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Full Length Research Paper

Study on the collision-mechanical properties of tomatoes gripped by harvesting robot fingers

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The data of collision-mechanical property of tomatoes gripped by robot fingers are important for the gripping control of tomato harvesting robot. In the study, tests of controlling the fingers to grip tomatoes were conducted to ascertain the effects of input current, motor speed and impact positions on the impact force of fingers and maximum deformation of tomatoes. The input current of the motor ranged from 1200 to 2100 mA, the motor speed from 25 to 3000 rpm and the three impact positions as follows, 1 (radial arm), 2 (sloping at an angle of 22.5° to the radial arm) and 3 (sloping at an angle of 45° to the radial arm). The results shown that under the condition of the same motor speed and input current, the peak impact force on the radial arm, compared with other impact positions, was maximum, the deformation of tomato was the smallest and the degree of mechanical damage was the lowest too. Under different speed and input current conditions, when the fingers grip the tomato on the radial arm, the peak force of fingers and the maximum deformation of tomatoes were highly influenced by the motor speed and input current, especially the input current. The peak impact force and the maximum deformation of the tomato increased respectively with increase in the motor speed and input current and these followed cubic polynomial regression equations.

Key words: Harvesting robot, fingers, mechanical properties, collision, tomato.

INTRODUCTION

Tomato is one of the most popular vegetables, with an annual production more than 120 million tons in the world (http://en.wikipedia.org/wiki/Tomato). Since 1995, China has become the largest producer of tomatoes, with the production accounting for about one quarter of the global output, followed by United States and Turkey (http://www.fao.org/es/ess/top/commodity. html). In the production of tomatoes, harvesting accounts for about 40% of its total labor, so automatic harvesting is significant to the liberation of labor and the promotion of intensive production of tomatoes. Since 1980s, some developed countries, such as Japan, Holland, and the United States, have been studying the tomato harvesting robot (Kondo et al., 1996, 2007, 2008; Monta et al., 1998; Takahashi et al., 2001; Gotou et al., 2003; Ling et al., 2005).

As the harvesting robot works, the suction pad moved backward to singulate the target fruit from the others in the same cluster. Then the fingers began to grasp the tomato fruit with an initial velocity when tomato was suctioned into the middle of the two fingers, which was a collision process. After the tomato was stably grasped, that is the finger velocity decreased to 0; the end-effector harvested the tomato by bending at the peduncle and released the tomato in a tray. Which means the harvesting is over (Jizhan et al., 2008; Zhiguo et al., 2008; Monta et al., 1998). As a mechatronics device that directly contact the fruits, the controlling strategy and operating principle of the harvesting robot must be determined according to the collision-mechanical properties of the tomatoes. Thus the study on the collision-mechanical properties of tomatoes gripped by the harvesting robot will provide some important basis for the stable and reliable gripping control of harvesting robot.

Over the past few years, many scholars have studied the collision-mechanical properties produced between tomatoes, a tomato and a stem, a tomato and different impact surfaces, such as cardboard, wood, metal, plastic and foam. Thiagu et al. (1993) studied the collision-

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mechanical characteristics of two varieties at various stages of maturity by whole fruit compression on an instron universal testing machine. Gonzalez et al. (1998) observed the effects of compression on the structure of red tomato using magnetic resonance imaging. Desmet et al. (2004) studied the effect of the intensity of impacts on tomato stem-puncture injury. Wang et al. (2006) characterized the mechanical behavior of single tomato fruit cells using high strain-rate micro-compression testing. Idah et al. (2007) investigated the effects of different impact surfaces and height of drops on bruise area and energy absorbed using the impact testing machine. Arazuri et al. (2007) studied the influence of mechanical harvest on the physical properties of processing tomato by means of impact test. Jizhan et al. (2008) conducted the tests of compression from transversal and longitudinal directions on tomato fruit at different ripening phases and tests of bending and stretching on tomato peduncle. Lien et al. (2009) developed a non-destructive method for assessing the maturity of tomatoes using the mechanical properties of the fruit under the falling impact test.

