Simulation of Vibration Harvesting Mechanism for Seabuckthorn

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ABSTRACT

Seabuckthorn (SBT) is an ideal plant for ecological management and was thus planted widely in the western of China. Its fruit is of high nutritional and medicinal values. However, its economic value is far from development because SBT fruit is very difficult to be harvested. Mechanical vibration is one of feasible way to make fruit separation. In order to design proper vibratory harvesters for a tree crops, in this paper, vibration harvesting mechanism of SBT was simulated and analyzed by finite element method. Firstly, three-dimensional solid model of SBT tree was built by Pro/E and imported into ANSYS. Next, modal analysis was used to determine natural vibration properties of SBT tree such as natural frequency and vibration mode. Finally, harmonic response analysis was applied to determine steady state response when the SBT tree is added a sine load. The modal analysis results showed that first twenty order natural frequencies of SBT tree varied from 8.8 Hz (the first order frequency) to 31.2 Hz (the twentieth order frequency). Results of harmonic response analysis showed that vibration force applied to the side branch is effective than to the truck, while with little damage to the tree. In addition, the vibration force applied to the side branch was 180~280 N with a frequency of 14.0 Hz, it could ensure the majority of SBT fruit to be detached from the tree. The simulation analysis in this paper could provide a basis for designing and development of SBT vibration harvester.

Keywords: Seabuckthorn fruit, vibration harvesting, finite element model, modal analysis and harmonic response analysis.

INTRODUCTION

Seabuckthorn (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 *et al*., 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 the SBT fruit because it does not easily form an abscission layer and the fruit is 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, harvesting is still mainly completed manually or using simple hand-held tools. This difficult and labor intensive process requires about 1500 h/ha (Liang *et al*., 2008). Therefore, the development of mechanical or other harvesting techniques for SBT have attracted widespread attention.

The attempts for harvesting include direct juicing harvesters (Stan *et al.,* 1985; Ishii, 2003), tree shakers (Gaetke, 1993), branch shakers (Bantle, 1996; Mann *et al.,* 2001; Olander, 1995) vacuum suctions units (Mu, 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 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 make the whole bush to be harvested at one time, it is only effective for bushes which have one central trunk with short branches. Bushes which have long and slender branches are more difficult to harvest by shaking the trunk because most of the energy is lost before reaching the berries (Mann *et al.,* 2001; Olander, 1995).

Therefore, there have been some attempts at harvesting SBT berries by vibrating the branch directly (Stan *et al*., 1985) used a black currant harvester to test seven SBT cultivars. Only one cultivar could be harvested successfully when using a vibration frequency of 18.5 Hz and amplitude of 25 mm. A prototype from Sweden was tested with amplitudes of 40 to 55 mm and frequency of 25 Hz (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 increasing of amplitude. The combination of 25 Hz and 32 mm produced the best effect that 98% of the berries were removed within 15 seconds of shaking during the November harvest period.

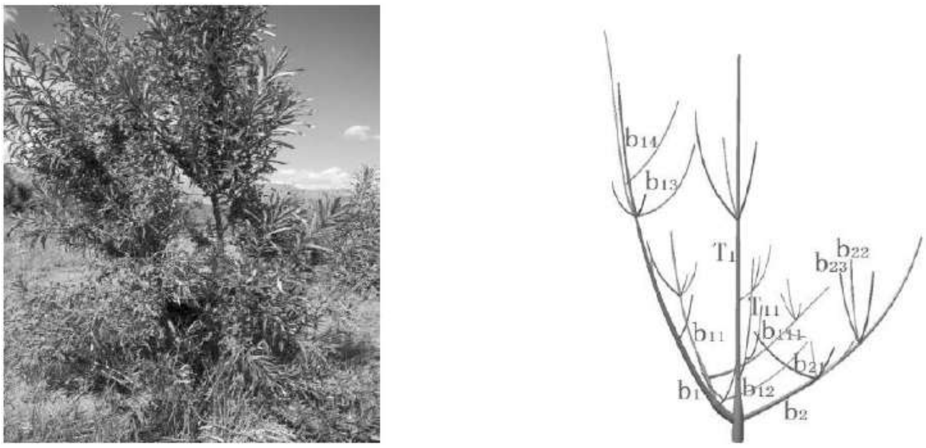
Normally, the optimal vibrating speed and amplitude vary from crop to crop, which related to their natural frequency. However, in the current equipment design process, main parameters were commonly acquired by observation and measurement of field experiment which needs to establish high cost testing platforms but obtains results of randomness. Finite element method had been proved to solve the problem partly (Tang *et al.,* 2006). (Huang *et al.,* 2011) had conducted the finite element simulation of sugarcane cutting process. Quan *et al.* (2011) had carried on the finite element analysis on corn stubble harvesting system. Taking SBT trees of Xinjiang, China as an example, this paper carried out a finite element analysis simulation of vibration harvesting for SBT fruit by combining ANSYS software (ANSYS 15.0, ANSYS, Inc., Canonsburg, USA) with Pro/Engineer (Wild Fire5.0, PTC Inc., Needham, USA) three-dimensional (3D) modeling software. This work provides a theoretical basis for designing and development of future vibration equipment.

