_s \theta + b_s w \quad (8)$$

Let

$$\tau_f(w) = \tau_f(w_m, w_L) = \tau_f(w_m) + \tau_f(w_L) \quad (9)$$

Eliminating τ_1 from equations (4) and combining the system nonlinear friction effect we get the overall nonlinear model of the BCD system expressed as [8]:

$$J\dot{w}_L = \tau_m + n\tau_L - Bw_L - \tau_f(w) \qquad (10)$$

$where,\quad J = J_m + n^2 J_L \ \ and\ B = b_m + n^2 b_L$

$\tau_f(w)$ - represent the overall nonlinear model of the system and expression (10) represents the dynamic load model of the system.

D. CBS Body

Consider a simple mechanical system consisting of a mass M and belt elasticity constant K_x. Where $f(t)$ is the external force, T_1 total pulling force and $x(t)$ is the displacement of the mass. Three forces (and inertia) influence the motion of the mass, namely the applied force and the spring force as shown in the free-body diagram, assuming finite damping.

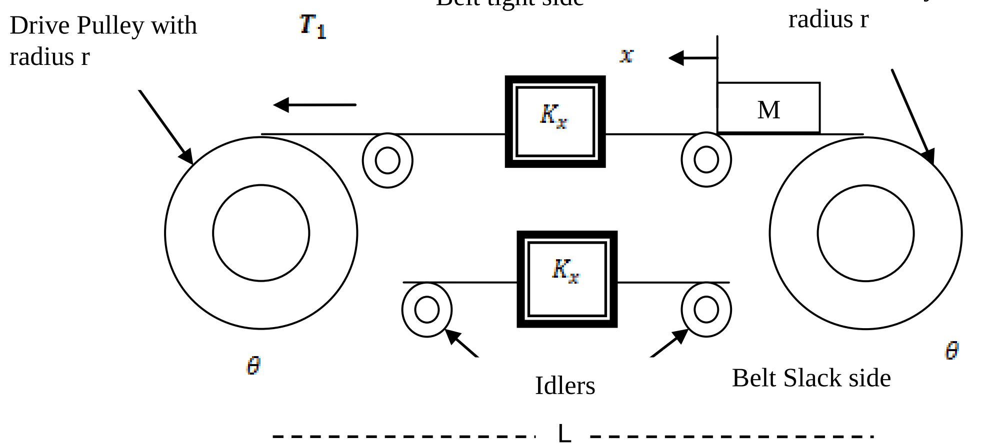

Fig. 7: CBS Diagram

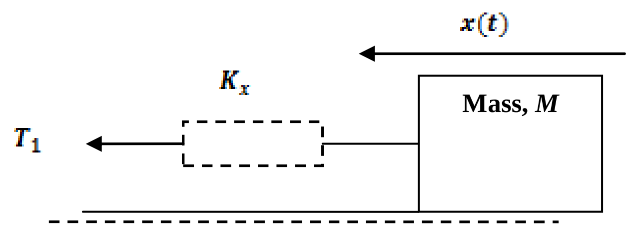

Fig. tiffness and Displacement ship

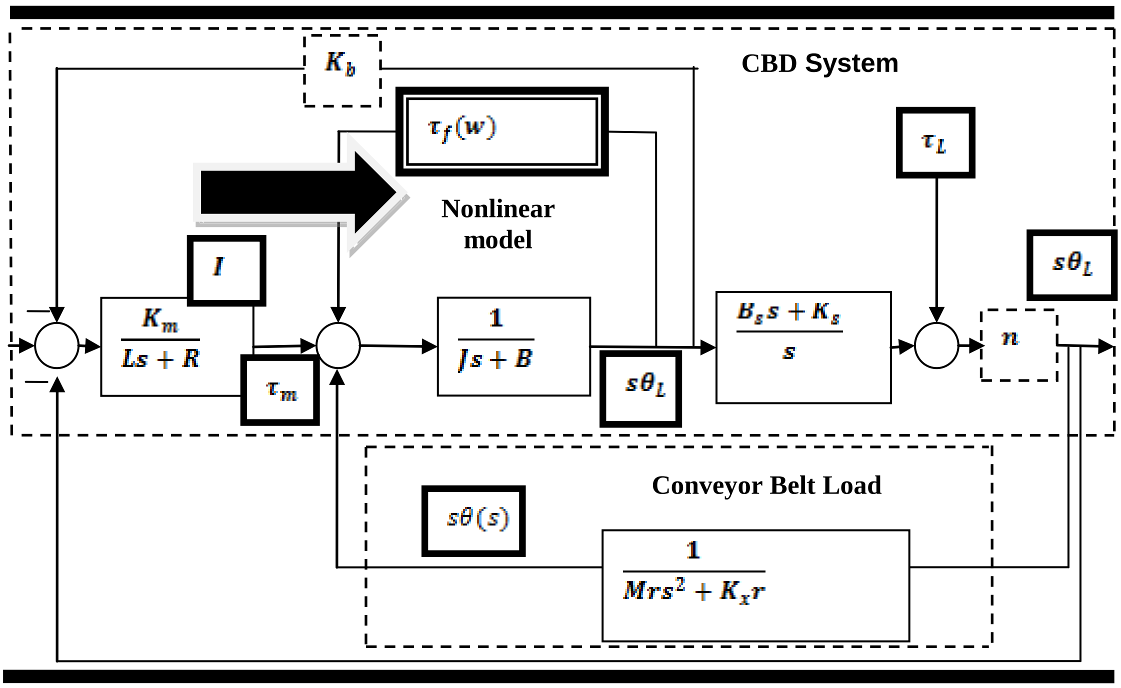

Fig. 9: Block Diagram for the Conveyor model

ISSN: 2277-3754
ISO 9001:2008 Certified
International Journal of Engineering and Innovative Technology (IJEIT)
Volume 3, Issue 1, July 2013