In conclusion, these researches on the collision-mechanical properties of tomatoes are usually carried out with universal testing machine or impact test bench. The surface of the instruments when contacts the tomatoes in the collision is plane and the process can be described as follows: the motor speed and output torque(input current) are set at a constant value and the compression experiment and impact experiment are conducted on a random position, then the collision-mechanical properties of tomatoes are obtained. However, compared with the actual harvesting condition of the robot, there still exist gaps: (i) the surface of robot fingers are usually curved; (ii) the different output torque and speed of the motor will affect the work efficiency, minimum stable gripping force of robot fingers gripping tomatoes and the degree of mechanical damage of tomatoes; (iii) considering the characteristics of internal structure of tomatoes, different gripping positions on transversal cross-section, such as the radial arm tissue and the locular tissue, will influence the minimum stable gripping force and the degree of mechanical damage. Therefore, the study of collision-mechanical properties of tomatoes will be carried out under different motor speed, input current and gripping positions.

MATERIALS AND METHODS

Fruit materials

The experiments were conducted in December 2008 at Education Ministry Key Lab of Modern Agricultural Equipment and Technology Jointly Constructed with Jiangsu Province. Fresh market ‘Fenguan 906’ tomatoes *Lycopersicon esculentum* Mill was used in this study. This cultivar fruit is mid-early ripening, heavy producer, large, smooth, round, excellent disease resistance and apparently high resistance to impact. It is suitable to plant at the season of spring and out-of -season. So the planting areas of ‘Fenguan 906’ tomatoes cover some major areas in China (Fenma, 2001; Zhihong et al., 2006). Because the stiffness of tomatoes at the light red stage is larger than red stage, the tomatoes at this ripe stage is convenient for storage and transportation (Kiyohide et al., 1991; Thiagu et al., 1993; Duprat et al., 1997; Allende et al., 2004; Lien et al., 2009), which period is optimal for harvesting tomatoes. Therefore, the research would focus on the tomato in light red ripe stage. The fruits in this experiment were uniformly from the Ruijing Vegetable Research Institute of Zhenjiang. 40 four-ventricular tomatoes were hand harvested at the light red ripe stage according to USDA Standards (USDA, 1991). Extremely large and small tomatoes were rejected. After they were carefully transported to the laboratory, the tomatoes were inspected again to ensure that they were uniform, non-damaged and not attacked by worms. In addition, the experiment would be conducted within 24 h.

Apparatus

The experiment was performed on the tomato harvesting robot (Jizhan et al., 2007; zhiguo et al., 2008), as shown in Figure 1. The fingers were driven by a *MAXON-24v 60W* DC motor. The fingers and the motor were connected by a reducer and a screw drive mechanism and the reduction ratio is 4.8:1. The *EPOS 24/5* position controller of the motor was installed inside the robot control cabinet and its *EPOS* software was installed on the computer. In current mode of *EPOS* software, the motor speed and the input current to control the fingers velocity and the gripping force were set. The two pressure sensors (Measuring range: 0~50 N, Sensitivity: 10 mv/N) installed in the back of the finger were a piezo-electric converter of output analog signals, which would receive the real-time impact force signals of fingers, then send them into the signal amplifier. The *USB5935* data acquisition instrument (Sampling Frequency: 100 kHz) transformed the amplified analog signals to digital signals, which then were transmitted into the computer through USB line. The data stored on the computer would be for subsequent off-line analysis.

Methods

The tomatoes were divided into four groups and labeled before experiment. In each experiment, firstly, the transverse diameter L_1 (Figure 2a, Perpendicular to the axis) of intact tomatoes was measured with a vernier caliper (Precision: 0.01 mm). Then, the stem of the tomato was tied to one end of a string and the other end of the string was fixed at the beam of height adjustable platform. The height of the beam was adjusted to ensure the tomato located at the center of two parallel fingers. Then, under the current mode of *EPOS* software, the finger to grip the tomato was controlled transversally by setting the motor speed and the input current at different values (Table 1). Finally, when the finger velocity is 0, the diameter L_2 (Figure 2a) of the deformed tomato was measured and the maximum deformation $\Delta L_{\max}$ of the tomato in the collision process was obtained as (L_1 - L_2)/2. For the first and second group, the data of impact force F and time t was recorded in the whole collision process and the data of peak force $F_{\max}$ and maximum deformation for the third and fourth group.

Figure 2b shows the cross-section of four-ventricular tomato and its simplified structure. Its structural is symmetrical on the radial arm. Therefore, in the process of gripping the tomato with the parallel fingers, the $^1/_4$ first half of the cross-sectional and its symmetrical part in the second half can be used to study the collision-mechanical properties of tomatoes, setting 1 (radial arm), 2 (sloping at an angle of 22.5° to the radial arm) and 3 (sloping at an angle of 45° to the radial arm) as the gripping positions.