MATERIALS AND METHODS

The establishment of SBT model

The SBT tree is usually about 1,500 mm tall, whose trunk is about 1,000 mm tall, crown is around 100 mm in diameter, main branch is about from 20 to 50 mm in diameter, and side branch is about 10 mm or smaller in diameter. Figure 1(a) shows a SBT tree in the Qinghe County, Xinjiang in northwest China.

A 3D model of SBT tree was built by Pro/Engineer (Pro/E), as shown in Figure 1(b). The shape of SBT tree is very irregular, so its trunk and branches were defined as variable cross-section cylinder. The fruit mainly grows on side branch. There are lots of side branches in a SBT tree, which degrade computational efficiency significantly. Therefore, the structure of SBT tree should be as simple as possible to reduce calculation time of finite element model (FEM) analysis.



(a) (b)

Figure 1. A SBT tree and its 3D model by Pro/E. (a) A SBT tree. (b) The 3D model of the SBT tree. The numbering system is that the first letter represents category (B represents branches, T representstrunk). The number represents grade of branches(branches are classified three grades, number represents thick branches, thin branches, thinner branches, respectively).

Creating finite element model of SBT tree

The FEM of SBT tree was imported from Pro/E. The unit system of m-t-s was adopted in this research. The solid model needs to be discretized into several sub domains before the finite element analysis. The Solid185 of 8-node 3D entity element in ANSYS was selected for FEM of SBT tree by considering its irregular geometric model.

Lignin, as the chief component of SBT tree, is a kind of amorphous structure material but has the isotropic property. Thus, the mechanical properties of the SBT tree wood were determined under the assumption that it is isotropic in nature (Savary *et al.,* 2010). The FEM of SBT tree was meshed by using Smart Size tool of Free Grid method of ANSYS, which was composed of 424,552 elements and 107,843 nodes. The material parameters of SBT tree were shown in Table 1 (Shang *et al.,* 2008; Ke, 1989).

Table 1. Material property parameters of SBT tree (Reference paper).

Density (kg/m^3)	Young's modulus (MPa)	Poisson ratio	Bending strength (MPa)
574	4959	0.348	75

Modal analysis of SBT tree

Modal analysis is a process for determining dynamic characteristics of a mechanical system (damping, natural frequencies and modes of vibration) with the aim to describe dynamic behavior of this system. Mode is the natural vibration characteristics of the mechanical system, and each mode has the specific natural frequency, damping ratio and modal shape. This study is based on the LS-DYNA simulation, to determine the vibration natural frequency and modal shape of SBT tree, which lays the foundation for the further dynamic analysis. This provides a new method for the study on optimal harvest frequency of SBT tree.

The Block Lanczos method was used in this study. All the constraints are concentrated in SBT tree connected to ground roots. In modal analysis, boundary conditions of the roots were zero degrees of freedom constraint, which meant the directions of X, Y and Z were defined as zero displacement constraint. Generally, if the frequency range was unknown, the highest frequency should be defined with a larger value. According to other studies (Tang, 2011), the influential frequency dynamic characteristics mainly concentrated in the low frequency range. Therefore, only the first twenty order modes of SBT tree were extracted and analyzed.

Harmonic response analysis of SBT tree

Harmonic response analysis is used to determine the steady state response when the SBT tree is added a load (sine excitation). Considering the complexity of SBT tree structure, the full method was used in the harmonic response analysis. The full method applies complete system matrix to calculate harmonic response (no matrix reduction).The matrix can be symmetric or asymmetric, so it doesn't involve mass matrix approximation, and using a single process to calculate all the displacement and stress. The essence of vibration harvesting is based on the load applied to trees to produce a resonance effect, which could separate the SBT fruit effectively. Figure 2 shows a SBT fruit with weight of 0.5g in average and its binding force to the branches is 0.859N, where the minimum acceleration needed for separating the fruit is 2g (g is the acceleration of gravity). According to Newton's second law:

$$F + mg - F_L = ma \quad (1)$$

Where F is the vibration load, m is the mass of fruit, F_L is binding force between the branches and SBT fruits.

A hypothesis that SBT fruit stalk is a cylindrical was made. The fruit stalk diameter is 1.0 mm, so the cross-sectional area (A) is 0.785 mm^2, and the stress (o) between stalks and branches is 1.101 MPa which is the minimum stress for SBT fruits being separated from branches.

