Study on the cardboard behavior during the vacuum picking process in automatic pantyhose packaging machine

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Abstract

This study presents a use case of Finite Element Method and comparative experimental studies on a subproblem in packaging machines. The variables in the vacuum picking system including baffle height, back pressure and friction between sheets are evaluated through simulations and experiments. It is found that baffle height, back pressure F and friction between sheets are all critical in successful operation of vacuum picking cardboards from in-feed magazine. This study is of some practical value for the implementation of vacuum picking board sheets from in-feed magazine on many types of packaging machinery.

Article Highlights

1. A proper baffle height is needed to facilitate feeding and avoid disorder and multiple feeds.
2. A appropriate magazine inclination angle is beneficial to close contact of the cardboards and avoiding plastic deformation.
3. The dynamic friction coefficient between the cardboards should be appropriate to facilitate feeding and avoid disorder and multiple feeds.

Keywords Cardboard · Vacuum picking · Baffle height · Back pressure · Friction

1 Introduction

In the pantyhose packaging process as shown in Fig. 1, there will be tension force on the pantyhose when it is wound on the cardboard and moves relatively. Minakov extended the classical Euler tension formula [1] to obtain the fabric tension on rough edge surface as formula (1)

$$T = (T_0 - Qv^2)e^{\mu\theta} + Qv^2 \quad (1)$$

here, T is the tension force at which the fabric leaves the edge surface, T_0 is the yarn tension when the fabric begins to wound on the edge surface, Q is the weight of the fabric per unit area, v is the velocity of the fabric, θ is the surrounding angle between the fabric and the edge surface, μ is friction coefficient between the fabric and the edge surface. Obviously, the pantyhose always keeps a tension state in the folding process, and the cardboard plays the role of shape retention and tension maintenance, which ensures the flatness of the pantyhose in the subsequent

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Fig. 1 Folding process of pantyhose

packaging process. Therefore, cardboard placing is important for automatic packaging machine.

Vacuum picking is widely used for sheet picking in practical industrial application. A specific case of pantyhose packaging is shown in Fig. 2, the magazine is inclined at a certain angle to ensure the close contact between the sucker and the cardboard stock under its own gravity. On the other hand, two baffles of a certain height are needed at the front end of the magazine to prevent the cardboards sliding down. The cardboard deforms to break away from the constraint of the baffles under the action of the sucker. Considering that the cardboard used in packaging is

usually made of paper whose stiffness and elasticity are limited, the design of the picking system is the key to avoid failures, damages and multiple feeds in the vacuum picking process.

Some research studied the mechanical performance of sheets with the help of relevant elasticity theory and special designed experiments. Biancolini [2] studied the buckling behavior of corrugated paper packages by means of an experimental and theoretical analysis. Mechanical behavior of paperboard was firstly evaluated experimentally, then a local geometry FEM model, able to reproduce buckling loads obtained experimentally in the standard

Fig. 2 Scheme of vacuum picking

edge compression test with a very good accuracy, was developed to accurately predict the experimental data of incipient buckling observed during the standard box compression test. Wen [3] tested four kinds of thickness paperboard according to longitudinal and transverse direction respectively, the curve of flexure load deflection was analyzed, the relationship between flexure yield load, flexure strength of face sheet, shear strength of core and thickness and direction of paperboard was studied. Hua [4] investigated the edge effect and the influence on edgewise compressive strength of the two sandwich paperboards by experimental and numerical simulation methods, constructed the finite element models of corrugated fiberboard and honeycomb paperboard and the edge enhancement finite element models of the two paperboards. Pathare [5] investigated the effects of different storage conditions on the mechanical performance of two types of ventilated packaging, the effects of storage condition on moisture content of package was also studied. Luong [6] estimated the repetitive shock induced damages leading to cumulative fatigue on corrugated cardboard boxes experimentally and numerically, a finite element approach is proposed using an elastoplastic homogenization model for corrugated cardboard to computationally determine the damage boundary curve. Wang [7] investigated the bending fatigue behavior of B-flute and C-flute corrugated paperboard under cycle loading through three-point bending fatigue test. Li [8] experimentally and numerically investigated the interface fracture behavior in pure crack opening mode and sliding mode in the paperboard creasing and folding process. Guo [9] evaluated the dynamic shock cushioning characteristics and vibration transmissibility of X-PLY corrugated paperboards by a series of experimental studies on the drop shock tester and vibration tester, the experimental formulas of dynamic cushioning curves, and the analysis of peak frequencies, vibration transmissibility and damping ratios were established. Park [10] carried out vibration transmissibility test and drop shock test for the transmissibility-frequency curve and dynamic cushion curve of corrugated fiberboard. Bivainis [11] used a standard triangular prism, corrugated paperboard fixation plates and a universal tension-compression machine to investigate the impact of corrugated paperboard structure and other parameters on the puncture resistance of corrugated paperboard.

