Design and experimental investigation of a lemon cutting machine

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Abstract: Lemon cutting by human labour in small and medium food producers such as restaurants and juice producers is a very time-consuming process that may result in high operating costs. In order to reduce the operating time, a machine for cutting lemons is an important tool to use instead of manual cutting by labour. The aim of this research is to design, develop and test a lemon cutting machine for processing lemon fruits. A prototype is designed and developed to consist of four main parts. Firstly, a power transmission system is designed as a source of power for driving a mechanism to rotate a rotor and blades. Secondly, a suspension system is fabricated with a lockable wheel that is able to fix the machine during the operation process without moving. Thirdly, a feeder system is constructed to include a hole with an incline tray that assists the feeding of lemons into the machine. Finally, a cutting system is manufactured for slicing a lemon into two pieces based on shear force. The experimental investigation is performed by a comparative study between the developed machine and the cutting of lemons by manual labour. The results show that the lemon cutting machine can demonstrate the higher performance than that of manual cutting by 3.31 times. In addition, for the lemon cutting process, the machine can produce the high-quality product of 88.79%. Moreover, the prediction of lemon shear stress provides the accuracy of 96.50%. It can be concluded that the developed lemon cutting machine can be used as a tool to reduce the operating time in the food producing sector.

Keywords: design, cutting device, machine design, cutting force, shear stress, lemon.

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1 Introduction

A lemon is an important fruit that can provide juice used for many a variety of purposes. Lemon juice is used as a food ingredient to increase the taste of meals. In addition, lemon juice is mixed by using water and sugar to produce a commercial drink which is contained and stored in cans or bottles. Lemon juice can also provide essential nutrition for the human body such as vitamins and minerals that can help reduce blood pressure in the circular blood system. Furthermore, it may prevent a risk of some types of cancer (Lyu et al., 2022).

Many researchers attempt to study the physical characteristics of lemons with varying techniques. Defects of sour lemon fruits are detected by the conventional neural network with image processing (Jahanbakhshi et al., 2020a). The results show that this method can provide higher accuracy when compared with other methods. In addition, a detection method for harvesting lemons is demonstrated to improve the accuracy and performance of detected lemons in real environments (Li et al., 2021). Moreover, the benefit of using a robot arm to harvest lemons is analyzed and modelled (Riyaz et al., 2015).

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Finally, the detection of mechanical damage to sweet lemons is performed by image processing and ultraviolet (UV) radiation methods (Firouzjaei et al., 2018).

In general, for cooking purposes within a household, a knife is an appropriate tool that is commonly used to cut lemons. However, for cutting lemons within small and medium manufacturers such as restaurants and food producers, it is a disadvantage to cut a large number of lemons through manual labour due to high operating costs. In addition, the safety of workers while cutting lemons by hand with a knife is also a crucial factor that needs to be considered. Therefore, a cutting machine for lemons should be designed and developed instead of relying upon manual cutting techniques. Regrading research on lemon processing machines, a continuous lemon cutting machine has been developed using a driving power from an electric motor (Hrishikesh et al., 2014). In this research, a lemon is cut into four pieces. However, normally for food manufactures such as a restaurant and a juice producer, lemons can be used after cutting into two pieces.

Therefore, the main objective of this study is to design, develop and test a lemon cutting machine that will be able to cut a lemon into two pieces, this is based on new design of the rotor for general purposes used within the food manufacturing sector. In addition, cutting forces of lemons are examined to use as basic data for designing the machine. The outcome of this research can be used as a tool for reducing the operating time in the food producer sector and for further design and research development of lemon cutting machines and other fruit cutting machinery.

2 Materials and methods

2.1 Materials

Major raw materials used in this study are lemons and stainless steel. Fresh lemons for conducting these experiments, as shown in Figure 1, are purchased from a local market. These lemons are used to test and evaluate variations of design factors within the lemon cutting machine. In order to build a prototype, stainless steel 304 is selected as a major material for the main components in the fabrication of the frame and structure. This is because stainless steel can exhibit good performance in terms of rust prevention. In addition, stainless steel is widely used for production of food machinery (Gana et al., 2017; Hmar et al., 2018). Mechanical properties of stainless steel 304 are shown in Table 1 (Hibbeler, 2011).

Figure 1 Lemons for conducting experiments

Table 1 Mechanical properties of stainless steel 304 (Hibbeler, 2011)

Material	Density ($Mg\ m^{-3}$)	Modulus of Elasticity (GPa)	Yield Strength (MPa)	Ultimate Strength (MPa)	Poisson’ s Ratio	Coefficient of Thermal Expansion (10^{-6})/ºC
Stainless steel 304	7.86	193	207	517	0.27	17

2.2 Measurement

Measurement tools used in this research are a photo/contact tachometer (Jedto, model: DT2236B) manufactured by Jedto Instruments, Thailand as presented in Figure 2, and a load cell (Commandor, model: DEF) manufactured by Advance Solution International, Thailand as shown in Figure 3. The Photo/contact tachometer is a tool for measuring the electric motor speed in a unite of round per minute (rpm). It can display data of the motor speed on a monitor without contacting a motor shaft and other equipment. Specifications of the tachometer are illustrated in Table 2. Another type of measurement equipment is a load cell for measuring loads in terms of cutting force in a lemon cutting process. A s-type load cell is used in this research as shown in Figure 3.

