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Multiple frictional impact dynamics of threshing process between flexible tooth and grain kernel ☆

Zhenjie Qian [a], Chengqian Jin [a,*], Dingguo Zhang [b]

[a] Nanjing Research Institute for Agricultural Mechanization of National Ministry of Agriculture, Nanjing 210014, PR China
[b] School of Sciences, Nanjing University of Science and Technology, Nanjing 210094, PR China

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ABSTRACT

The flexible threshing tooth is of interest to researchers in agricultural mechanization, due to the fact that impact, knead force, and rate of damnification decreases obviously compared to the traditional rigid pole-tooth, and it is propitious to increase the synthesis benefit for grain production. The multiple frictional contact dynamics of the flexible threshing tooth against grain kernels is presented by using an addition-deletion constraints approach in this study. The flexible threshing tooth is based on flexible-rigid coupling theory. A correlation matrix and four contact points index metrics are introduced. The system formulations for separation, initial contact, stick, and slip are established respectively by using different Lagrange multipliers. The impulse-momentum method is adopted herein to calculate the jump discontinuities. And the concept of a tangential sliding friction potential is introduced to represent the sliding friction effects. The corresponding computational strategy and numerical simulation C++ software are implemented. Several numerical examples adopted to demonstrate the efficiency of the presented approach and algorithms. The peak collision forces on normal and tangential directions are not synchronized. The occurrence of numerous sub-collisions among one macro-collision arises from the coupling of rigid motion and high-frequency deformation vibration of the flexible tooth. The flexible tooth has a less impactful knead force than the rigid one for cracked grains or seed, so as to reduce rate of grain damnification, and is thus propitious for increasing the synthesis benefit for paddy production.

1. Introduction

The threshing of grains is a key research focus in determining the performance of combine harvesters. For the rigid threshing components, impact and knead force are so large that it leads to crushing of the grain or inner stress. This will reduce the grade of rice and, moreover, reduce the germination rate of seed. There is a large body of literature that shows that the mechanical damage degree of rice kernels is influenced by the material of the threshing tooth, the velocity of impact, the form of impact with the kernel, etc. Cain and Holmes (1977) evaluated the impact damage to soya bean seed as the result of a single high-speed collision with a steel plate and concluded that impact damage is dependent on both seed moisture content and impact velocity. Paulsen (1978) stated that the seed damage in grain-handling depends on the particle pre-impact velocity and the surface rigidity. It is known that the work capacity and efficiency of grain threshing increase with increasing drum speed. Mesquita and Hanna (1993) reported that a small amount of energy is required to open soya bean pods by combine reel and cutter bar impacting. This means that impact velocities could be low so as to avoid pronounced seed damage, and yet achieve pod shattering.

A new lower-force threshing system with flexible teeth is developed to reduce damnification and be propitious to increase the synthesis benefit for paddy production. A new type of drum containing rubble and flexible teeth is developed to displace a conventional steel drum, which is shown to be suitable for some varieties of rice and wheat by Xie and Luo (2005). Wang et al. (2007) analyzed the energy transfer between a threshing tooth and multi-rice kernels during their impact in terms of energy balance. Li et al. (2007) created a FEM (Finite-Element-Method) model of rice and maize pressing considering plastic damage of the structure, which was in close agreement with experimental data. Michal et al. (2012) analyzed the FEM results for all stages of seed maturity for J. curcas L. Ukatu (2006) developed a threshing unit that reduces seed damage by combining lower rotor speeds with

☆ Fully documented templates are available in the elsarticle package on CTAN.

* Corresponding author.
E-mail address: jinchengqian@caas.cn (C. Jin).

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less severe impact from modified threshing fingers and appropriate clearances between the moving and stationary components. Xu et al. (2013) developed a critical velocity formula for impact damage considering the threshing tooth obliquely impacts the rice kernel. For flexible threshing components, the deformation and vibration undergoing overall rotation and impact process becomes larger with increasing speed. Liu et al. (2009) established dynamic model of rotating flexible beam undergoing large overall motion, in which the flexible deformation of beam is based on higher-order rigid-flexible coupling theory. Zhang (2009) considered both the bending and torsional flexibility of a flexible beam for dynamic simulation.

The states of the threshing process can be characterized by separation, sliding contact, and stick contact, as well as in any combination. The Lagrange multiplier method is a widely studied and used computational paradigm for such issues, in which the contact forces are handled by introducing additional quantities imposing the contact constraints (Wu and Haug, 1990; Glocker and Pfeiffer, 1992; Laulusa and Bauchau, 2008). Shabana et al. (2005) invested four nonlinear dynamic formulations that can be used in the analysis of the wheel/rail contact. Pfeiffer et al. (2006) proposed a general theory of non-smooth multibody dynamics with unilateral contacts. Flores et al. (2010) used the Baumgarte stabilization method for solving constraints violation problem, which is aroused by additional constraints attaching to the system dynamics equations.