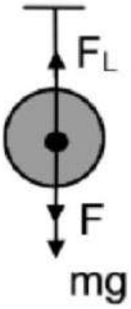


Figure 2. Force model of a SBT fruit.

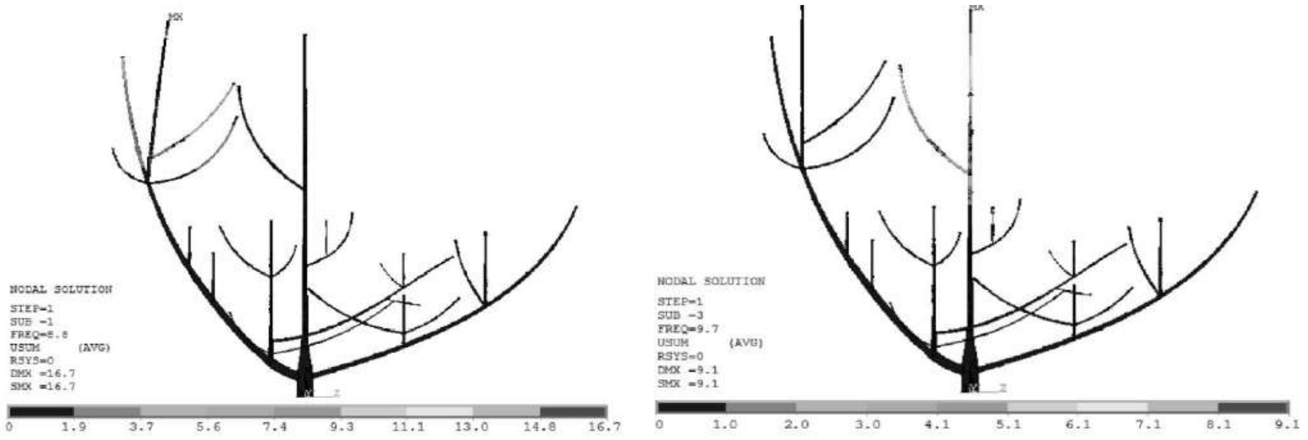
RESULTS AND DISCUSSIONS

Modal analysis of SBT tree

The FEM of SBT tree includes107,843 nodes, so it was very difficult to solve all the natural frequencies and vibration modes. In general, the vibration of SBT tree can be expressed as a linear combination of all order natural vibration modes. At the same time, the low order vibration modes have more influence to dynamic response of SBT tree than high order vibration, and vibration modes corresponding with high frequencies will attenuate rapidly because of the structural damping of SBT tree. Therefore, the dynamic characters of SBT tree are mainly decided by the low order vibration modes. The first twenty order natural frequencies of SBT tree were extracted in this study, they are from 8.8 Hz to 31.2 Hz which were increased with increasing of order, as shown in Table 1. Among them, eight representative vibration modes were selected and shown in Figure 3. The 1st order natural frequency was 8.8 Hz closed with the 2nd order natural frequency of 9.2 Hz, and they mainly reflect vibration of the upper part of left branch b_3, as shown in Figure 3(a), which showed a low integrated structure rigidity of SBT tree. The 3rd order 9.7 Hz closed to 4th order 10.0 Hz, and they mainly reflect vibration of the upper trunk T_p as shown in Figure 3(b). The 5ft order 10.8 Hz neared to 6th order 10.9 Hz, and they mainly describe vibration of branch b, as shown in Figure 3(c). The 7th order 12.6 Hz and 8th order 12.8 Hz mainly reflect vibration of the upper part of right branch b_2, as shown in Figure 3(d). The 9th order 15.8 Hz and 10th order 18.1 Hz were mainly described the top part of left branch b_{14} and b_{13}, as shown in Figure 3(e). The 11th order 18.8 Hz was almost same to 12th order, and closed to 13th order 19.3 Hz, they mainly reflect vibration of the branch b_{111}, as shown in Figure 3(f). The 14th order 19.6 Hz was mainly describe the branch T as shown in Figure 3(g).The 15th order 21.2 Hz closed with 16th order 21.7 Hz, and they mainly reflect vibration of the top part of left branch b, as shown in Figure 3(h). The 17th order 25.6 Hz and 18th order 28.1 Hz mainly reflect vibration of the right branches b_{21}, b_{22}, and b_{23}, as shown in Figure 3(i).The 19th order 29.3Hz is closed to 20th order 31.2 Hz and mainly reflects vibration of the top part of left branch b_{13}, as shown in Figure 3(j). The maximum displacement is occurring in the top branches. When the frequency is 21.2Hz, the left branch b_{12} has the maximum amplitude because of it has the smallest branch of the SBT tree.