Figure 2 Gear accuracy testing using a photo tachometer

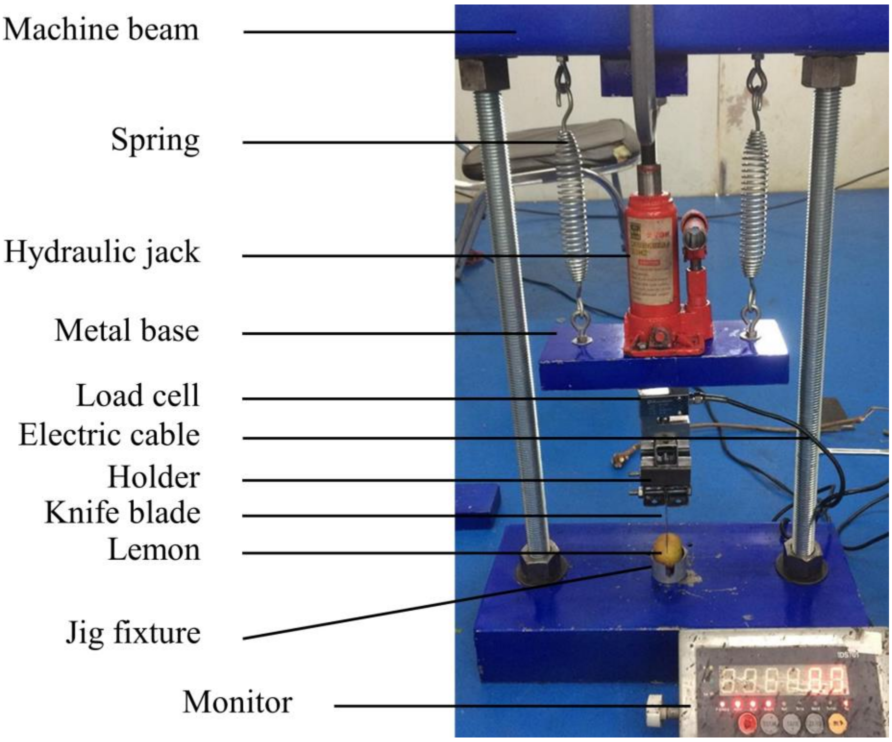


Figure 3 Apparatus for testing the cutting force

Table 2 Main specifications of Photo/contact tachometer model: DT2236B

Specification	Range
Display	5 digits, 18 mm LCD
Measuring range	2.5 to 99,999 rpm
Resolution	0.1 rpm (2.5 to 999.9 rpm)
Accuracy	± (0.05%+1 digit)
Test range selected	Automatic
Detecting distance	50 to 500 mm

2.3 Design of a prototype

An engineering drawing of a prototype of the lemon cutting machine is shown in Figure 4. Major components comprise of four parts, namely the power transmission system, the suspension system, the feeder system and the cutting system. The technical details of these components are described within the next sections.

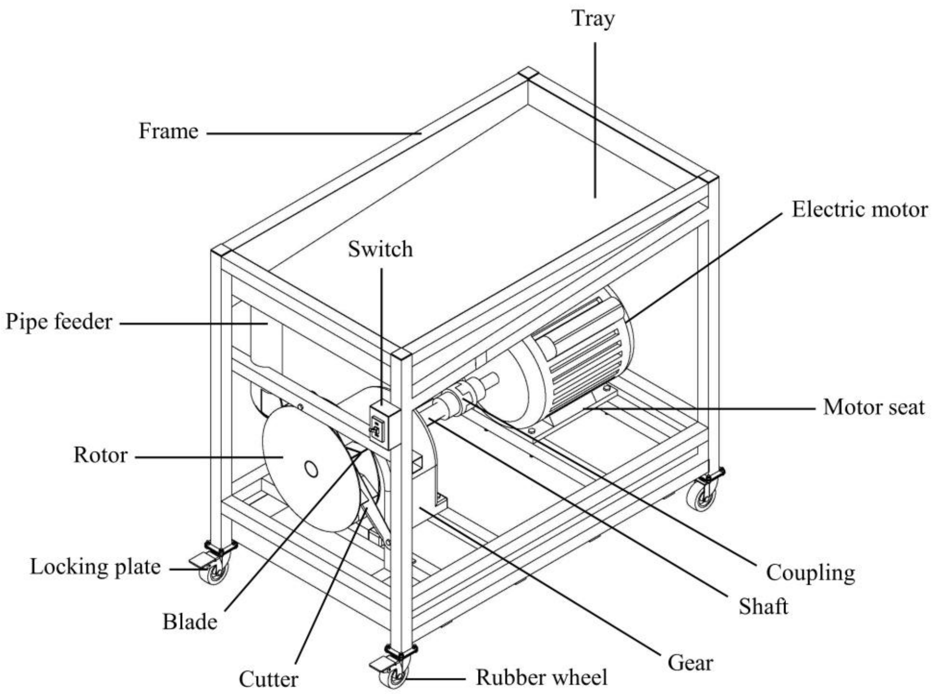


Figure 4 Detailed drawing of the lemon cutting machine

2.3.1 The power transmission system

An electric motor which is designed to locate on a motor seat, generates power to drive a shaft as shown in Figure 4. The shaft is connected to a coupling. The main function of the coupling is to connect a motor and a gear shaft for transmitting power from the motor to the gear with a ratio of reduction 1:30. The gear connects with a rotor to rotate a blade and bring a lemon from a pipe feeder to contact with a cutter before separating the lemon into two halves by shear force. The machine can be turned on and off by an electric switch. In order to design a prototype for an experimental purpose in a small scale with enough power and saving electrical energy, the power of electric motor for fabricating the prototype in this study is 0.37 kw or 370 w using alternating current (AC) by 220 V. The power and torque requirements with a gearbox are calculated by the following equations (Budynas and Nisbett, 2011).

$$P = T_i \omega_i = T_0 \omega_0 = T_i \frac{2\pi n_i}{60} = T_0 \frac{2\pi n_o}{60} \quad (1)$$

$$T = FR \quad (2)$$

where, P is the power requirement (w), ω_i is the angular velocity of the input gear (rad s^{-1}), ω_o is the angular velocity of the output gear (rad s^{-1}), T_i is the torque input of the motor (N.m), T_o is the torque output of the gear (N.m), n_i is the motor speed (rpm), n_o is the rotor speed (rpm), T is the torque requirement (N.m), F is the cutting force (N) and R is the radius of the rotor (m). Substituting Equation 2 into Equation 1, the power requirement can be calculated as follow:

$$P = \frac{2\pi n_o RF}{60} \quad (3)$$

$$P = \frac{\pi n_o RF}{30} \quad (4)$$

According to the maximum cutting force of 58.86 N in Table 3, the radius of the rotor by 0.115 m, the rotor speed of 47 rpm and a safety factor of 1.8, the power requirement for cutting a lemon can be calculated by Equation 4. The result is 60 W. Therefore, the electric motor and the power transmission system which are designed, have enough power to cut lemons.