Figure 1. Experimental system.1: tomato-harvesting robot; 2: finger; 3: motor; 4: control cabinet; 5: computer; 6: pressure sensor; 7: signal amplifier; 8: *USB5935* data acquisition instrument; 9: tomato; 10: string; 11: beam; 12: height-adjustable stand 13: sucker; 14: end-effector.

RESULTS AND DISCUSSION

Research of collision process

After making an experiment on the first group tomatoes, Figure 3 shows the curves of the impact force on the tomatoes and time in the collision process when the motor speed was 25 and 250 rpm, respectively. When the time ranged from 0 to t_0, the impact force on the tomato was 0. The impact force from t_0 increased nonlinearly with the increase in time under both 25 rpm as well as 250 rpm conditions, which was consistent with the mechanical properties of the fruit under compression loading (Thiagu et al., 1993; Williams et al., 2005; Flood et al., 2006; Jizhan et al., 2008; Kilickan and Guner, 2008). The period from t_0 to t_1 was the collision process at the motor speed of 25 rpm (the finger velocity is about 0.09 mm/s) and the impact force F_1 increased to the maximum 15.72 N at t_1. The period from t_0 to t_2 was the collision process at the motor speed of 250rpm (the finger velocity is about 0.9 mm/s) and the impact force F_2 increased to the maximum 20.06N at t_2, the growth rate of F_2 faster than F_1 ($t_2 < t_1$) . The maximum deformation ΔL of transverse diameter was measured as 1.58 and 1.89 mm under two conditions, respectively.

Figure 2a shows the process of robot fingers gripping tomato. In phase I, the fingers moved from the initial position to the position where they just contact the tomato skin, whose displacement was L_3. The fingers velocity increased from 0 to V and then kept uniform. There was no real contact between the fingers and the tomato in the process above, so, from 0 to t_0, the impact force of fingers on tomato was 0. In phase II, the fingers moved from the position where they just contact the tomato skin to the stable gripping, whose displacement was L_4. At that time, a point contact between fingers and the tomato changed into surface contact. The fingers were in decelerated motion and its velocity decreased from V to 0. According to the principle of conservation of energy, all the reduced kinetic energy of fingers would be transferred to deformation energy of the tomato, so the faster the initial velocity of fingers gripping tomato, the larger the peak impact force of fingers on tomato and the maximum

