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Movement modes of a fruit during vibration harvesting

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Abstract. The article describes the movement of the fruit as a mathematical pendulum during branch vibrations. A non-linear numerical mathematical model was obtained. The article stated the presence of the fruit's complex movements, including non-sinusoidal oscillations, oscillations-beats, rotational modes, as well as oscillations that have a stochastic appearance. Subresonances are detected at operating frequencies $\omega \approx p\omega_0$ $(p=2,3,4,5\ldots)$; at the same time, the fruit oscillates with almost its own frequency ω_0. It is established that the maximum efforts in the stem necessary for its destruction appear at a subharmonic resonance with the frequency $\omega \approx 3\omega_0$. This mode is recommended as a working one for garden vibration installations.

1. Introduction

The Altai region, the Altai Republic and a number of adjacent territories have a great potential for the development of horticulture, the ability to increase the production of fruits and berries. The revival and renovation of gardens requires the simultaneous improvement of mechanization tools for the care of fruit crops and the harvesting of finished products. In particular, the vibration working bodies of the machines show high efficiency when removing fruits. The works of Russian and Chinese scientists and designers are devoted to the development of these methods of harvesting fruits (see, for example, [1,2]). The purpose of this article is the mechanic-technological substantiation of the modes of the process of vibration harvesting of fruits based on a non-linear mathematical model. This paper continues the previously published research [3].

2. Materials and Methods

The vibration method of harvesting fruits is that the stem of a tree vibrates, and the branches fluctuate mainly in the horizontal direction (Fig. 1a). The developing inertial forces are much greater than the force of gravity acting on the fruit, making it possible to destroy the stem.

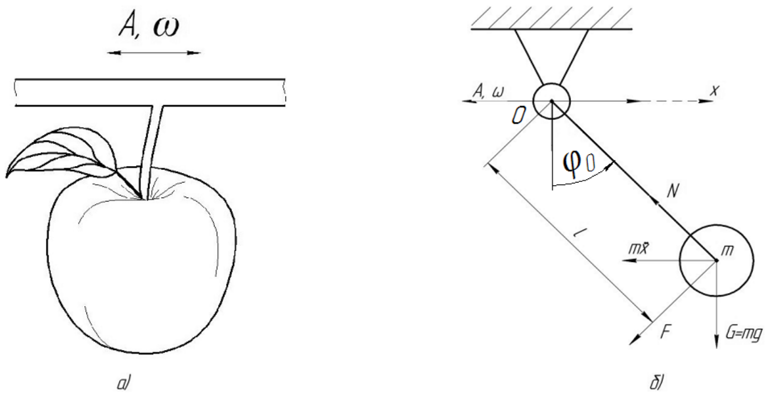

Figure 1. Physical (a) and calculated (b) diagrams of the model describing the process of the fruits' vibrational removal

We will simulate the "vibrating branch – fruit stem – fruit" system in the form of a mathematical pendulum, while we do not take into account the weight of the stem (Fig. 1b).

In a non-inertial (associated with a vibrating branch) coordinate system, the equation of fruit's oscillations, as a mathematical pendulum, has the following form [3]:

$$I\ddot{\varphi} = -k \cdot \ell \cdot (\ell \cdot \dot{\varphi})^2 \cdot sign(\dot{\varphi}) - m \cdot g \cdot l \cdot \sin(\varphi) - m \cdot l \cdot \ddot{x} \cdot \cos{(\varphi)}, \quad (1)$$

where m is the mass of the fruit; l is the distance from the center of gravity of the fetus to the point of suspension of the stem to the branch; I is the moment of inertia of the fruit relative to the point of suspension 0 ($I = m \cdot l^2$); $k = \frac{1}{2} \cdot \mathrm{c} \cdot \rho \cdot S$ – the air resistance coefficient (where c – is the proportionality coefficient, c = 0,3-0,4; ρ - is the air density; *S* is the midsection of the fetus);

$$sign(\dot{\varphi}) = \begin{cases} 1 \text{ when } \dot{\varphi} > 0 \\ 0 \text{ when } \dot{\varphi} = 0 \\ -1 \text{ when } \dot{\varphi} < 0. \end{cases} \text{ – a sign function.}$$

We divide all terms of the equation (1) by *I*, taking into account that $I = m \cdot l^2$; by calculating the derivative $\ddot{x}$, we get:

$$\ddot{\varphi} + \frac{k \cdot l}{m} \cdot \dot{\varphi}^2 \cdot sign(\dot{\varphi}) + \frac{g}{l} \cdot \sin(\varphi) = \frac{A}{l} \cdot \omega^2 \cdot \cos{(\varphi)} \cdot \sin{(\omega t)}, \quad (2)$$

where *A, ω* are the amplitude and angular frequency of horizontal oscillations of the branch.