Rather than the features of fiber-based material including corrugated paperboard, paperboard, corrugated fiberboard and honeycomb paperboard studied in the literature above, in this paper it regards cardboard placing as a systematic operation, and focuses on the behavior of the cardboard during the specific vacuum picking process. Baffle height, back pressure and friction between sheets

are taken into consideration as the three main variables of the system which may be critical in successful operation of cardboard picking. These variables in the vacuum picking system are evaluated through simulations and experiments. The objective is to analyze the cardboard behavior during the vacuum picking process and the interactions of baffle height, back pressure and friction in successful operation of cardboard picking.

This paper is organized as follows. After the introduction of the related literature in Sect. 1, the method to establish and solve the Finite Element Model are studied in Sect. 2. Then the Finite Element Model is used to evaluate the variables of the system in Sect. 3. In Sect. 4, experiments are conducted to verify the simulations. In Sect. 5, the results of the experiments and simulations are compared with results presented in relevant papers. In Sect. 6, some conclusions are given.

2 Modeling and solution

The cardboard deforms and separates itself from the constraint of the baffles under a certain adsorption force. In the following, the relationship between the cardboard behavior and the variables of the system is evaluated through simulations.

2.1 Establishment of the model

The solid model is established as shown in Fig. 3. As listed in Table 1, the dimensions and property values of the cardboard, baffles, stock and suckers are consistent with the real ones, Shell 181 element and Solid185 element of ANSYS are chosen to mesh them. The type of surface contact between the cardboard and the baffles is no separate, which keeps cardboard in close contact with the baffles during the picking process. The type of surface contact between the cardboard and the suckers is bond, which ensures no relative move during the picking process. The type of surface contact between the cardboard and the stock is standard, which allows the two to be separated.

2.2 Solution of the model

The method and convergence criterion are the key to solve this contact problem.

2.2.1 Method

Assume that K is the stiffness matrix of the picking system, u represents the corresponding displacement of the picking system while q is the exerted load, its variation of potential energy is

Fig. 3 Model of the simulations **Table 1** Property values

Solid model	Cardboard	Baffle	Stock	Solid model	Sucker
x-dimension(mm)	220	2, 3, 4, 5, 6, 7, 8	220	Diameter(mm)	35
y-dimension(mm)	160	160	160		
Thickness(mm)	0.46	4	92	Distance ratio	0.3
Elastic modulus (GPa)	2E-3	210	210	Elastic modulus (GPa)	7.84E-3
Poisson's ratio	0.353	0.269	0.269	Poisson's ratio	0.47
Meshing	Shell181	Shell181	Shell181	Meshing	Solid185

$$\delta \Pi = [K]\{u\} - \{q\} \quad (2)$$

In order to achieve the balance of the picking system [12–17], there should be the following relationship

$$[K]\{u\} = \{q\} \quad (3)$$

If the load is divided into a series of components and exerted gradually, the stiffness matrix is amended at each step, there will be the new equilibrium equation for the picking system as

$$[K_i]^T \{\Delta u_{i+1}\} = \{\Delta q_{i+1}\} \quad (4)$$

$$\{u_{i+1}\} = \{u_i\} + \{\Delta u_i\} \quad (5)$$

here Δu_i is the displacement increment reflecting the deformation of the picking system. In order to eliminate the cumulative deviation, it is still necessary to amend Eq. (4) as

$$\{u_{i+1}\} = \{u_i\} - \omega_i [K_i]^{-1} \left([K_i]^{-1} \{u_i\} - \{q\} \right) \quad (6)$$

here ω_i is the iteration coefficient.