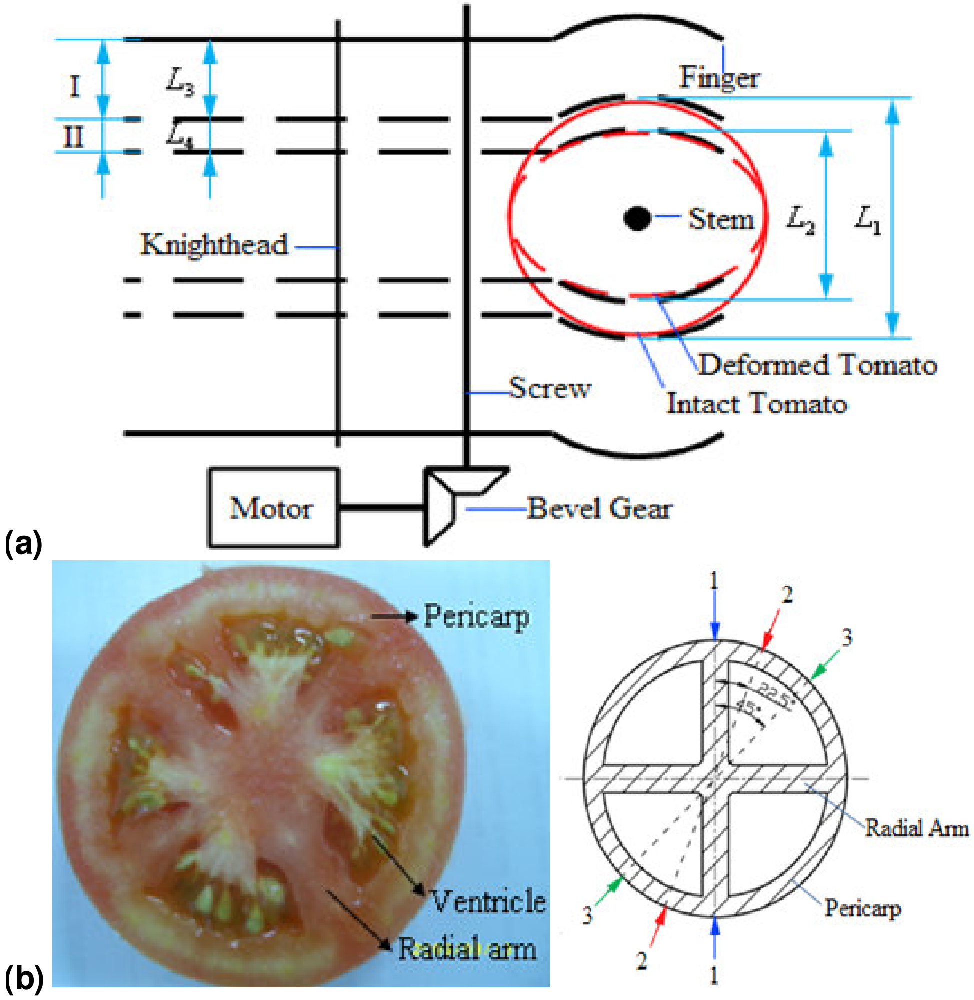

Figure 2. The process of robot fingers gripping tomato and the structure of four-ventricular tomatoes. (a) The process of robot fingers gripping tomato. (b) The cross-section of four-ventricular tomatoes and its simplified structure.

Table 1. The experimental method.

Group	Position	Number	*I* (mA)	*V* (rpm)
1	1	5	1200	25 250
2	1 2 3	5	1200	3000
3	1	5 5 5	1000 1200 1400	*V* [10]
4	1	5 5 5	*I* [10]	25 1500 2500

V [10] : 25, 50, 250, 500 rpm, 750 ,1000,1500, 2000, 2500, 3000 rpm。

I [10] : 1200, 1300, 1400, 1500, 1600, 1700, 1800, 1900, 2000, 2100 mA。

deformation of tomato. When the fingers velocity decreased to 0, the impact force on the tomato and the deformation of the tomato would reach the maximum. This viewpoint is supported by the impact loading theory of mechanics of materials (Hibbeler, 2003; Lianggui and Yongjun, 2005). Therefore, under such two conditions, $F_1 < F_2$, $\Delta L_1 < \Delta L_2$. At last, the collision time was calculated with the data of fingers displacement and average velocity: $t_2 < t_1$.

Collision from different positions

In the second experiment, the fingers gripped the tomatoes on the 1, 2 and 3 positions respectively. Figure 4 shows the curves of the impact force on the tomatoes and time in the collision processes. The fingers contacted the tomato on the 1, 2 and 3 positions respectively at t_0.The period from t_0 and t_1 was the collision process of

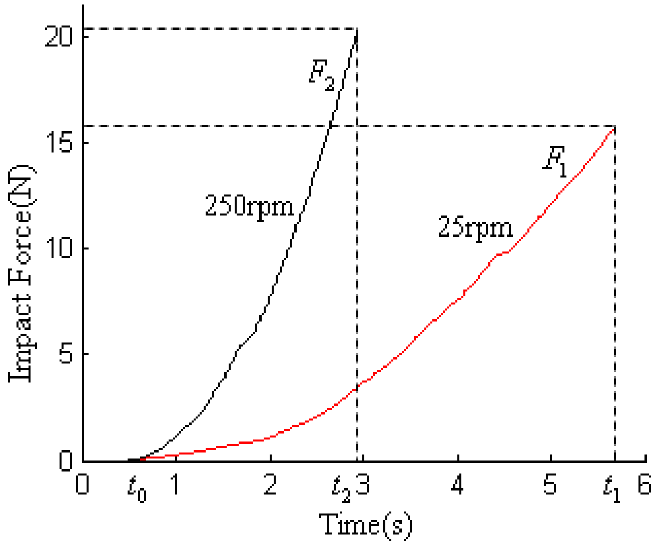

Figure 3. The curves of the impact force on the tomatoes and time in the collision process at 25 and 250 rpm respectively.