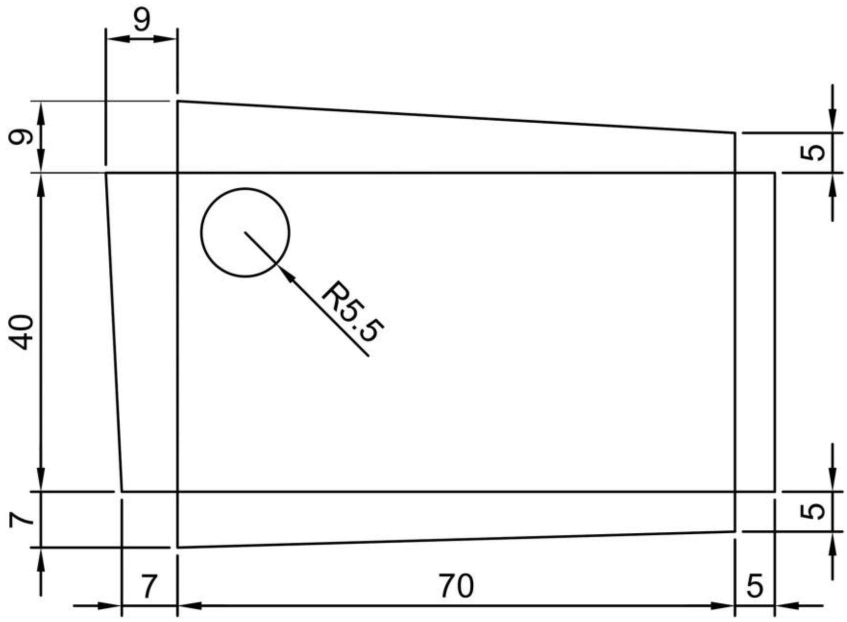


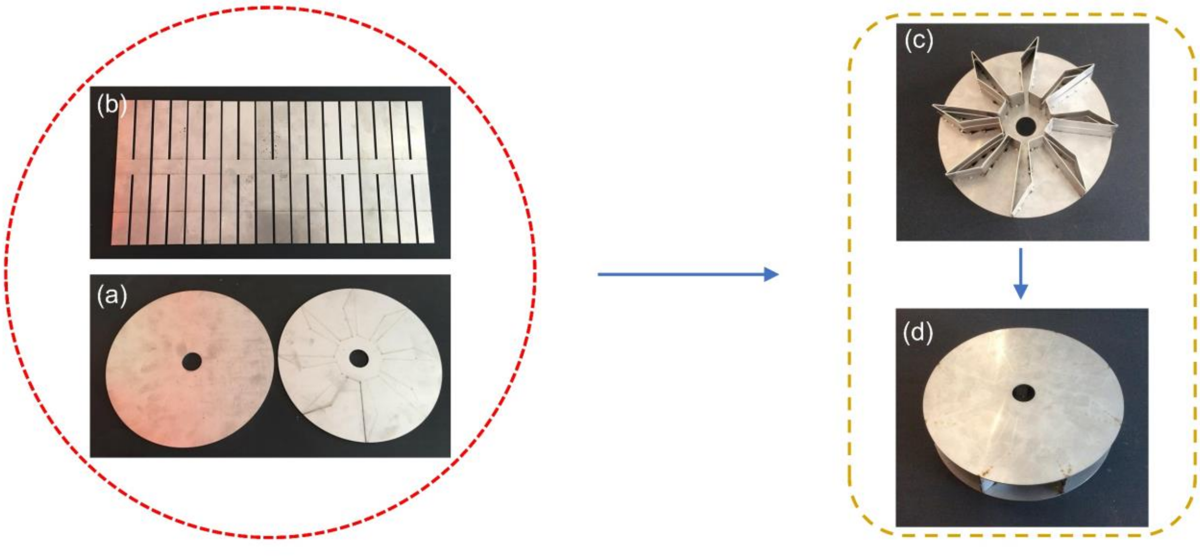
Figure 5 Development drawing of the upper tray

2.3.2 The suspension system

In order to support the weight of the machine, the lower parts of the frame are attached with four rubber wheels with a locking plate as shown in Figure 4. The wheels are locked by the locking plates to provide stability to the machine whilst in operation without sliding when situated on the floor. Furthermore, each wheel can turn freely by 360 degrees. As a result, the machine can be smoothly moved by a worker to a different area with minimal energy exerted.

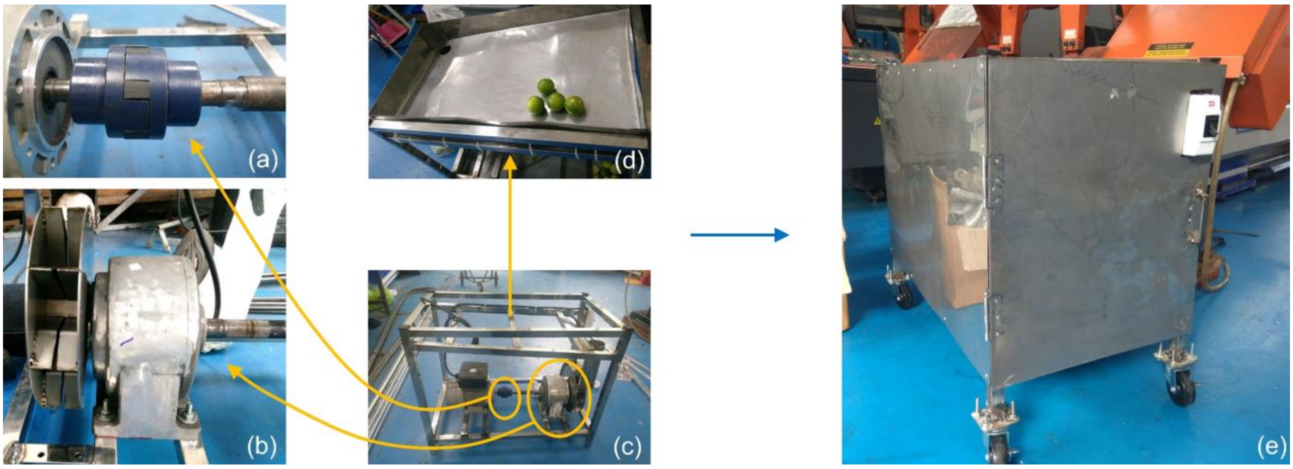
2.3.3 The feeder system

A rectangular tray is designed to be a container for the lemons as shown in Figure 4. It is made of a stainless-steel sheet with thickness of 0.5 millimeters. Dimensions of the tray are 70 centimeters in length, 40 centimeters in width and a hole with a diameter of 5.5 centimeters as shown in Figure 5. In order to move a lemon into a pipe feeder automatically, the tray is designed to have an incline. The inclined tray will position a lemon then drop the lemon down through a pipe feeder before approaching the rotor. Finally, a lemon is carried by the rotor and the blade to touch a cutter or a knife before separating the lemon into two halves based on shear force.