2.2.2 Convergence criteria

When the method is adopted to solve the nonlinear contact problem, the convergence of the iteration needs to be considered at every step [18–22]. Assume $\{q_i\}$ is the exerted load, $\{p_i\}$ is the force vector balanced with internal force, then $\{q_i\} - \{p_i\}$ is the unbalanced force. Let λ_F represents convergence tolerance of unbalanced force, then the convergence of iteration may be judged through the comparison of the unbalanced force and exerted load as follows

$$\{q\} - \{p_i\} \leq \lambda_F \{q\} \quad (7)$$

here $\{p_i\} = [K_i]\{u_i\}$.

3 Evaluation of the variables of the system

In the vacuum picking process, the picked cardboard slides relatively to the stock and the baffles under the action of the suckers, so the dynamic friction between the contact surfaces are considered. Besides, the variables of the system including baffle height, back pressure are analyzed through the following simulations.

The coordinate system shown in Fig. 4 is established to facilitate the following discussion. Here, L is the length of the cardboard, H is its width, L_v is the distance between the position line of the suckers and the side of the cardboard with zero abscissa. The baffles respectively constrain the cardboard in z -direction.

In the simulations, the baffles are fixed in all directions, while the stock may move in z -direction. The central points of the suckers are selected as their control node Pilot, and the loads represented by z -direction displacements are exerted by them step by step. The cardboard is bent gradually, resulting shrinking along the x -direction.

3.1 x-dimension baffle height

3.1.1 Settings

The height of the baffles is 5 mm, the dynamic friction coefficient between the cardboard and the baffles is 0.6, the dynamic friction coefficient between the cardboard and the stock is 0.3, the magazine is inclined at an angle of 30° , the distance between the position line of the suckers and the side of the cardboard with zero abscissa is $L/2$.

3.1.2 Results

The Von Mises stress and x -direction displacement of the cardboard are shown in Fig. 5. They are symmetrically distributed with respect to the position line of the suckers.

Therefore, six evenly distributed points of the cardboard at $x=0$ are selected and marked as A, B, C, D, E, F. The y -direction intervals between adjacent points are $H/5$, and the coordinates of point A are (0, 0, 0). Taking 1 mm as load gain, the loads are exerted by the Pilot of the suckers. The x -direction displacements of the six points corresponding to each load are picked up to calculate the relative deviations. It can be seen from Table 2 that the maximum relative displacement deviation is only 0.26%, so the x -direction displacement of the observed side may be represented by the average displacement of the six points.

In this way, the x -direction displacements of the observed side under the variety of loads are derived through simulations. In order to intuitively analyze the simulation results, the data is dotted in a coordinate system as shown in Fig. 6a. It can be seen that a quadratic polynomial curve is chosen to fit the dots and the fitting degree of the curve is good. Therefore, the relation between the x -direction displacements of the observed side and the loads exerted by the Pilot of the suckers may be further expressed by a quadratic polynomial as follows

$$U(x) = -0.00625Q(z)^2 + 0.5Q(z) \quad (8)$$

here $U(x)$ represents the x -direction displacements of the observed side, $Q(z)$ is the loads exerted by the Pilot of the suckers.