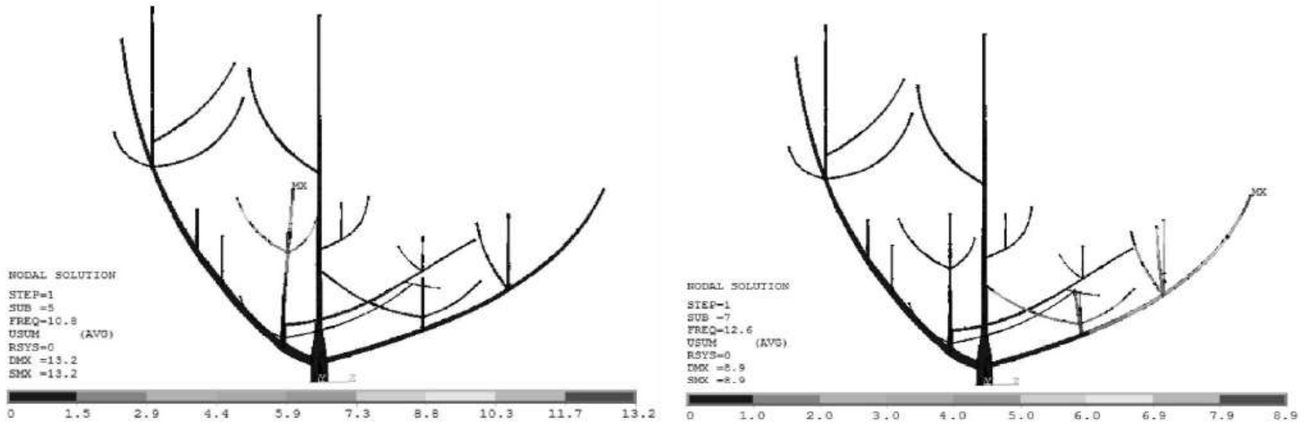
Table 2. First twenty order natural frequencies

Order	1	2	3	4	5	6	7	8	9	10
Natural frequency(Hz)	8.8	9.2	9.7	10.0	10.8	10.9	12.6	12.8	15.8	18.1
Order	11	12	13	14	15	16	17	18	19	20
Natural frequency (Hz)	18.8	18.8	19.3	19.6	21.2	21.7	25.6	28.1	29.3	31.2



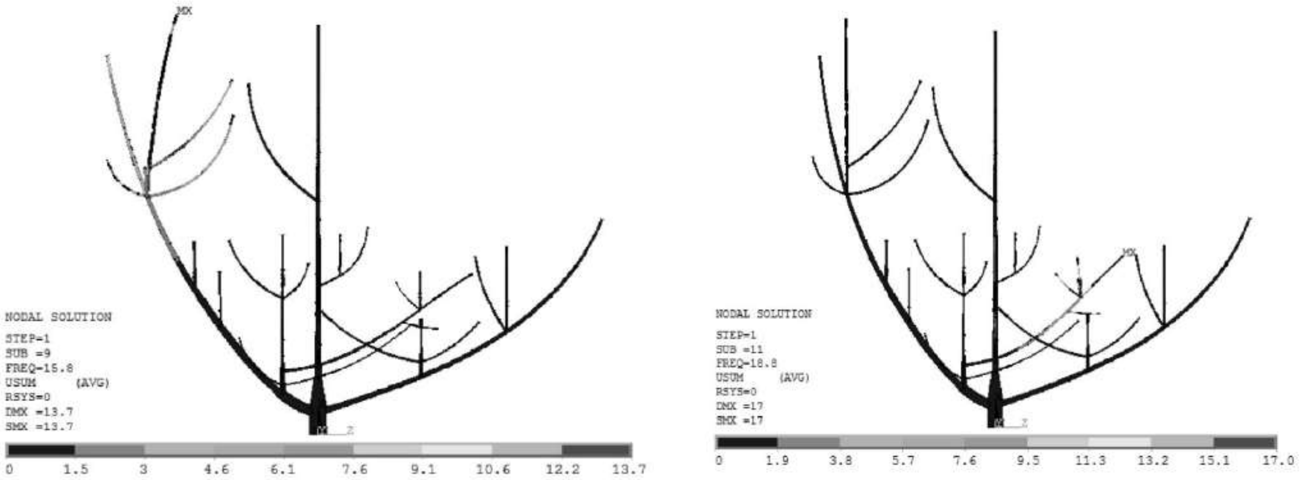
(a) First order (8.8 Hz)

(b) Third order (9.7 Hz)



