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Research paper

Simulation of vibration harvesting mechanism for sea buckthorn

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ABSTRACT

Sea buckthorn (SBT) is an ideal plant for ecological management and thus planted widely in western China. Its fruit is of high nutritional and medicinal values. However, its economic value is far from development because of high cost for harvesting SBT fruits. Mechanical vibration is one of feasible way to make fruit separation. To design proper vibratory harvesters for tree crops, the vibration harvesting mechanism of SBT was simulated and analyzed by the finite element method. First, a three-dimensional solid model of SBT tree was built by Pro/E and imported into ANSYS. Next, modal analysis was performed to determine the natural vibration properties of SBT tree such as the natural frequency and vibration mode. Finally, harmonic response analysis was applied to determine the steady-state response when a sine load was added to the SBT tree. The modal analysis results indicated that the first twenty order natural frequencies of SBT tree varied from 6.6 Hz (the first order frequency) to 31.8 Hz (the twentieth order frequency). Results of harmonic response analysis showed that the application of vibration force to the side branches is effective than to the trunk, with a slight damage to the tree. Moreover, the vibration force applied to the side branches was 58–78 N with a frequencies range of from 20 to 30 Hz, which ensured that the majority of SBT fruits were harvested from the tree. The simulation analysis results obtained in this study could provide a basis for the design and development of SBT vibration harvesters.

1. Introduction

Sea buckthorn (SBT) (Hippophae rhamnoides L.) is a hardy and deciduous shrub with yellow or orange berries. The wide adaptation, fast growth, strong coppicing, and sucking habits, coupled with efficient nitrogen fixation, make SBT an optimal pioneer plant in soil and water conservation, desertification control, land reclamation and reforestation of eroded areas (Yang and Kallio, 2002). Two million hectares of SBT trees have been planted for the need of ecological management in China, accounting for more than 90% of the world total area of SBT, among which more than 80% are located in the western region (Wu and Zhao, 2000). On the other hand, SBT fruit is rich in vitamins and phenolic compounds and used for medicinal purposes and as food in some parts of the world (Bal et al., 2011; Song et al., 2014).

Unfortunately, it is difficult to harvest SBT fruits because they do not easily form an abscission layer, and the fruits are tightly clustered on thorn-covered branches. In Saskatchewan, Canada, the total labor cost for harvesting an orchard of 4 ha was estimated to be 58% of the total cumulative production cost over 10 years (Li, 2002). In Asia, SBT fruits are still mainly harvested manually or using simple hand-held tools. This difficult and labor-intensive process requires approximately 1500 h/ha (Liang et al., 2008). Therefore, the development of mechanical or other harvesting techniques for SBT fruits have attracted much attention.

The attempts for harvesting include direct juicing harvesters (Stan et al., 1985; Ishii, 2003), tree shakers (Gaetke and Triquart, 1993), branch shakers (Bantle et al., 1996; Olander, 1995), vacuum suctions units (Mu et al., 2012), hormone treatments (Demenko et al., 1986; Zhu, 1991), and whole branch harvesters (Olander, 2012). Among them, the trunk vibration harvester from Russia was the highest harvesting efficiency reaching 50 kg/h, but its removal rate of 50% is too low to be acceptable. The best harvester is the cutting harvester from Germany, it could remove 80% of the fruit at a harvest rate of 30 kg/h, while only damage 5% of the fruit. Therefore, this method, supplied by the Kranemann Co. Ltd., is the only commercially viable way for mechanical harvesting of SBT fruit. In addition, it was found that some cultivars could be harvested in the field without freezing, such as “Hergo”. Therefore, it could be possible to breed SBT cultivars suited for harvesting by

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shaking. For large scale harvesting, the only feasible method is to shake or vibrate the berries off the plant (Fu et al., 2014).

Although the trunk vibration harvester can be used to harvest the entire bush at one time, it is only effective for bushes with one central trunk with short branches. Bushes with long and slender branches are more difficult to harvest by shaking the trunk because most of the energy is lost on the way before reaching the berries (Mann et al., 2001; Olander, 1995). Therefore, some attempts have been made at harvesting SBT berries by vibrating the branches directly. Stan et al. (1985) used a black currant harvester to investigate seven SBT cultivars. Only one cultivar was harvested successfully using a vibration frequency of 18.5 Hz and an amplitude of 25 mm. A prototype from Sweden with amplitudes of 40–55 mm and a frequency of 25 Hz was investigated (Olander, 1995). For the "Indian Summer" cultivar in western Canada, Mann et al. (2001) found that at frequencies of both 20 and 25 Hz, the percentage of berries removed by shaking increased linearly with the increase in amplitude. A combination of 25 Hz and 32 mm produced the best effect: 98% of the berries were removed within 15 s of shaking during the November harvest period.