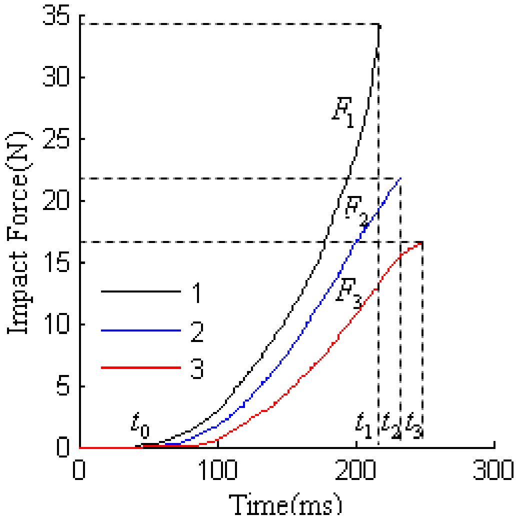

Figure 4. The curves of the impact force on the tomatoes and time in the collision processes as the fingers gripped the tomatoes on the 1, 2 and 3 positions respectively.

fingers gripping the tomato on the position 1; the collision process from t_0 and t_2 was for the position 2; the collision process from t_0 and t_3 was for the position 3. In the three collision processes, the peak impact force on tomatoes was 34.29, 21.97 and 16.52 N respectively; the maximum deformation of the tomato was 2.08, 2.36 and 2.62 mm respectively. It was obvious that the same tomato received different peak forces and different maximum deformations as it was contacted by the fingers on three different positions. The results shown the biological material of tomatoes was inhomogeneous and aniso-tropic, so the obtained mechanical properties from the compression test on the random surface position (Rong et al., 2004; Qiujun et al., 2005; Kabas et al., 2008; Yingyi et al., 2008) were not suitable to apply to the study of whole tomato. Analyzing the results from the internal structure of tomatoes, it is obvious that the elastic mo-dulus of radial arm tissue is greater than the locular tissue and the resistance of radial arm on the impact force of fingers is greater than that of the locular tissue (Xingqian, 1992).

Therefore, in the three collision processes: the impact time: $t_1 < t_2 < t_3$, the maximum deformation:$\Delta L_1 < \Delta L_2 < \Delta L_3$. According to the principle of conservation of energy, the peak impact force was deduced as $F_{1max} > F_{2max} > F_{3maximum}$. When the robot harvests tomatoes, the peak impact force on tomatoes is the stable gripping force that the fingers can provide. The tomato deformation is regards as the main indicator that measures the degree of mechanical damage of tomatoes(Idah et al., 2007) and the larger the deformation of tomatoes in the collision process, the greater the degree of mechanical damage of tomatoes. Thus, when the motor speed and input current are constant and the tomatoes are grasped on position 1, the stable gripping force is the largest while the deformation of tomato is the smallest and the degree of mechanical damage of tomatoes is the lowest.

Different motor speed and output torque

The same input current and different motor speed

In the third experiment, under the conditions that the input current (output torque) of the motor is 1000, 1200 and 1400 mA, respectively, Figure 5a shows the curves of the peak impact force and the motor speed and shows the curves of the maximum deformation of tomatoes and the motor speed. On the whole, the curves in Figure 5a are closely parallel to each other; and the curves in Figure 5b are closely parallel to each other too. As are shown in Figures 5a and 5b, the peak impact force and the maximum deformation of tomatoes rise with the increasing motor speed under the three conditions, which followed cubic polynomial regression equations (Equations (1), (2) and (3)).

1000 mA condition:

$$F_{\max} = 6.007\times10^{-10}v^3 - 3.413\times10^{-6}v^2 + 0.0105v + 10.26$$
$$(R^2 = 0.99) \qquad (1)$$

$$\Delta L_{\max} = 4.195\times10^{-11}v^3 - 2.031\times10^{-7}v^2 + 4.098\times10^{-4}v + 0.323$$
$$(R^2 = 0.95)$$

1200 mA condition:

$$F_{\max} = 8.083\times10^{-10}v^3 - 4.549\times10^{-6}v^2 + 0.0121v + 17.32$$
$$(R^2 = 0.99) \qquad (2)$$