$$T_1 = F = \tau$$
$$x = r\theta$$
$$M\ddot{x} + K_x x = \tau$$
$$Mr\ddot{\theta} + K_x r\theta = \tau \qquad (11)$$

The transfer functions of the models above are obtained by using the Laplace transform with zero initial conditions. Substitute equation (1) into (2) and taking the transfer function of each expression

$$V(s) = RI(s) + sLI(s) + sK_m\theta_m(s) \qquad (12)$$
$$s^2J\theta_L(s) + sB\theta_L(s) + \tau_f(s\theta) - n\tau_L(s) = \tau_m(s) \qquad (13)$$
$$\tau_2(s) = k_s\theta(s) + sb_s\theta(s) \qquad (14)$$
$$Mrs^2\theta(s) + K_x\theta(s) = \tau(s) \qquad (15)$$

NB: Abstract Parameter values were used for simulation purposes hence yielding a numeric continuous transfer function.

The overall continuous transfer function of the CBS is expressed as:

$$G_p(s) = \frac{0.09625\,s^2 + 0.3396\,s + 0.09806}{0.4208\,s^3 + 0.4608\,s^2 + 0.1659\,s + 0.01968} \qquad (16)$$

$G_p(s)$ Represent the CBS continuous time model. The plant has three LHP poles at $s = -0.4500, -0.3333, and\ -0.3118$ and two LHP zeros at $z = -3.2106\ and\ -0.3173$. Based on open loop poles and zeros the system is stable. Corresponding discrete transfer function with sampling time of one second is expressed as:

$$G_p(z) = \frac{0.4398\,z^2 - 0.2558\,z - 0.04694}{z^3 - 2.086\,z^2 + 1.448\,z - 0.3345} \qquad (17)$$

Also can be expressed as

$$G_p(z) = z^{-1}\frac{0.4398 - 0.2558z^{-1} - 0.04694z^{-2}}{1 - 2.086z^{-1} + 1.448z^{-2} - 0.3345z^{-3}} \qquad (18)$$

$G_p(z)$ Represents the CBS discrete time model.

IV. CONCLUSION

This paper provided an explicit overview of the conveyor belt system and fair consideration of nonlinear friction. The mathematical model of the conveyor system was derived considering the nonlinear friction on the system. Assumptions were made and all important dynamics of the drive system and the belt body were considered. The principal nonlinear effect of the conveyor system arises from contacting gears, transmission shafts and most importantly the internal friction of the actuator. The nonlinear effect is realizable as the system is traversing therefore this effect depends entirely on velocity forces. The model was tested, evaluated and validated. The interactive conveyor model will be used mainly for case study, to test any future control algorithms. The system is already modelled and parameters identified therefore identification algorithms such as autoregressive moving average (ARMA), recursive least squares (RLS) are not considered in this paper. The control aspect can also be studied using the integration of the closed loop channel.

REFERENCES

[1] J. Arkansas, "Hytrol Drive," 2020 Hytrol Conveyor Company Inc., 2000.

[2] R. Mikail, "Fundamentals of Electric Motors and Transformers," Short Course on Energy Efficiency, vol. 32, pp. 1 - 13, 2006.

[3] A. W. Phyo, "Analysis on Modelling and Simulink of DC Motor and its Driving System Used for Wheeled Mobile Robot," Mandalay, pp. 299 - 301, Nov. 2007.

[4] L. da. Vinci, "Introduction to Tribology Friction," Contact Mechanics of Moving Interfaces, 1699.

[5] H. C. a. J. R. Barber, "Stability of the three-dimensional," The Royal Society, pp. 839 - 861, 1998.

[6] P. S. a. H. Dulaney, "Friction in Applications of Newton's Second Law," Physnet, pp. 1 - 27, May 2002.

[7] J.A. Rossiter, “Model – Based Predictive Control,” Sheffield: CRC Press control Series, 2003.

[8] I. E. Tolgay Kara, "Nonlinear modeling and identification of a DC motor for bidirectional operation with real time experiments," 2003.

AUTHOR’S PROFILE

Kenneth O.M. Mapoka is with the Department of Agricultural Engineering and Land Planning, Botswana College of Agriculture, Gaborone, BOTSWANA. He received Master of Engineering in Mechatronics from Sheffield University, United Kingdom in 2012. His special fields of interest include predictive and robust control applications.

Keneilwe Zuva is currently a Senior Lecturer at the University of Botswana in the Department of Computer Science. She received Masters of Engineering in Information Systems and Networking from the University of Essex, UK in 2001. Her research interests are networking, image processing, and network security.

Tranos. Zuva is with the Department of Computer Systems Engineering, Tshwane University of Technology, and Pretoria, SOUTH AFRICA