Including the following notations $\frac{k \cdot l}{m} = 2n$; $\frac{g}{l} = \omega_0^2$; $\frac{A}{l} = K$, we get the final equation of fetal oscillations transmitted from the branch:

$$\ddot{\varphi} + 2 \cdot n \cdot \dot{\varphi}^2 sign(\dot{\varphi}) + \omega_0^2 \cdot sin(\varphi) = K \cdot \omega^2 \cdot \cos{(\varphi)} \cdot \sin{(\omega t)} \quad (3)$$

where *n* is the damping coefficient; ω_0 is the natural frequency of the fruit's oscillation on the stem.

We have obtained the nonlinear equation of the forced fruit's oscillations as a mathematical pendulum. Recent studies of forced oscillations of a mathematical pendulum have shown its highly complex dynamic behavior [4, 5]. Moreover, the equation (3) is more complicated than the equation considered by professor E. I. Butikov in his relevant resesearch[4, 5]. This prompted us to conduct a computer simulation of the process of fetal removal, using our non-linear model. We carried out a simulation for apples of medium size, while the necessary data for calculating the parameters *n*, ω_0 and *K* were obtained from sources [1, 6]. For the numerical solution of a differential equation, we used the Runge-Kutta method with an adaptable integration step.

3. Results

The computational experiments implemented by us really show the presence of complex modes of the fruit's movement, which are not displayed by a linear oscillatory system. Non-sinusoidal oscillations, oscillations-beats, rotational modes, as well as oscillations that have a stochastic appearance belong to them. It was established that nonlinearity manifests itself even with small fruit's fluctuations (about 5º). Thus, the linear model of the forced fruit's oscillations, used in many studies, is untenable.

Subharmonic resonances, which manifest themselves at working frequencies $\omega \approx p\omega_0$ $(p=2,3,4,5\ldots)$, were also detected, while the fruit oscillates almost with its own frequency ω_0. The subharmonic resonance of the order of 1/3 is particularly strong when the frequency of fruit's oscillations is about 3 times less than the frequency of the driving force (the frequency of oscillation of the branch).

In order to identify the conditions of destruction of the stem, we consider the load acting on the stem during the vibrations of the branch to which the fruit is attached. The tension of the stem N in general is determined by the following forces: a part of gravity – $mg\cos\varphi$, a centrifugal force of inertia – $m\dot{\varphi}^2 l$, a part of the portable force of inertia – $mA\omega^2\sin\varphi$. So we have the following equation:

$$N = mg\cos\varphi + m\dot{\varphi}^2 l - mA\omega^2\sin\varphi.$$

We divide all terms of the equation by $G=mg$, we get

$$\lambda = \cos\varphi + \frac{\dot{\varphi}^2}{\omega_0^2} - \frac{A\omega^2}{g}\sin\varphi,$$

where the value $\lambda=N/G$ represents the multiplicity of an increase in the weight of an apple during vibration overloads.

Figure 2 shows the load on the stem at extreme values of the amplitude of the fruit's oscillations with an angular frequency of $\omega \approx 3\omega_0 = 27$ c^{-1}. It is noteworthy that the values of λ can take negative values. This means that during vibrations, the fruit can both stretch and shrink. Consequently, it bends and collapses.

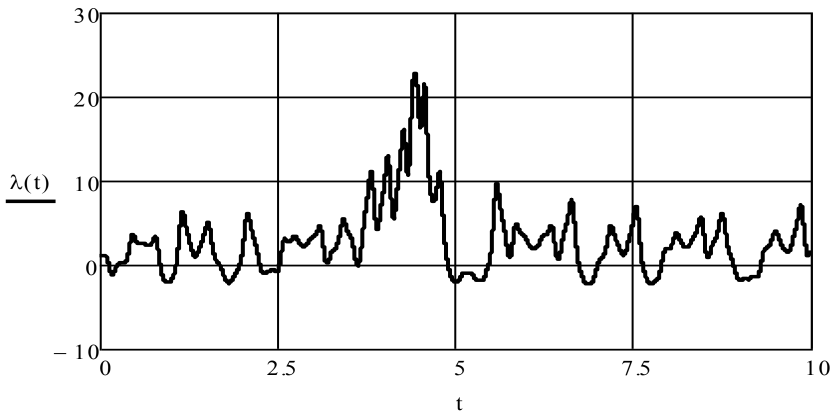

Figure 2. Developing overload λ in the fruit stem at an angular oscillation frequency ω=27 c^{-1}.

4. Conclusion

The strongest loads are tested on oscillation modes with $\omega \approx 3\omega_0$, i.e. the frequency of the forcing effect should be about 3 times higher than the natural frequency of the fetus on the peduncle. The short-term value of the overload λ must reach 20 or more units, which determines the corresponding amplitude of oscillations of the branches of the fruit tree. This ensures high efficiencies in vibratory harvesting of apples and other types of fruit. Therefore, the mode with a driving frequency is $\omega \approx 3\omega_0$. This mode is recommended as a working one for garden vibration installations.

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