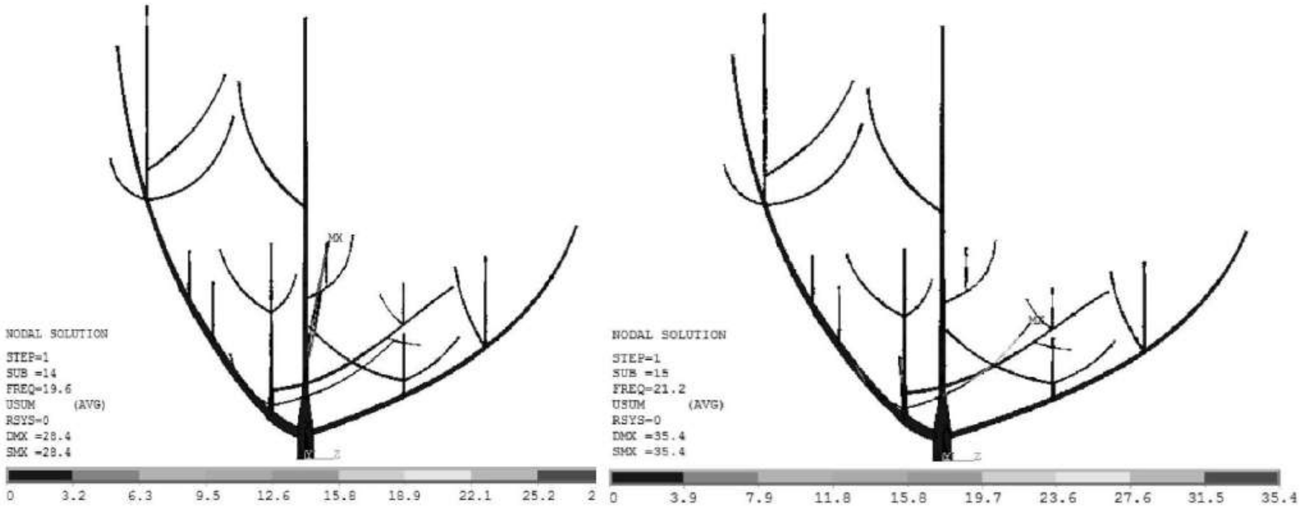
(c) Fifth order (10.8 Hz)

(d) Seventh order (12.6 Hz)



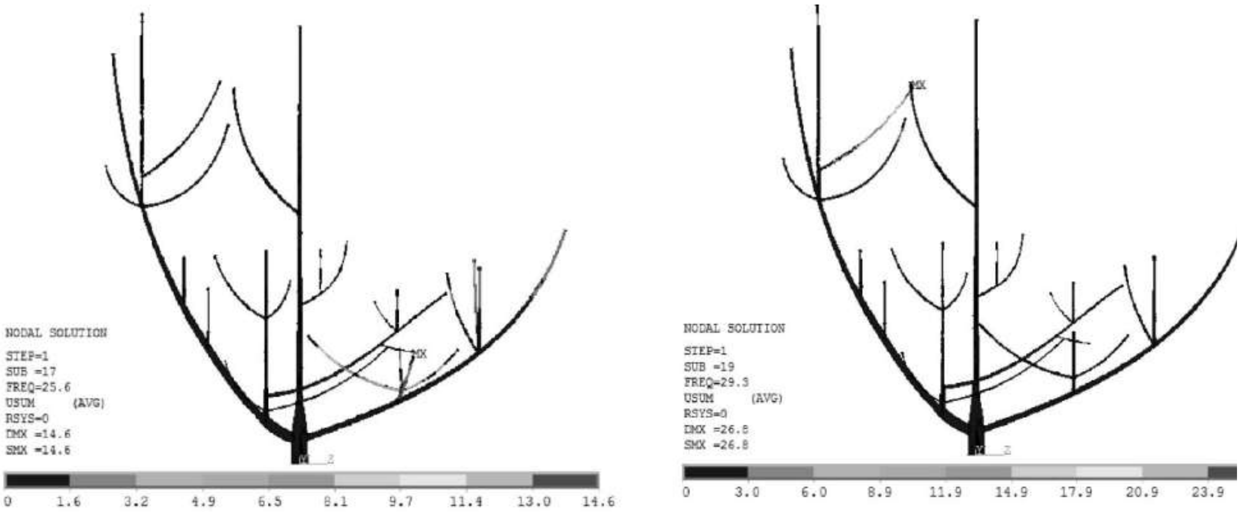
(e) Ninth order (15.8 Hz)

(f) Eleventh order (18.8 Hz)



(g) Fourteenth order (19.6 Hz)

(h) Fifteenth order (21.2 Hz)



(i) Seventeenth order (25.6 Hz)

(j) Nineteenth order (29.3 Hz)

Figure 3. The selected ten order natural frequencies of SBT tree and their natural modes.

