Computers and Electronics in Agriculture 150 (2018) 476–483

Contents lists available at ScienceDirect

Computers and Electronics in Agriculture

journal homepage: www.elsevier.com/locate/compag

Original papers

Evaluation of the interaction between a harvester rod and a coffee branch based on finite element analysis

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A R T I C L E I N F O

Keywords:
Agricultural mechanization
Coffee harvesting
Numerical simulations

A B S T R A C T

The validation of agricultural mechanization issues often involves experimental tests. However, with the increase of computers processing capacity, numerical analysis became common in agricultural applications, which reduces costs for prototyping. The use of Finite Element Analysis (FEA) in new applications, the improvement of the existing models, together with a constant computers development can contribute significantly for the cost reduction in the agricultural industry. This work aimed to evaluate the interaction between a harvester rod and a coffee branch by using computational modeling via FEA. In order to perform dynamic simulations, three-dimensional models from a plagiotropic branch of a coffee tree and a harvester rod were obtained. In addition, samples from plagiotropic coffee branches were tested. The tests were supported by an accelerometer installed in the coffee branches in order to provide acceleration signals for FEA model validation. Results indicated that accelerations obtained from simulations were 3.14% higher than experiments, simulated displacements were 23.2% lower than experiments and simulated Von Mises stresses were close to values from the literature. This showed FEA potentiality for agricultural applications taking in consideration the interaction between machines and plants.

1. Introduction

Coffee production has significant importance for the global socio-economic scenario. In this context, Brazil is one of the largest coffee producer, considering an estimated coffee production around 43.65 million bags (60 kg per bag) per year, according to the Brazilian National Supply Company (CONAB, 2017). In addition to that, the global production of coffee for season 2016/2017 was estimated in 151.6 million of bags according to the International Coffee Organization (ICO, 2017).

The transformation of the coffee production process emerged with pioneering works and research in mechanization of coffee plantations, with emphasis on harvesting operations, productivity evaluation and operational cost. Considering the evolution of computing and processing capacity, more complex processes can also be evaluated. In this context, numerical simulations via Finite Element Analysis (FEA) (Zienkiewicz et al., 2005) have become more complete in many applications, reaching all engineering fields and other areas. In agricultural industry, it is already possible to predict, via numerical simulation, not only the mechanical behavior of machines, but also identify stresses and displacements from trees and fruits such as the vibration from coffee branches during the harvesting process. FEA can be used as a simulation tool in fruits and vegetables modelling (Vagenas and Marinos-Kouris, 1991), in structural analysis for agricultural machines (Magalhaes et al., 2006) and also for stress analysis applied to agricultural machines (Silva et al., 2014) and implements (Oliveira et al., 2014).

In terms of machine-tree interaction, Savary et al. (2010) evaluated the interaction between tree and canopy agitator using FEA, supported by field experiment performed on citrus trees and a shaker. Carvalho et al. (2016) used FEA to evaluate the mechanical behavior of a coffee tree. Results from numerical simulations using a three-dimensional modeling from the coffee tree showed the feasibility for predicting displacements of coffee branches from FEA static analysis.

However, most of agricultural applications involves vibrations. Agricultural machines used for harvesting, such as coffee harvester, are subjected to vibrations and the harvesting process still need to be studied (Tinoco et al., 2014; Coelho et al., 2016). Oliveira et al. (2007) performed a study about the influence of the sticks vibration and the speed of the harvester machine on the mechanized coffee harvest process. Santos et al. (2010) analyzed frequency, amplitude and degree of maturation of fruits and they performed laboratory vibration tests using an electromagnetic vibrating machine.

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https://doi.org/10.1016/j.compag.2018.05.020
Received 3 February 2018; Received in revised form 9 May 2018; Accepted 15 May 2018
0168-1699/

Based on that, this paper is aimed on the interaction of a rod used for coffee harvesting and a coffee branch by using numerical simulations via FEA in order to evaluate the plant mechanical behavior when this is submitted to vibration.

2. Vibration basics theoretical background

According to Huebner et al. (2001), three-dimensional modeling for finite element procedures has considerable improvements regarding to engineering problems, since it allows the use of a large number of degrees of freedom for physical systems representation. Therefore, by means of finite element modeling, the modal characteristics of a system, natural frequencies and modes of vibration is obtained from the formulation and solution of eigenvalues and eigenvectors problems. The eigenvalues correspond to the natural frequencies of the system, while the eigenvectors refer to the modes of vibration of the system associated to each natural frequency (Rao, 2009).

A mechanical system, subjected to forced vibrations, can be modeled by multiples degrees of freedom, whose equation in matrix form is given by Eq. (1) (Rao, 2009). For simplifications, some materials are considered homogeneous and isotropic.

$$[\mathrm{M}]\{\ddot{v}\} + [\mathrm{C}]\{\{\dot{v}\} + [\mathrm{K}]\{v\} = \{\mathrm{F}\} \quad (1)$$

where [M] is the matrix of mass, $\{\ddot{v}\}$ is the acceleration vector, [C] is the damping matrix, $\dot{v}$is the velocity vector, [K] is the stiffness matrix, $\{v\}$ is the displacement vector and [F] is an external load vector.