(a) circular disks; (b) the stainless-steel plate; (c) the half side rotor; (d) the complete rotor

Figure 6 Manufacturing process of the blade and rotor



(a) the coupling, the motor and shaft; (b) the gear; (c) an initial frame; (d) the tray; (e) the complete lemon cutting machine

Figure 7 Assembly process of the complete prototype

2.3.4 The cutting system

Manufacturing process of the blade and the rotor which are made of stainless-steel plate with the thickness of 2 millimeters, is shown in Figure 6. First of all, the stainless-steel plate is cut into two circular disks with a diameter of 23 centimeters as shown in Figure 6a. Disks have a centrally punched hole with a diameter of 3 centimeters before drawing a layout of 8 blades on the disk. Secondly, another stainless-steel plate with the length of 18 centimeters and the width of 4.3 centimeters is cut to create small rectangular lines of 0.8 centimeters in width and 8 centimeters in length as shown in Figure 6b. Thirdly, the plate in Figure 6b is folded to create a blade from the layout in Figure 6a before being assembled to make one half of the rotor as shown in Figure 6c. Finally, the half of the rotor is covered by the circular disk plate from Figure 6a to construct the complete rotor as shown in Figure 6d.

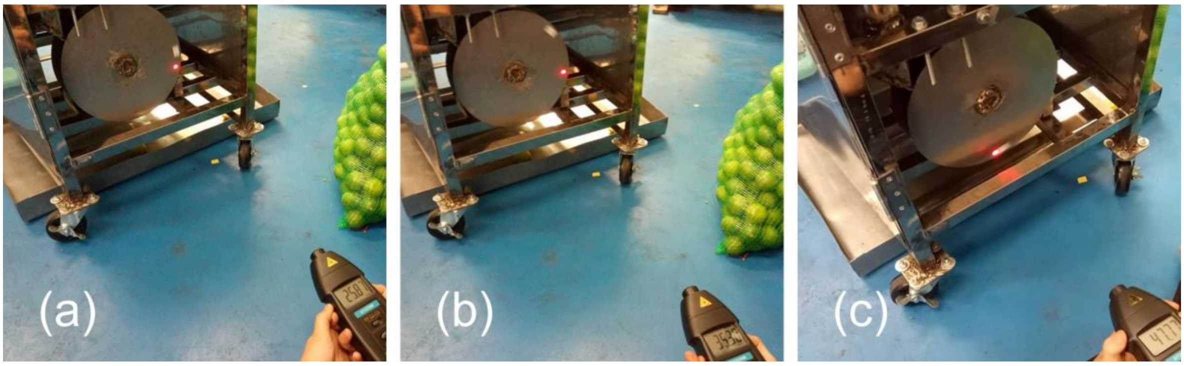
2.4 Prototype assembly

First of all, the coupling, the motor and the shaft are connected as shown in Figure 7a. Second, the complete rotor is combined to the gear as shown in Figure 7b. Third, all components and standard equipment such as the coupling and the switch are assembled together to create the initial frame as shown in Figure 7c. Then, the initial frame is covered by a stainless-steel sheet. Finally, after putting the tray on the top as shown in Figure 7d, the complete lemon cutting machine is presented in Figure 7e.

2.5 Design of experiments

2.5.1 Testing parameters

In order to test the performance of the lemon cutting machine, the speeds of the electric motor in a unit of rounds per minute (rpm) are varied by 25 rpm, 35 rpm and 47 rpm. The speeds of the motor are measured by the photo tachometer as shown in Figure 8a for 25 rpm, Figure 8b for 35 rpm and Figure 8c for 47 rpm. In order to obtain an average value of accuracy, the experiments are performed 3 times.



(a) 25 rpm; (b) 35 rpm; (c) 47 rpm

Figure 8 Rotor speed measurement using a photo tachometer

2.6 Shear force on a lemon

Shear force is a force required by a knife to cut a lemon into two halves. In order to measure the shear force, a special jig fixture is designed to hold a lemon as shown in Figure 3. The shear force can be calculated by the following formulas.

$$\tau = \frac{F}{A} \quad (5)$$

$$\tau = \frac{F}{2\pi\frac{D^2}{4}} \quad (6)$$

$$\tau = \frac{2F}{\pi D^2} \quad (7)$$

where, F is the cutting force or shear force for a lemon (N) which is parallel to a surface of a lemon, A is the cross-sectional area of a lemon fruit (m^2), D is the diameter of a lemon and τ is the shear stress (Pa).

2.6 Machine performance

The performance of the lemon cutting machine is defined as the ability of the machine to cut a number of lemon fruits in a particular time. Therefore, it can be calculated by the following equation.

$$M_p = \frac{N_f}{T} \quad (8)$$

Where, M_p is the machine performance (fruit min^{-1}), N_f is the number of cutting lemons (fruit) and T is time (minute).

3 Results and discussion

3.1 Gear testing

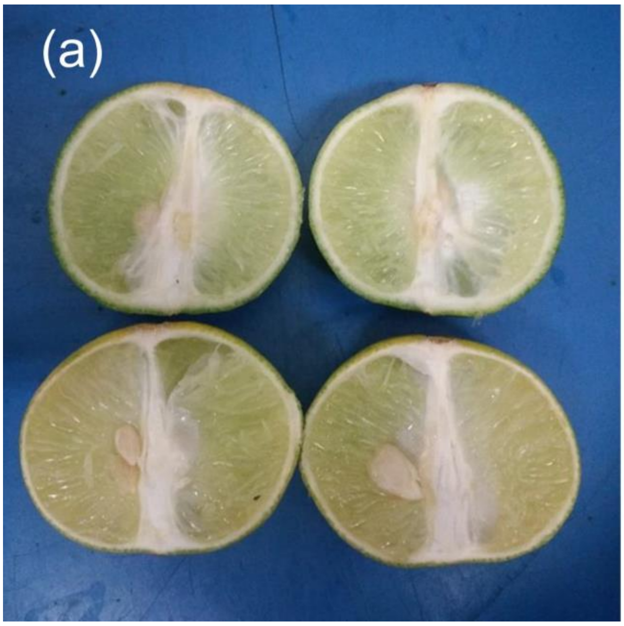
In order to ensure accuracy of the gear reduction ratio of 1:30, the gear is tested by the photo tachometer as shown in Figure 2. First, a small white sticker is placed on the end of the gear shaft to reflect light to the tachometer. Then, the gear shaft is connected to the electric motor and operated at 1500 round per minutes (rpm). In this test, if the gear is reliable, the shaft revolution should be reduced to 50 rpm. Finally, the digital tachometer is held by hand and is parallel to the ground level at the position of white sticker. As a result, a monitor of digital tachometer displays the value of 50.07 rpm as shown in Figure 2. This means that the gear in this study can provide the accuracy of 99.86%. Therefore, the reliable of the gear is validated.

