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A coupled FEM/DEM model for pipe conveyor systems: Analysis of the contact forces on belt

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ABSTRACT

The use of Pipe Belt Conveyor (PBC) has gained more and more popularity in bulk solids handling. Compared to the traditional trough conveyors, PBC can allow tighter curves and steeper gradients of conveyor routes and thus better suits the applications in difficult terrains. It has many unique mechanical characteristics which are not well understood yet. This paper proposes a coupled finite element model (FEM) and discrete element method (DEM) model to investigate the mechanics of a PBC system, with particular reference to the distribution of contact force in the pipe section. This FEM/DEM model considers comprehensively the formation of pipe from a flat belt and the microscopic structure of discrete particles under gravity, and thus can well describe the states of both conveyor belt and bulk solids. The predictions of the contact forces are shown to agree well with the previous experimental data under different conditions. Using this approach, the distribution of contact forces under different load conditions, i.e. zero gravity (ZG), empty pipe (VF 0%), volume fill of 40% (VF 40%) and 80% (VF 80%) are obtained and their dependencies on the rotation angle of pipe are investigated.

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1. Introduction

The Pipe Belt Conveyor (PBC), invented by Japan Pipe Conveyor (JPC) in early 1980's, has become more and more popular in bulk solids handling [1–3]. This type of conveyor uses a pipe-shaped belt to enclose granular materials during conveyance, which can effectively prevent dust emission or other environmental pollutions. It is particularly suitable for difficult terrains due to its high adaptability to tight curves and steep gradients of conveying route. However, PBC differs from the conventional trough conveyor in many mechanical aspects and requires special considerations in design. For example, the choice of the transverse stiffness of belt is more important in PBC than in trough conveyor—insufficient stiffness may result in undesirable collapse and misalignment of pipe while over large stiffness can significantly increase the energy requirement and capital investment [4]. More fundamental researches are needed in this area in order to achieve better operational safety and economic profits.

In designing a PBC, several points are usually important: the coefficient of main friction between belt and rolling idlers, and how to ensure the electric motor and belt run steadily without abrupt fluctuations. The main friction is mainly concerned in the power calculation of PBC, which is in theory determined by the properties of belt and granular material [5–13]. Nuttall et al. [9] derived an analytical model of the rolling resistance between roller and belt by taking into account the viscoelasticity of the cover material. Wheeler et al. [14] studied another type of resistance in PBC, i.e. flexural resistance, resulting from the successive lift/sag of granular material when passing through the idler panel. The second important issue is mainly related to the dynamic characteristic of a PBC. Such a belt may be deemed as a long elastic spring supplemented with viscous dampers and distributed masses, including the masses of belt and bulk material as well as the rotational inertia of idlers and accessories. Therefore, a large stress wave is often generated in the belt when starting or braking the conveyor, which should be properly smoothed by adjusting the loading curve [15–18].

Investigating the contact force between belt and idler rolls is of fundamental significance to understand the behaviours of conveyor, because these forces determine the value of rolling resistance [7] and affect the overall energy consumption and dynamic behaviours of PBC. It is also useful to understand the mechanism behind the abnormal rotation of pipe during conveyance [19]. Hötte et al. [20] measured the quasi-static contact forces in a curved pipe and quantified their dependencies on the radius of curve, the belt construction, and the belt tension. Michalik and Zajac [21] designed a computer integrated system for the evaluation of the contact forces on idlers and the strains at different locations of a belt. Using a similar test rig, Molnar et al. [22,23] surveyed the idler forces in the transition region of conveyor and formulated an empirical equation based on the measured data. Another

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work by Molnár et al. [24] highlighted the asymmetrical distribution of contact force due to the asymmetry of the belt tension. Zamiralova and Lodewijks [25–27] reviewed the usable experimental devices for determining the contact force including the six-point bending test, the quasi-static test equipped with different frames and the dynamic test. Using the six-point bending test device, Zamiralova and Lodewijks [19] investigated the influences of pipe diameter and overlap location on the spatial distribution of contact force. The force behaviours of pipe were shown to be rather complex and sensitive, although the effects of friction and longitudinal tension had been excluded in their measurements. Recently, Liu et al. [28,29] also proposed a stress discontinuity approach to predict the pressure profile on conveying belt and verified their approach against experimental measurement.

Many studies of PBC have been conducted by means of finite element method (FEM) in the literature. del Coz Díaz [30] investigated the warping effect of belt in a curved pipe and its correlation to the stress and strain distributions. Fedorko et al. [31] simulated the moulding process of belt and estimated the contact forces acting on the idler rolls. Pang and Lodewijks [32] utilised FEM to calculate the contact forces of a short pipe and compared the numerical results with experimental measurements. However, all these FEM studies accounted for the structural components of conveyor only, i.e. the belt and idlers, but not granular materials and their dynamics during conveying. Recently, a coupled FEM and discrete element method (DEM) approach has been used to predict the belt deflection of conventional trough conveyor [33] and the bulk flexural resistance [34]. However, to date no such attempts have been made for pipe conveyors.