Harmonic response analysis of SBT tree

The harmonic response analysis is a technology which can determine the structural response of a structure under known frequency harmonic load. Its purpose is to calculate the response of SBT trees under different frequency and obtain response, and find the frequency where the responses reach peak. Firstly, the primary results of harmonic response analysis were obtained by simulation with a random force of200 N applied on the trunk at position P_2, as shown in Figure 4. Secondly, it was the same as the first step, but the location on which force applied on was the side branches at position P_t and P_3. Then the harmonic response analysis was conducted to determine the magnitude of force and appropriate vibrating position. Figure 4 showed ten representative points for analyzing and the three force load positions.

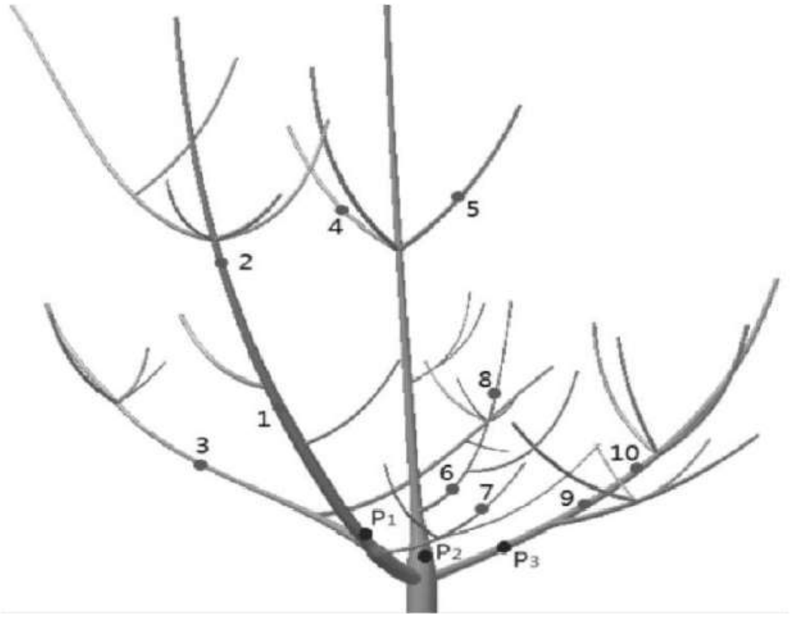


Figure 4. Three force loading positions and ten representative points.

Force on truck

The force of 200 N applied on P_2 of trunk, and obtained the Von Mises stress curve of the ten points, as shown in Figure 5(a). The frequencies of maximum stress point are 12 Hz, 14 Hz, 16 Hz and 24 Hz respectively. The maximum stress of three points (3, 6 and 8) are relatively large (0.137 MPa, 0.250 MPa and 0.126 MPa respectively), while that of the remaining seven points are far less than 1.101 MPa. It means that the force of 200 N acting on the trunk can't make fruits separated from branches. Modal analysis and harmonic response analysis can be considered as linear approximately. In order to ensure the fruits in the three points (3, 6 and 8) being separated from tree, it needs to exert appropriate force. The linear equation can be described as:

$$F / o = F^2 / \Omega_b \quad (2)$$

Where F is the primary vibration force, F^2 is the appropriate vibration force, Ω is the maximum stress of certain point, Ω_b is the required stress of fruits detaching from tree.

Therefore, the force needed to make the stress at points 3, 6, and 8 to reach 1.101 MPa is 1748 N. Figure 5(b) shows the simulation results when 1748 N applied on SBT tree trunk. By comparing Figure 5(a) and Figure 5(b), it can be seen the Von Mises stress of each point increase with the increase of applied force, and the variation trend has not changed. The value of stress of point 3, 6, 8 has reached the value of separation stress, but the tree root stress has exceeded the strength limit. It may damage the trunk, so it is not reasonable to apply the force of 1748 N on SBT tree trunk.