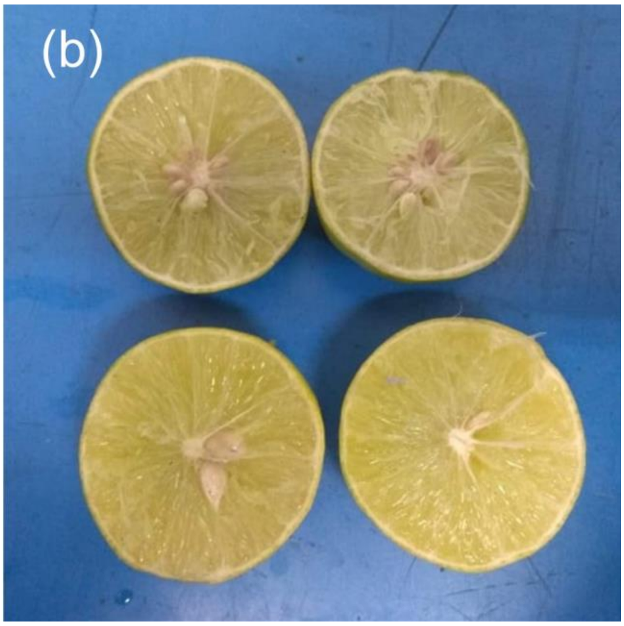
3.2 Cutting force testing

Figure 3 shows the apparatus for cutting force testing which is developed and adapted from a machine for shearing force measurement of a palm bunch (Mueangdee et al., 2021). In order to test a cutting force, a lemon is placed on a jig fixture that is a hollow shape with long grooves in the middle on two sides. The long grooves in the middle can permit a knife moving though a lemon fruit without damaging the knife blade. The knife blade is fixed on a holder which is attached by the load cell. A black electric cable is connected between the load cell and a monitor for transmitting a signal. The upper part of the load cell is connected with a metal base which is held by two springs to stabilize the system. A hydraulic jack is put between the metal base and the machine beam for producing a reaction force to the knife blade. In order to test a cutting force, a lemon is cut by a knife in two directions which are on axis as and off axis as shown in Figures 9a and 9b, respectively. The testing results are shown in Tables 3, 4 and Figure 10. Product of lemons after the process of cutting force testing for off axis (a) and on axis (b) is demonstrated in Figure 9.

It can be clearly seen that the average cutting force in the case of on axis is 47.38 N as shown in Table 3. This result seems to be a similar direction with a study elsewhere (Ihueze and Mgbemena, 2017) on a compressive axial loading of orange fruits showing a range of forces between 19 N and 83 N which are equal to the average compressive force of 45.55 N. In addition to compare the result with other fruits, a range of shearing force for a banana between 30.70 N and 56.80 N which are equal to the median value of 43.75 N reported by Jahanbakhshi et al. (2020b). In contrast, the average cutting force of a cantaloupe is 108.3 N which is higher than that of lemons (Jahanbakhshi et al., 2019). However, the maximum cutting force of some vegetables such as carrots for 44.40 N, and snake melons for 39.21 N (Jahanbakhshi et al., 2018; Jahanbakhshi, 2018) demonstrates comparably with lemons in this study.

In the case of off axis as shown in Table 4, the average cutting force is reduced considerably to 35.77 N which is lower than that of on axis by 11.61 N. This is because in the middle axis of fresh lemons has a long white axis as shown in Finger 9a that requires more shearing force for cutting into two halves.





(a) on axis; (b) off axis

Figure 9 Product of lemons after the process of testing the cutting force

Table 3 Cutting force testing results for on axis

Sample no.	Diameter (mm)	Cutting force (N)
1	39	56.90
2	39	51.01
3	41	56.90
4	40	55.92
5	38	51.01
6	41	53.96
7	38	57.88
8	38	45.13
9	40	44.15
10	39	48.07
11	39	58.86
12	39	51.01
13	40	43.16
14	38	45.13
15	41	48.07
16	39	47.09
17	39	37.28
18	40	36.30
19	39	45.13
20	39	41.20
21	38	35.32
22	38	52.97
23	38	51.99
24	41	44.15
25	38	45.13
26	38	44.15
27	39	45.13
28	40	38.26
29	37	39.24
30	38	51.01
Average	39.03	47.38

Table 4 Cutting force testing results for off axis

Sample no.	Diameter (mm)	Cutting force (N)
1	40	36.30
2	37	35.32
3	38	35.32
4	38	35.32
5	40	32.37
6	40	37.28
7	38	37.28
8	37	33.35
9	40	35.32
10	37	38.26
11	38	37.28
12	39	36.30
13	41	38.26
14	39	34.34
15	38	36.30
16	37	36.30
17	40	37.28
18	38	36.30
19	40	38.26
20	37	37.28
21	37	33.35
22	39	35.32
23	38	36.30
24	39	34.34
25	40	36.30
26	37	35.32
27	37	34.34
28	42	35.32
29	38	33.35
30	39	35.32
Average	38.60	35.77