Normally, the optimal vibrating speed and amplitude vary from crop to crop, according to their natural frequency. However, in the current equipment design process, the main parameters were commonly obtained by the observation and measurement in field experiments which involve high cost testing platforms but provide random results. The finite element method has been proved to solve the problem effectively (Tang et al., 2006). Savary et al. (2010) developed and evaluated a simulation framework for predicting the interactions between a tree and canopy shaker using the finite element method and concluded that the simulation framework can be applied for studying the behavior of trees under the dynamic loading conditions of a continuous canopy shaker. Quan et al. (2011) carried out finite element analysis on corn stubble harvesting system. Tinoc et al. (2014) developed a heuristic process for the identification of natural frequencies and modes of vibration for the fruit-peduncle system of Coffea arabica L. var. Colombia using a modal analysis and found that the modes associated with natural frequencies in specific intervals probably facilitated the separation between the interface fruit-pedicel for the ripe stage; however, these intervals were different from other ripening stages. Taking the SBT trees of Xinjiang, China as an example, a finite element analysis simulation of the vibration harvesting for SBT fruit was carried out in this study by using a combination of ANSYS software (ANSYS 15.0, ANSYS, Inc., Canonsburg, USA) and Pro/Engineer (WildFire 5.0, PTC Inc., Needham, USA) three-dimensional (3D) modeling software. This study provides a theoretical basis for the design and development of vibration equipment.

2. Materials and methods

2.1. Establishment of SBT model

The SBT tree is usually about 1500 mm tall, whose trunk is about 1000 mm tall, crown is around 100 mm in diameter, main branch is approximately 20–50 mm in diameter, and side branch is about 10 mm or smaller in diameter. In this study, a five-year-old SBT tree was randomly selected from the Qinghe County, Xinjiang in northwest China as an experimental sample. The tree's crown height was approximately 1.5 m, and its trunk width was near 40 mm, as shown in Fig. 1(a). The Size of trunk and branches were measured manually in August, 2014 using a flexible measuring tape with a resolution of 1 mm and a Vernier caliper with a resolution of 0.1 mm.

The SBT tree was modeled in Pro/Engineer (Pro/E). It was assumed that the cross section of the branches were circular. The diameters at every node location along the branches of the tree were measured. A local Cartesian coordinate system was assigned to the tree, and the coordinates for each diameter location were measured based on this coordinate system. The coordinate position was measured by dropping a weighted string to the ground for projection of the point onto the X–Y plane and measure the X and Y coordinates. The length of the string was taken to be the Z value. The diameter was measured using a Vernier caliper and the circumference was measured using a flexible measuring tape. These points were plotted in 3D space, and a 3D spline was drawn connecting them in Pro/E. At each point, a reference plane was drawn so that it was normal to the 3D spline. The circular cross-section was drawn on these planes using the diameters measured. Using the cross-sections and spline as the guide curve, the tree was drawn using the swept blend tool in Pro/E, as shown in Fig. 1(b). The uppermost portions of the branches were not modeled as they are very thin and will not affect the forces on the tree. Therefore, the structure of SBT tree was simplified to reduce calculation time of finite element model (FEM) analysis.

2.2. Mechanical properties of SBT tree

To obtain the FEM of a SBT tree, some mechanical properties of SBT should be measured, such as density, modulus of elasticity (MOE), Shear modulus, Poisson ratio, and damping ratio. The branches of the tree were wrapped by a PVC cling film to prevent water evaporation and maintain the samples fresh.

2.2.1. Density

Density was measured by the drainage method. The volume of a short branch was measured using a measuring cylinder with a resolution of 1 mL, and the mass was measured using an electronic balance with a resolution of 0.01 g.

2.2.2. Dynamic MOE

The MOE was determined using an FFT analyzer. Five samples were measured using an acceleration transducer (AS-2GB, Tokyo Sokki Kenkyujo Co., Ltd.) with an excitation voltage of 2V DC (vibration hammer LC-1, Far East Vibration (Beijing) System Eng. Tec. Co., Ltd.), and the fundamental resonance frequencies were observed, as shown in Fig. 2. The MOE can be calculated using Eq. (1).

$$E = \frac{m}{I}(2\pi f)^2\left(\frac{l}{1.875}\right)^4 \tag{1}$$

where m (kg) is the mass of the sample, l (m) is the length of the sample, I (m^4) is the sectional moment of inertia of the sample, and f (Hz) is the fundamental resonance frequency.

Shear modulus was determined using acceleration transducers and a large vibration table. The specimen was driven inertially using a large vibration table, usually by swept-sine-wave excitation. The Shear modulus (S) can be calculated using Eq. (2). Thus, Poisson's ratio (P) can be calculated using Eq. (3).

$$S = \frac{m_e(2\pi f)^2 h}{2wl} \tag{2}$$

$$P = \frac{E}{2S} - 1 \tag{3}$$

where m_e (kg) is the effective mass, including the added mass m and the effective mass of the specimen damping material, which is approximately one-third of its actual mass. l (m) is the length; w (m) is the width; h (m) is the cross-section thickness; f (Hz) is the fundamental resonance frequency.