In analysis using FEA, the mass [M], damping [C] and stiffness [K] matrices, as well as acceleration vector $\{\ddot{v}\}$, velocity vector $\{\dot{v}\}$ and displacement vector $\{v\}$ correspond to the global matrices and vectors, obtained from the assembly of each element of the system. Considering an undamped vibration analysis, the Eq. (1) is reduced for the form presented in Eq. (2) (Rao, 2009).

$$[\mathrm{M}]\{\ddot{v}\} + [\mathrm{K}]\{v\} = \{\mathrm{F}\} \quad (2)$$

It should be emphasized that, in three-dimensional finite element models, the nodal displacements of a given element are represented by Eq. (3).

$$\{v\} = \begin{Bmatrix} u(x, y, z) \\ v(x, y, z) \\ w(x, y, z) \end{Bmatrix} \quad (3)$$

where u, v and w are nodal displacements.

The relation between deformations and the respective strain generated in a body can be determined by Hooke's law for homogeneous and isotropic materials, according to Eqs. (4)–(6) (Huebner et al., 2001).

$$\{\sigma\} = [D]\{\varepsilon\} \quad (4)$$

$$\{\sigma\} = \{\sigma_{xx}\sigma_{yy}\sigma_{zz}\tau_{xy}\tau_{xz}\tau_{yz}\} \quad (5)$$

$$\{\varepsilon\} = \{\varepsilon_{xx}\varepsilon_{yy}\varepsilon_{zz}\varepsilon_{xy}\varepsilon_{xz}\varepsilon_{yz}\} \quad (6)$$

where $\{\sigma\}$ is the strain vector, $\{\varepsilon\}$ is the deformation vector; σ_{xx}, σ_{yy}, σ_{zz} are normal stresses; τ_{xy}, τ_{xz}, τ_{yz} are shearing stresses; ε_{xx}, ε_{yy}, ε_{zz} are normal deformations; ε_{xy}, ε_{xz}, ε_{yz} are shearing deformations and $[D]$ is the mechanical properties matrix.

Von Mises stress results from all normal and shear stresses and acts at one point of the body. The maximum von Mises stresses corresponds to the peak of stress over the excitation period and it can be calculated by Eq. (7).

$$\sigma_{VM} = \sqrt{\frac{(\sigma_{xx}-\sigma_{yy})^2 + (\sigma_{yy}-\sigma_{zz})^2 + (\sigma_{zz}-\sigma_{xx})^2 + 6({\tau_{xy}}^2{\tau_{xz}}^2{\tau_{yz}}^2)}{2}} \quad (7)$$

where σ_{VM} is the von Mises Stress.

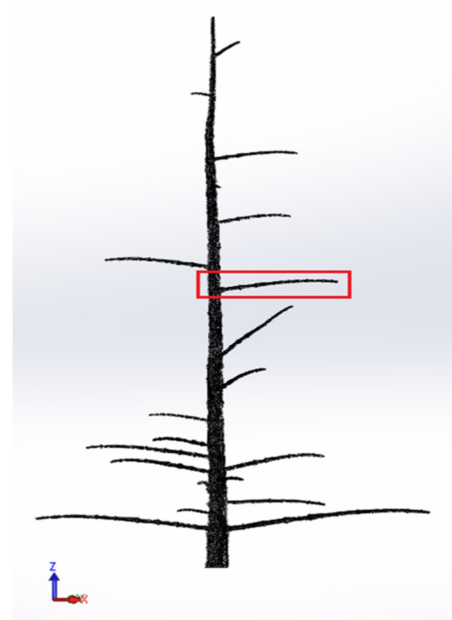

Fig. 1. Coffee tree geometry (Carvalho et al., 2016).

3. Materials and methods

3.1. Coffee branch and rod geometries

The first stage of this work involved the geometry modeling from the coffee tree branch and the rod by using the commercial software Solidworks®. Numerical simulations via FEA for stresses and displacements analysis were performed by means of the commercial software Ansys®.

For the coffee branch modeling, an adaptation of the model from Carvalho, Magalhaes and Santos (2016) was performed, reducing the entire plant geometry to a single plagiotropic branch (Fig. 1). This simplification was necessary in order to reduce computational costs since FEA dynamic studies require high memory.

After model importation from the entire plant, geometry trims and simplifications were performed in order to obtain the coffee tree plagiotropic branch final geometry used in the simulations, Fig. 2.

For the harvester rod modeling, it was used as reference, a rod of 570 mm in length and 13 mm in diameter, Fig. 3.

After the coffee branch and rod modeling, parts were positioned accordingly in order to provide the interaction between the parts for the dynamic simulations, Fig. 4.

3.2. Mechanical properties of the materials used for simulations

Material library was used in Ansys® commercial software for the harvester rod model (Table 1). This kind of material is normally used by rod manufacturers and for this reason it was chosen for the simulations. A new material was assigned for the coffee branch model, which was considered linear, homogeneous and isotropic as proposed by Carvalho, Magalhaes and Santos (2016), Table 2.

Fig. 2. Coffee branch geometry.