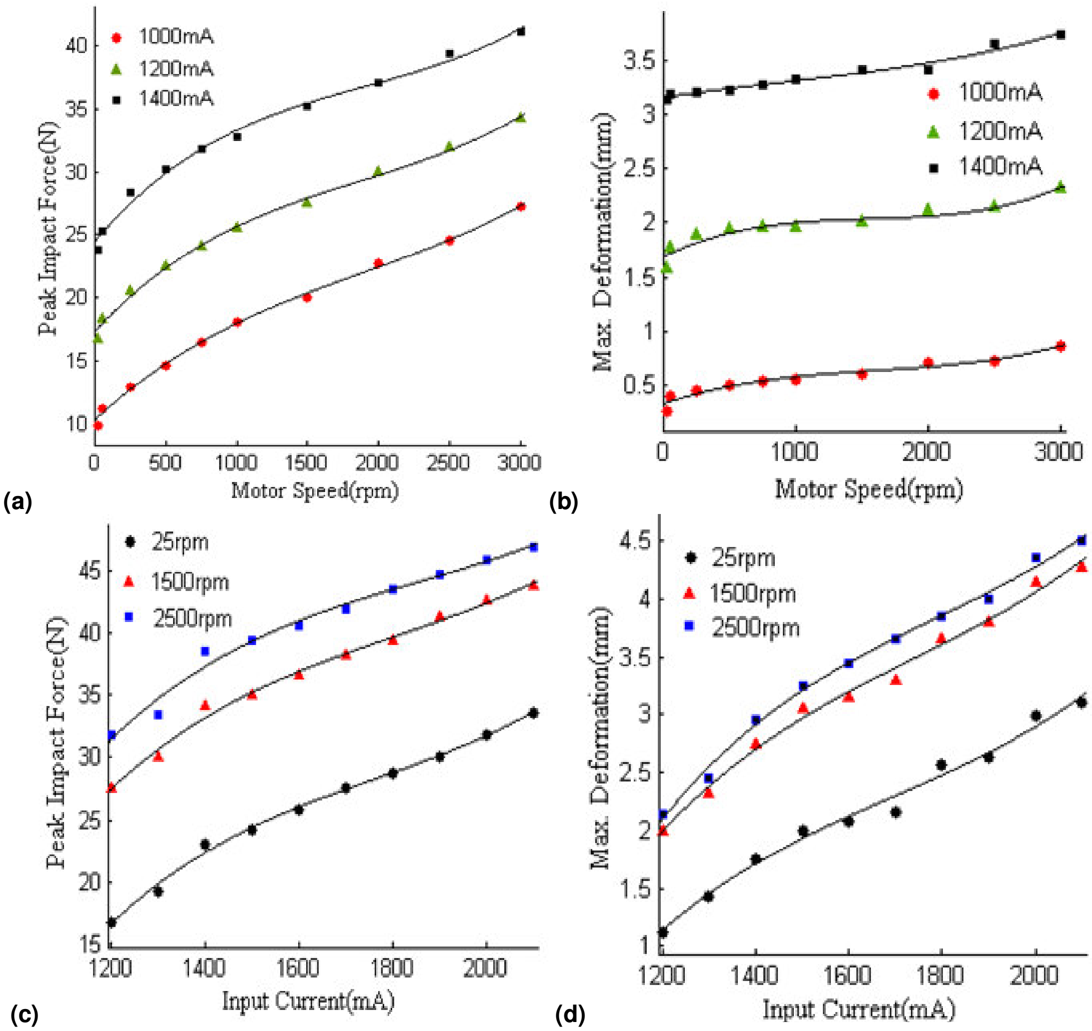

Figure 5. the results of the third experiment and the fourth experiment. (a) Peak impact force and motor speed, (b) maximum deformation and motor speed, (c) Peak impact force and input current (d) maximum deformation and input current.

$$\Delta L_{\max} = 0.778\times10^{-10} v^3 - 3.624\times10^{-7} v^2 + 0.603\times10^{-3} v + 1.682$$
$(R^2 = 0.92)$

1400 mA condition:

$$F_{\max} = 9.217\times10^{-10} v^3 - 5.282\times10^{-6} v^2 + 0.0132v + 24.46$$
$(R^2 = 0.99)$ (3)

$$\Delta L_{\max} = 1.592\times10^{-11} v^3 - 4.123\times10^{-8} v^2 + 1.771\times10^{-4} v + 3.16$$
$(R^2 = 0.98)$

The same motor speed and different input current

In the last experiment, under the conditions that the motor speed is 25, 1500 and 2500 rpm respectively, Figure 5c shows the curves of the peak impact force and the input current (output torque) of the motor and Figure 5d shows the curves of the maximum deformation of tomatoes and the input current of the motor. On the whole, the curves in Figure 5c are closely parallel to each other and the curves in Figure 5d are closely parallel to each other too. As are shown in Figures 5c and 5d, the peak impact force and the maximum deformation of tomatoes rose with the increase in the input current under the three conditions, which also followed cubic polynomial regression equations (Equations (4), (5) and (6)).