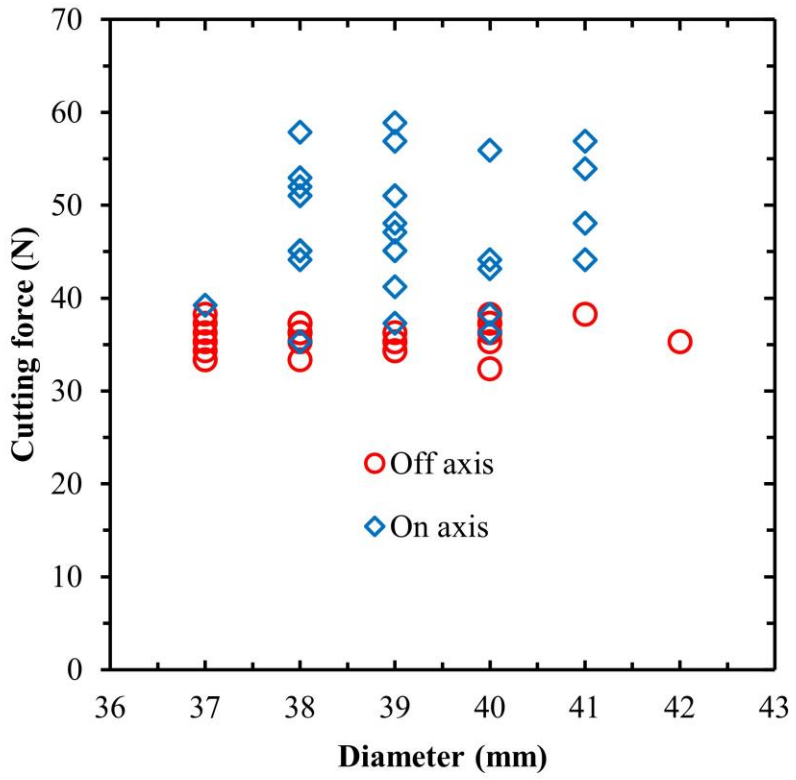


Figure 10 Cutting force testing for off axis and on axis

The relation between a cutting force and a diameter of lemon is shown in Figure 10. It can be clearly seen that in the case of on axis, cutting force is significantly higher than that of off axis. When a range of diameters between around 37 and 40 millimeters, there are some considerable overlaps in cutting forces between on axis and off axis. However, from a diameter of 41 millimeters, all of on axis demonstrates over off axis. In addition, the distribution of lemon diameters for off axis in this study is similar to studies elsewhere (Hrishikesh et al., 2014) as shown in Figure 11.

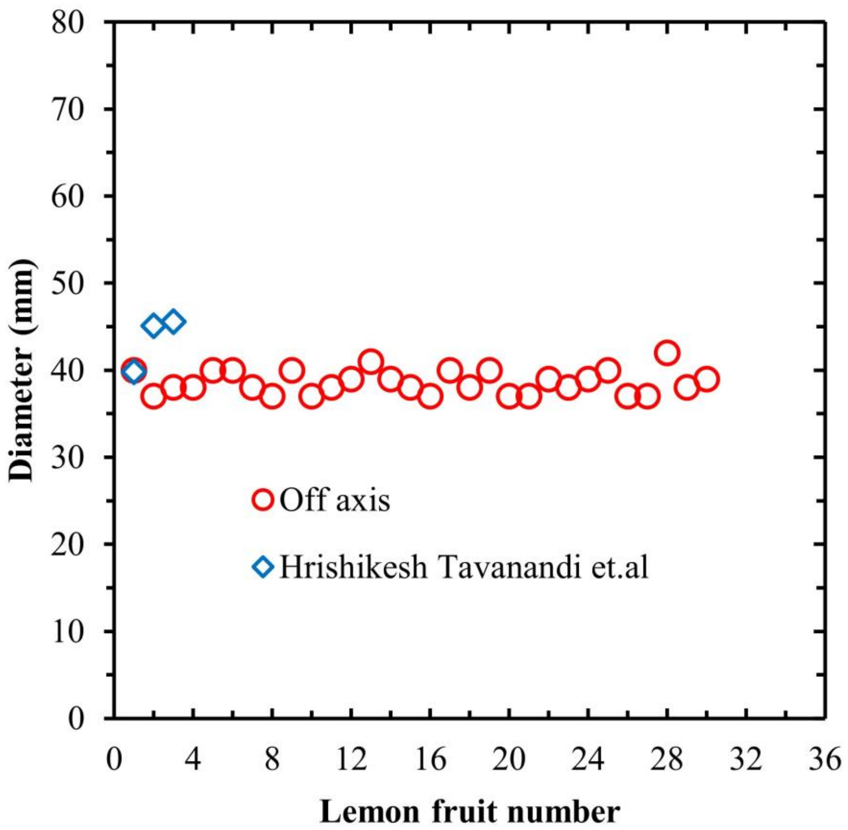


Figure 11 Distribution of lemon diameters in the case of off axis compared with the study by Hrishikesh et al. (2014)

3.3 Prediction of lemon shear stress

Regarding the experimental data on a cutting force and a diameter of lemons as shown in Tables 3 and 4, the experimental shear stress of lemons is calculated by Equation 7. An average cutting force in the case of off axis is considerably stable at 35.77 N as shown in Table 4 and Figure 10. Therefore, it is reasonable to trial this value for shear stress estimation by substituting for Equation 7 as a constant. As a result, when a lemon diameter provided, shear stress occurred on a surface of a lemon can be predicted as Equation 9.

$$\tau = \frac{71.55}{\pi D^2} \quad (9)$$

The comparison between experiment and prediction is shown in Figure 12. The results show that shear stress is approximately 17 kPa for a lemon diameter of 37 millimeters. After that it reduces gradually to around 13 kPa for a dimeter of 42 millimeters. It can be clearly seen that a trend in sheer stress between experiment and prediction is decreased in the same direction as demonstrated in Figure 12 with an accuracy of 96.50% as shown in Figure 13. However, due to an irregular shape of lemons in the case of on axis as shown in Figure 9a, thus leading to difficulty in calculation of sheared lemon surface arears. Therefore, in this case, shear stress cannot be estimated.

3.4 Machine performance testing

3.4.1 Manual lemon cutting

Table 5 shows the manual cutting of lemons by three persons. The results show that lemons can be cut by three persons as an average of 14.22 fruits per minute.