This paper investigates the contact forces of pipe conveyor by use of a coupled FEM/DEM approach, in which the conveying belt is modelled by FEM and granular materials by DEM. In what follows, we will present in sequence the theory and the implementation of FEM/DEM approach, the model validation against previous experiments, the outcome of contact forces under a variety of loads, and finally a summary of the major findings.

2. Model setup

2.1. FEM model of conveying belt

The belt manufactured for conveying purpose is usually a composite of steel cord (or fabrics) and rubber covers, as shown in Fig. 1. The steel cord serves mainly to carry the longitudinal tension, while the rubber together with some lateral reinforcements sustains the transverse bending of belt. The conveying belt has three major mechanical features that need to be reflected in FEM model. First, the belt is in essence orthotropic, with disparate stiffness in the longitudinal and transverse directions as mentioned above. Secondly, the belt has remarkable viscosity due to the constituent of rubber, and can dissipate energy when dynamically tensioned or bent. This viscosity comes into play mainly in dynamic conditions, whilst is relatively less important in quasi-static situations where the strain rate of material is slow. Thirdly, the bending stiffness is non-uniform along the belt width, but usually reduced in the edge area in order to ensure a good seal of pipe. However, there is by far no standard with regard to the reduced value of stiffness and how wide

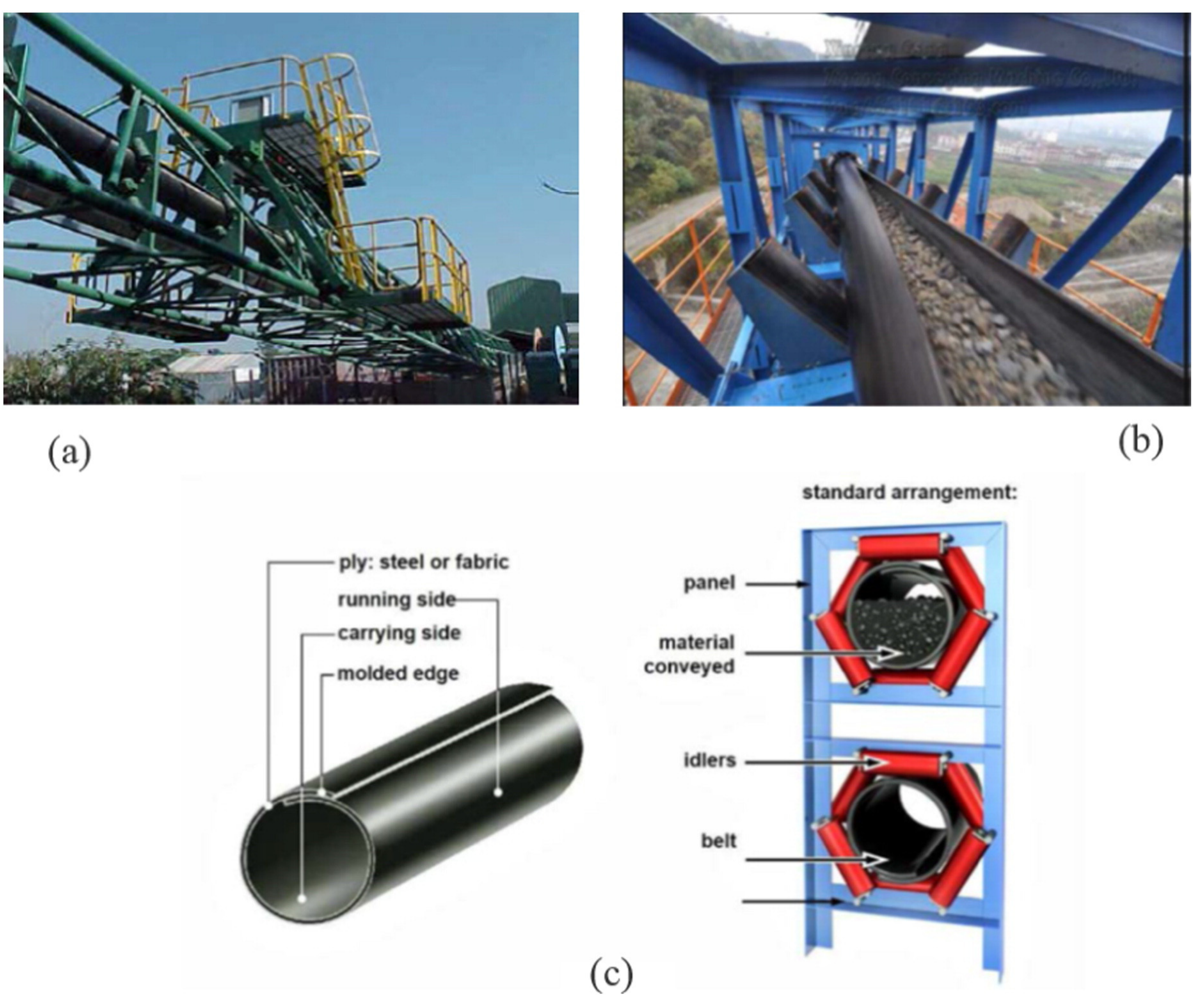

Fig. 1. (a) Industrial installation of pipe conveyor; (b) the loading point and (c) the general concept and structural arrangement [3].

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