25 rpm condition:

$$F_{\max} = 2.355\times10^{-8} I^3 - 1.246\times10^{-4} I^2 + 0.2328I - 124.1$$
$(R^2 = 0.99)$ (4)

$$\Delta L_{\max} = 2.34\times10^{-9} I^3 - 1.119\times10^{-5} I^2 + 2.196\times10^{-2} I - 12.11$$

$$(R^2 = 0.98)$$

1500 rpm condition:

$$F_{\max} = 1.984 \times 10^{-8} I^3 - 1.075 \times 10^{-4} I^2 + 0.2072I - 100.6$$
$$(R^2 = 0.99) \quad (5)$$

$$\Delta L_{\max} = 2.496 \times 10^{-9} I^3 - 1.305 \times 10^{-5} I^2 + 2.476 \times 10^{-2} I - 13.26$$
$$(R^2 = 0.99)$$

2500 rpm condition:

$$F_{\max} = 1.93 \times 10^{-8} I^3 - 1.075 \times 10^{-4} I^2 + 0.2105I - 99.65$$
$$(R^2 = 0.98) \quad (6)$$

$$\Delta L_{\max} = 2.864 \times 10^{-9} I^3 - 1.542 \times 10^{-5} I^2 + 2.956 \times 10^{-2} I - 16.12$$
$$(R^2 = 0.99)$$

The results have shown that under the conditions of different motor speed and input current, when the fingers grip the tomato on the radial arm, the peak force of fingers and the maximum deformation of tomatoes were highly influenced by the motor speed and input current. Therefore, with respect to the collision-mechanical properties of tomatoes, the motor speed and output torque should also be take into account, besides the influencing factors such as the maturity, shape and impact energy of the tomato which were more helpful to make the controlling strategy of stable gripping for tomato harvesting robot (Thiagu et al. 1993; Rong et al., 2004; Qiujun et al., 2005; Idah et al., 2007).

To sum up, when the input current and motor speed (the finger velocity) increased, the peak impact force became greater and the maximum deformation of tomatoes got larger. By calculating, some conclusions can be confirmed that the average growth rate of the maximum impact force and the maximum deformation with motor speed are 0.0058 N/rpm and 0.0002 mm/rpm, respectively; the average growth rate of the peak impact force and the maximum deformation with input current are 0.018 N/mA and 0.0021 mm/mA, respectively. It is clear that the growth rate of the peak impact force and the maximum deformation with the input current is faster than that with the motor speed, which means that the stable gripping force and the degree of mechanical damage of tomatoes were higher influenced by the input current.

Conclusion

In the study, tests of controlling the fingers to grip tomatoes were conducted to ascertain the effects of input current of the motor (output torque), motor speed and impact position on the impact force and maximum deformation of tomatoes. It can be concluded from the experiments that under the condition of the same motor speed and input current, the peak impact force on the radial arm, compared with other impact positions, was the maximum, the maximum deformation of tomato was the smallest and the degree of mechanical damage was the lowest too. Under different motor speed and input current conditions, when the fingers grip the tomato on the radial arm, the peak force of fingers and the maximum deformation of tomatoes were highly influenced by the motor speed and input current, especially the input current. The peak impact force and the maximum deformation of the tomato increased respectively with increase in the motor speed and input current, which followed cubic polynomial regression equations.

When the harvesting robot works, the three requirements are proposed as follows, 1) the fingers' gripping force should be stable. 2) No mechanical damage of tomatoes. 3) The grip efficiency should be as high as possible. The results of the above experiments shown that the motor speed determined the grip efficiency of fingers; the fingers stable gripping force and the degree of mechanical damage were determined by the motor speed, input current and gripping positions. Therefore, to realize the stable grasp on tomatoes, the control parameters (motor speed, input current and gripping position) should be optimized in the actual environment. Additionally, the data obtained can be of great help to the package, transportation and handlers of the produce in minimizing the mechanical damage that may result especially those due to impact and ensure deliverance of good quality products to consumers and processors.

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