Friction arouses complex contact phenomena, involving micro-sliding, forward/backward sliding, stick-slip transition, etc. Moreover, Newton's collision law usually leads to an system energy increase and other error results (Brach, 1984). Han and Gilmore (1993) analyzed three kinds of possible micro-tangential motion with friction and collision and carried out theoretical analysis and experimental verification. Pfister and Eberhard (2002) presented planar frictional contact problems of both flexible and rigid bodies. Glocker and Pfeiffer (1995) developed a multiple frictional impact model for two-dimensional contact situations.

Most of the studies have been based only on experiments and there is a lack of impact dynamics analysis of the impact between the threshing tooth and the grain kernel. This work aims to demonstrate the dynamic models for the flexible threshing tooth frictional impacts against the grain kernel during the threshing process. The dynamic equations in four periods, i.e., non-collision, collision initiation, stick impact and slip impact are established, respectively. Based on the rigid-flexible coupling dynamic theory of flexible multibody systems, the dynamic equations of the flexible beam without impact are established. The impulse-momentum method is used to achieve kinematic transformation during collision initiation. In addition, the contact constraint method (also known as the Lagrange multipliers method) is used to solve the impact process stick impact and slip impact. The criteria are given to realize the kinematic transformation and dynamic solution, including contact/separation, and forward or backward slip/stick. The rest of this study is organized as follows. In Section 2, the frictional impact kinematics of the system is presented. In Section 3, the kinematic description based on the flexible-rigid coupling theory is presented. Subsequently, the Lagrange multipliers formulations of system global dynamics are proposed in Section 4, including four system states, namely separation, initial contact, stick contact, and slipping contact. In Section 5, numerical examples are given to demonstrate the efficiency of the presented approach and algorithms. Finally, a brief summary of the conclusions drawn in this study is given in Section 6.

2. Frictional impact kinematics

In threshing, corn kernels experience a serious of collisions. The vibrational deformation and duration of shock force can be calculated. The compression force or motion yields the kernel permanent plastic deformation or brittle failure, consequently, stress cracking or rupture. The frictional force is created because of mutual sliding between kernels and the threshing tooth. When the frictional force is above the maximum applied force of the husk, it becomes torn and broken-shell damage is created (Xu et al., 2013). During the threshing process, kernels undergo impacts and rubbing as they fall from straw to become free particles; thus, the husk of a kernel is easily damaged and there is internal cracking of the kernel due to stress. Tandon et al. (1988) considered five parameters that influenced threshing efficiency and kernel damage, namely cylinder peripheral speed, cylinder type, concave type, concave clearance and grain moisture content.

A flexible threshing component consists of flexible teeth fixed on rigid body of a threshing roller, and threshing is the impact between threshing teeth and grain. Fig. 1a shows the cross-sections of the threshing unit elevation. The rotor consists of flexible pole-teeth spaced equidistantly around a thresher drum with rotor shaft concave cross teeth. Multiple frictional impacts occur between the threshing flexible tooth and grain kernels. The grain kernel is simplified as a uniform isotropic ellipsoid. The flexible pole-tooth can be approximated as a flexible beam based on Euler-Bernoulli beam theory in the elastic small displacement field. Fig. 1b depicts the pole-tooth and grain kernel B approaching each other by a relative gap between potential contact points P and Q. In order to describe the position and orientation of the flexible pole-tooth and grain kernel with respect to the global coordinate system, the inertial coordinate system OXY and body-fixed frame Oxy are established at joint O and the proximal end of the flexible pole-tooth, respectively, and coordinate system $O'X'Y'$ is fixed on the grain kernel surface.

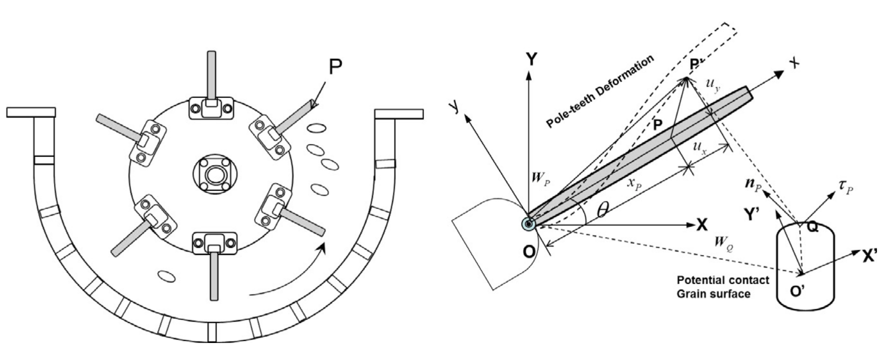

Fig. 1. Schematic representation of threshing unit: (a) the cross-sections of the threshing unit elevation, and (b) the frictional contact between the flexible threshing pole-tooth and grain kernel.