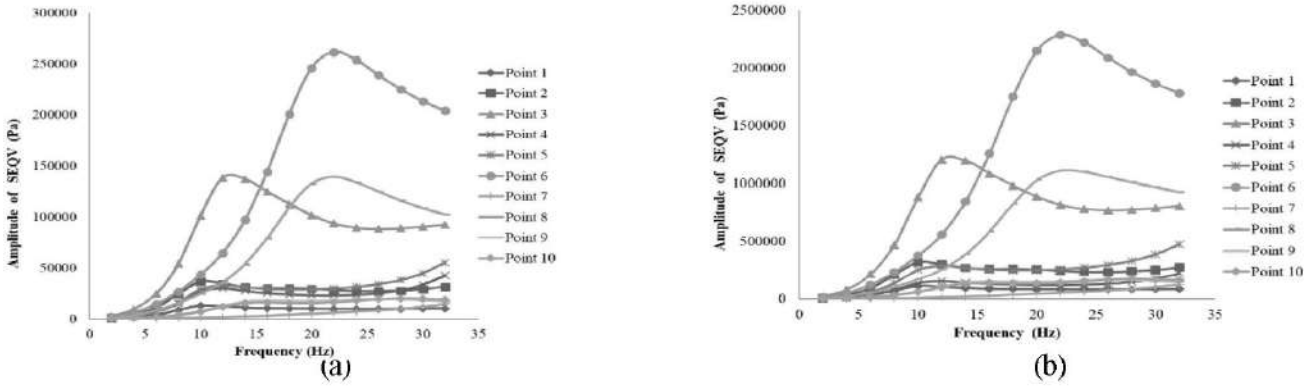
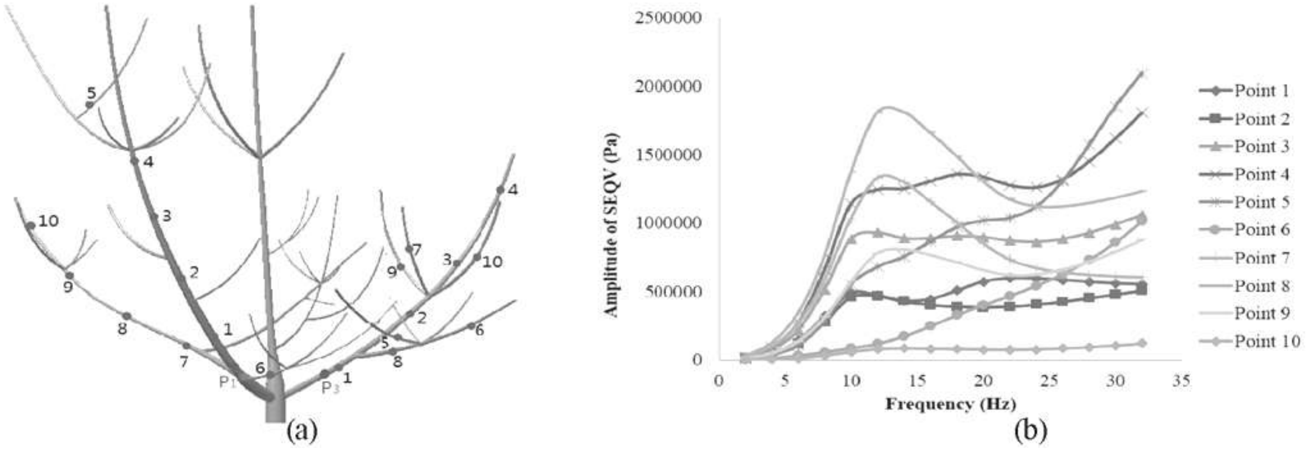


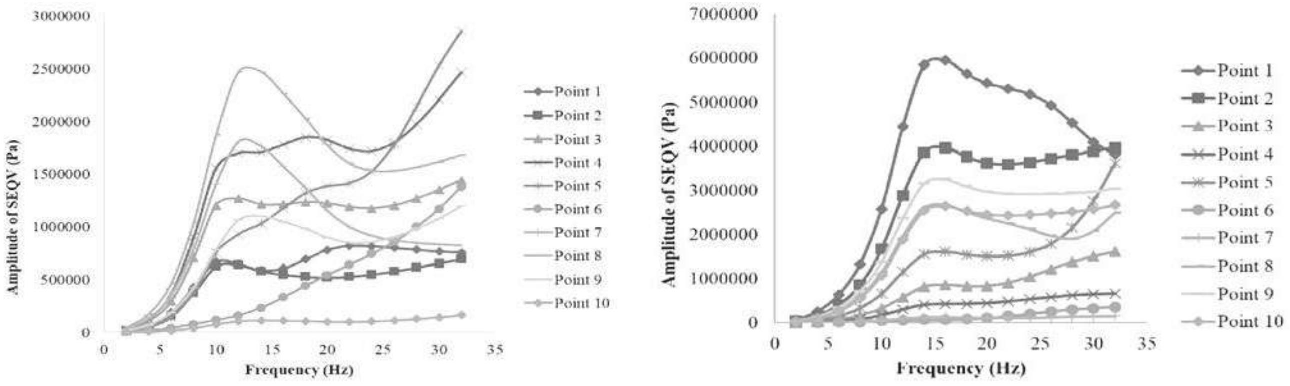
Figure 5. Harmonic response analysis of the trunk: (a) SEQV of the ten representative points when the load force is 200 N. (b) SEQV of the ten representative points when the load force is 1784 N.