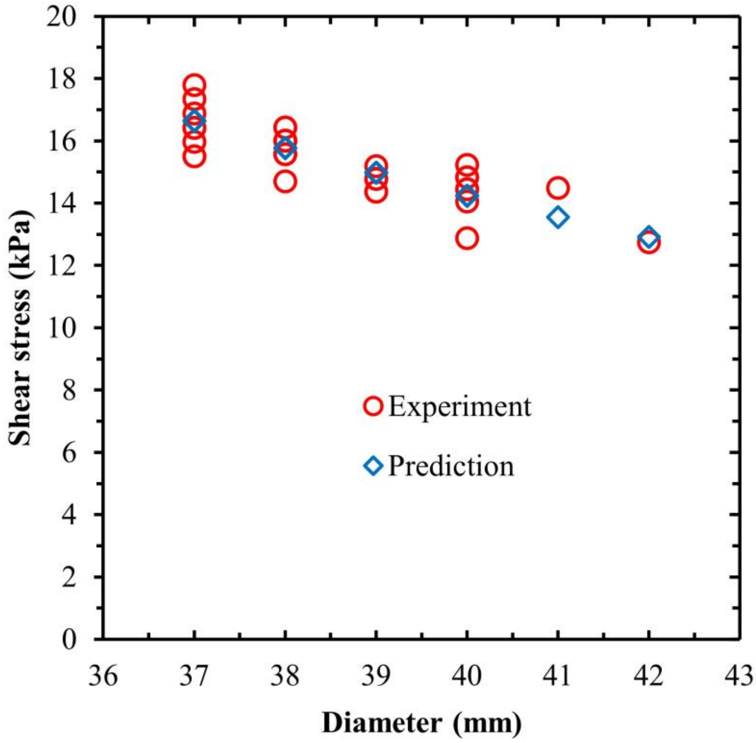


Figure 12 Shear stress of lemons in the case of off axis

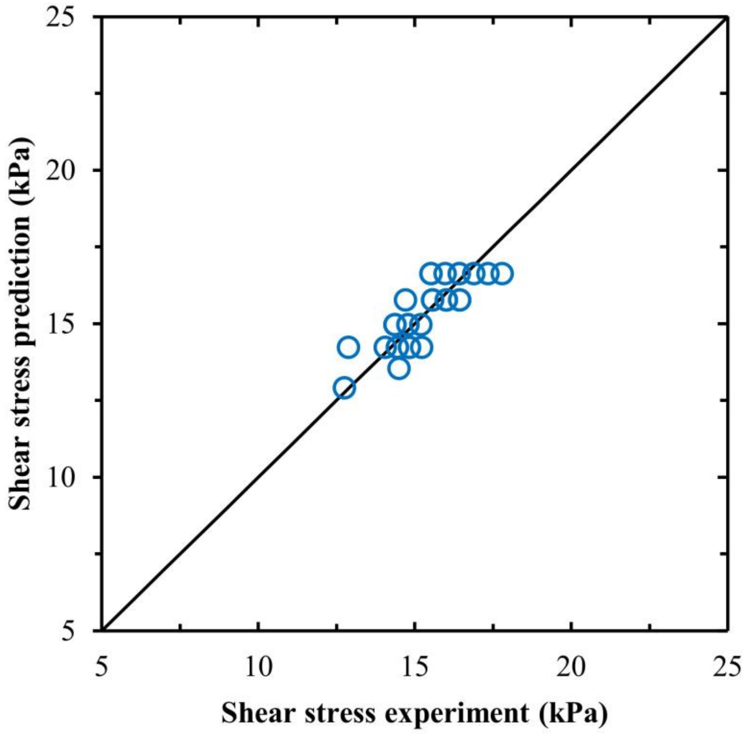


Figure 13 Shear stress of lemons between experiment and prediction in the case of off axis

Table 5 Manual lemon cutting by labour

Experiment no.	Person			Average (f min^{-1})
	1 (f min^{-1})	2 (f min^{-1})	3 (f min^{-1})	
1	12	11	15	12.67
2	14	14	16	14.67
3	15	14	17	15.33
Average (fruit/minute)	13.67	13.00	16.00	14.22

3.4.2 Lemon cutting by the machine

Table 6 and Figure 14 show the lemons cut by the machine. Product of lemons from the cutting process is shown in Figure15. For the rotor speed of 25 rounds per minute, the average amount of lemons cut by the machine is 23 fruits per minute. The failure of cut lemons were 5 fruits which are equal to 21.74% of total lemons. When increasing the rotor speed to 35 rounds per minute, the average of cut lemons increases to 38.67 fruits per minute. However, in this case, the failure of cut lemons decreased significantly to 4.33 fruits that were equal to 11.21% of total lemons. Even though, the highest average of cut lemon can be achieved by the rotor speed of 47 rounds per minute at 49 fruits per minute, the failure of cut lemons were significantly higher at 14.29 precents. A comparison of product quality between good and failure product of cutting lemons is shown in Figure 16. It can be discussed that the failure of cut lemons occurred when a lemon fruit is cut by a cutter not in the middle of fruit, thus leading to a change in lemon shape resulting in a thin side and a thick side as shown in Figure 16b.

Table 6 Lemon cutting by the machine

	Rotor speed (rpm)								
	25 rpm			35 rpm			47 rpm		
Experiment no.	f m^{-1}	Failure (f min^{-1})	Failure (%)	f m^{-1}	Failure (f min^{-1})	Failure (%)	f m^{-1}	Failure (f min^{-1})	Failure (%)
1	22	4	18.18	40	4	10.00	50	7	14.00
2	22	5	22.73	36	5	13.89	48	6	12.50
3	25	6	24.00	40	4	10.00	49	8	16.33
Average (f/min)	23.00	5.00	21.74	38.67	4.33	11.21	49.00	7.00	14.29