Force on side branch

When the force was applied on the side branch, only the points on the forced branch can reach a reasonable value for analyzing. Ten points from each side branch was thus selected for a comprehensive analysis, respectively, as shown in Figure 6(a).

Firstly, simulation was conducted when the force of 200 N applied on position P_t of left side branch, as shown in Figure 6 (b). It can be seen resonance frequency is about 12 Hz, 14 Hz and 22 Hz. Only the branches exerted on force and the thin branches collateral and close to the acting position had large swing, while the other branches which didn’t act on force had very slight swing. Most points achieved the maximum stress value when frequency is 14 Hz; the stress value of points 4, 5, 7, 8 achieved the value of separation stress. At this time, the maximum stress 8.950MPa is much smaller than the strength limit. In order to make more fruits abscise down and reduce the grasping, so the force can be increased to guarantee most of fruits separated from branches. However, branches where points 1 and 2 locate have very large diameter, and point 10 is far from the force acting point and the force direction is the timber parallel to grain direction, so the stresses of points 1, 2 and 10 are relatively small. According to the growth characteristics of SBT tree, there are no fruits in the branches in large diameter, and the vibration of one position can’t make all fruits abscission. So the points 1, 2 and 10 can be ignored, and only need to ensure that the stress of the other seven points are larger than separation stress, and this can make most fruit separated from side branches. In the remaining seven points, the maximum stress of point 9 is smallest, only 0.804 MPa. In order to reach its separation stress, the force can be calculated by the linear approximation equation is 273 N.





(c) (d)

Figure 6. Harmonic response analysis of the branch. (a) The each ten point selected from left and right branches. (b) SEQV of the ten points in left branches (200 N). (c) SEQV of the ten points in left branches (273 N). (d) SEQV of the ten points in right branches (180 N).

Figure 6 (c) shows the Von Mises stress curve when the load (273 N) applied on the left branches, and from this figure, the maximum stress of all the points except from points 1, 2 and 10 have achieved minimum separation stress, which is consistent with the expectation. Different branches have different sizes, so the value of vibration force is different. Therefore the diameter is the main influential factor of points stress value.

Therefore, the right branches were selected as the research object, using the same force (273 N) to act on the position (P_3) of right branch. In order to eliminate the position of acting point influence the outcome of analysis, P_3 and P_3were selected symmetrical for the trunk. The maximum stresses of points (1, 2 and 10) don't reach the minimum stress, and the stress of other points are larger than 1.101 MPa. Obviously, the force 273 N can make the fruit separation, but the stress of some points is too large, which is not economical and may damage the branches. In the harmonic response analysis, only linear behavior is effective, so it can be assumed that the optimum vibration force is linear relationship with branch's diameter. The average diameter of force point in left branch is 22.9 mm, and that in the right branch is 15.2 mm. The linear equation can be described as:

$$F / D_1 = F2 / D_2 \quad (3)$$

Where F is the appropriate vibration force applied on left branches, F2 is the appropriate vibration force applied on right branches; D_1 is the average diameter of force point in left branches, D_2 the average diameter of force point in right branch.

By the equation, the vibration load (F2) is180 N. Figure 6 (d) shows the Von Mises stress curve when 180 N applied on the right branches, only three points 4, 6 and 7 cannot reach the minimum stress for fruit separation. Therefore, the proper force can be obtained by the linear relationship, and the vibration force of 180N can make most fruits be separated.

CONCLUSIONS

A vibration harvesting simulation for SBT fruit has been carried out in this paper by combining ANSYS FEM analysis software with Pro/E modeling software. First, a 3D solid model of SBT tree was created and imported into ANSYS, and then defined finite element type and material type. Second, first twenty order natural frequencies and vibration modes were obtained by modal analysis. A SBT tree has many order natural frequencies in theory, and this is related to the internal degrees of freedom. The number of internal degrees of freedom is equal to the number of natural frequency. Considering the high frequency vibration unsuitable for picking fruits, first twenty order natural frequencies (8.8 Hz to 31.2 Hz) were extracted. Frequency is related to many factors, such as hardness, quality and dimension. The first order modal frequency is 8.8 Hz by harmonic response analysis, which represents the natural frequency of top part in left branch, and each mode represents vibration of different parts.

The harmonic response analyses were carried when the force acted on the trunk and branches. The analysis results show it is inefficient and uneconomical that the vibration force acting on the trunk of SBT tree. It is better that vibration force acting on SBT tree side branches, and its damage is less. From the simulation results, the conclusion that the vibration load ranging from 180 N to 280 N acting on branches can separate most of fruits. The specific value of force acting on branches is related to shape and size of branches. The stress of point in the pedicels and branches connection place is relevant to diameter and distance between the point and point forced. Further experiments, simulation and data analysis are needed to be done for finding relationship between stress and diameter or distance.

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