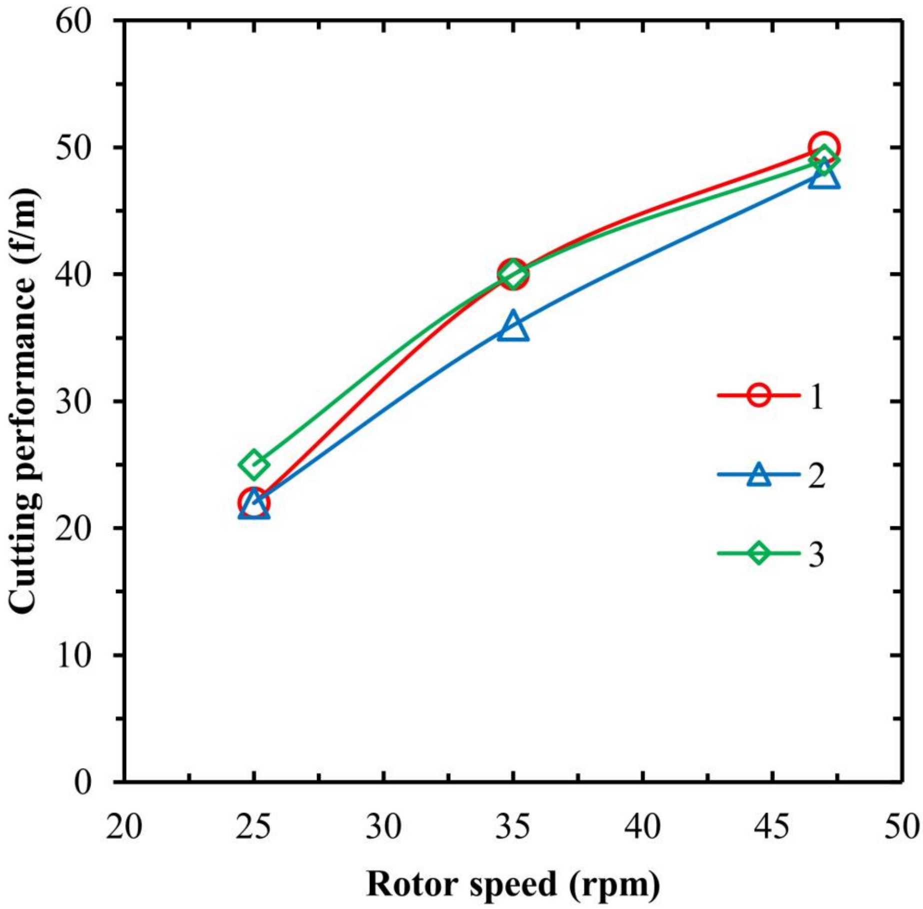


Figure 14 Cutting performance of the machine

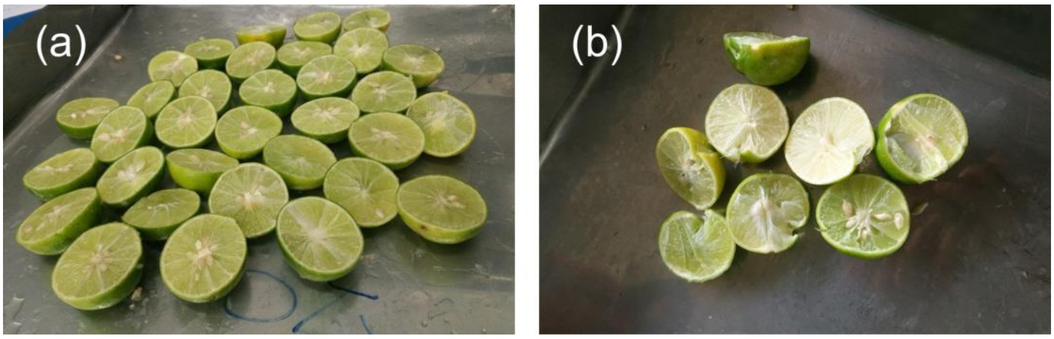
3.5 Analysis of machine capacity

The capacity of the lemon cutting machine in operation for one hour can be calculated by the average cutting of fruits per minute using Equation 8. In the case of the rotor speed at 35 rpm as shown in Figures 8b and 14, the machine can provide the capacity of 38.67 f min^{-1} which is equal to 2320 f h^{-1}. When increasing the rotor speed to 47 rpm, it results in the capacity of 49 f min^{-1} as shown in Figure 8c, the machine can exhibit the capacity of 2940 fruits or 5880 sides per hour compared with 1,200-5,040 fruits per hour from a study elsewhere (Hrishikesh et al., 2014). If the machine operates by 8 hours a day, it can provide 23,520 fruits or 47,040 sides. According to Table 5 for the average manual labour cutting of 14.22 f min^{-1} which is equal to 853 fruits per hour. Normally, a worker works 8 hours a day which is equal to 6,825 fruits without interruption in the cutting operation. However, in the real working condition, considering the fatigue of the human body, a worker cannot operate 8 hours continuously. Therefore, the machine can provide a higher capacity of 3.44 times when compared with one worker with using manual cutting.

3.6 Practical applications

Regarding the difficulty and the time-consumption concerned with cutting lemons by manual labour for a large scale of use in the small and medium food industry, a lemon cutting machine is designed and developed. It is a significant contribution to small businesses such as food manufacturers, restaurants, and hotels for processing lemons to be used as a basic ingredient for food and drink. In addition, it has potential for an expansion in a machine capacity for an industrial scale. Furthermore, it can be used as a prototype and benchmark for further design, research and development not only for processing lemons but also for cutting other types of fruits.

Figure 15 Product of lemons from the machine



(a) good product; (b) failure product

Figure 16 Lemon comparison after cutting process by the machine

3.7 Implication of future design and development

Regarding this research, a lemon can be fed continuously to the rotor under the natural gravity force based on designing of the incline tray. Therefore, to increase the machine capacity per minute, an automatic feeder system should be designed and developed to control the lemon feeding rate per minute in relation to an angular velocity of the rotor. However, there is an interesting suggestion, when increasing the feeding rate with the higher rotor speed, the failure of product would be one of significant factors that needs to be carefully considered to design the cutting process. In addition, the new design of the rotor offers different geometry that can provide a higher cutting efficiency which would be examined in the future.

3.8 Limitations

Limitations of this study are lemon size and the direction of cutting. The machine can operate to cut a range of lemon sizes between the diameter of 3 and 5 mm. In addition, the machine cannot cut lemons in the same direction for every fruit as shown in Figure 16, because it is dependent on the position of lemon fruits in the feeder pipe before feeding to the rotor.

4 Conclusions

The lemon cutting machine is designed, developed and tested as a prototype to use instead of a manual cutting by human labour. The results show that the average productivity of 14.22 fruits per minute can be obtained by the manual labour cutting of three volunteers. In contrast, the machine can provide the higher productivity level of 49 fruits per minute at 47 rpm. It can be clearly seen that the lemon cutting machine can exhibit the higher performance than that of manual cutting by 3.31 times. Percentages of production failure after cutting are 21.74%, 11.21% and 14.29% at the rotor speeds of 25 rpm, 35 rpm and 47 rpm, respectively. In terms of production failure, running the machine at 35 rpm can provide the lowest waste of 11.21%. As a result, an operating machine at 35 rpm can be an appropriate rotor-speed condition for this lemon cutting machine provided the good product of 88.79%. In addition, the shear stress prediction for cutting lemons provides the accuracy of 96.5%. The lemon cutting machine in this study has potential to be a benchmark for further design, research and development not only for lemon cutting but also for other types of fruit cutting machinery.

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