Similarly, the z -direction displacements of the cardboard at $x=L/5$ under the variety of loads are derived through

Fig. 4 Coordinate system

(a) Von Mises stress

(b) x-direction displacement

Fig. 5 Distribution of stress and x-direction displacement when $L_y = L/2$ **Table 2** Relative displacement deviations when the load is 10 mm

Points	A	B	C	D	E	F
Relative deviations	0	0.25%	0.24%	0.26%	0.255%	0.252%

(a) x-direction displacements under different loads

(b) z-direction displacements under different loads

Fig. 6 Displacements under loads

simulations. The data is dotted in a coordinate system as shown in Fig. 6b. It can be seen that three segmental curves are chosen to fit the dots and the fitting degree of the curves is good. Therefore, the relation between the z-direction displacements of the cardboard at $x = L/5$ and the loads exerted by the Pilot of the suckers may be further expressed by Piecewise functions as follows

$$\left\{ \begin{array}{ll} U(z) = 0.01Q(z)^2 & 0 \leq Q(z) \leq 9.5 \\ U(z) = 0.2Q(z) - 1 & 9.5 < Q(z) \leq 28.9 \\ U(z) = -0.01(Q(z) - 40)^2 + 6 & 28.9 < Q(z) \leq 40 \end{array} \right\} \quad (9)$$

here $U(z)$ represents the z-direction displacements, $Q(z)$ is the loads exerted by the Pilot of the suckers.

Fig. 7 Maximum Von Mises stress at each step

By analyzing the stress distributions of the cardboard under the variety of loads, it is found that the distribution areas of the maximum Von Mises stress are basically stationary, but its values change. It can be seen from Fig. 7 that the maximum Von Mises stress of the cardboard rises with the increase of the loads, while the yield stress of the cardboard itself is constant 18.07 MPa. If the maximum Von Mises stress of the cardboard exceeds its yield stress, the cardboard will undergo plastic deformation. So, it should be ensured that the cardboard can break away from the constraint of the baffles when the maximum Von Mises stress of the cardboard is still less than its yield stress. That is to say, the x-dimension baffle height of the baffles should be smaller than the x-direction displacement of the observed side at the beginning of yielding deformation. Considering the material specifics of the cardboard, the yield stress of the cardboard cannot be utilized to the maximum, so in practical design it is usually multiplied by a coefficient whose value is smaller than 1.

3.2 Back pressure

3.2.1 Settings

When the magazine is inclined at a certain angle, the stock will exert back pressure on the cardboard to be fed due to its own gravity. So even back pressure is exerted on the

stock, its values are listed in Table 3. The dynamic friction coefficient between the cardboard and the baffles is 0.6, the dynamic friction coefficient between the cardboard and the stock is 0.3, the x-dimension heights of the baffles are 2 mm, 3 mm, 4 mm, 5 mm, 6 mm, 7 mm and 8 mm respectively, the inclination angles of the magazine are 30°, 45° and 60° respectively.

3.2.2 Results

The z-direction displacements of the cardboard to be fed at $x = L/2$ under the effect of the gravity are derived through simulations. The data is dotted in a coordinate system as shown in Fig. 8. It can be seen from Fig. 8 that the z-direction displacements of the cardboard to be fed increase with the decrease of the x-dimension baffle height when the inclination angle of the magazine is constant, and the z-direction displacements of the cardboard to be fed increase with the increase of the inclination angle of the magazine when the x-dimension baffle height is constant.

It can be inferred that a certain inclination angle of the magazine is beneficial to the close contact between the cardboard to be fed and the suckers, but the z-direction displacements of the cardboard to be fed will expand. It will lead to plastic deformation of the cardboard if the inclination angle is large or the storage

Table 3 Back pressure values corresponding to inclination angles

Inclination angles	30°	45°	60°
Back pressure	$6.96 \times 10^{-4} \text{ N/mm}^2$	$9.84 \times 10^{-4} \text{ N/mm}^2$	$1.208 \times 10^{-3} \text{ N/mm}^2$

Fig. 8 Inclination angles vs z-direction displacements

time is long. The baffles should be as narrow as possible to facilitate feeding, but at the same time it will lead to z-direction displacement expansion of the cardboard to be fed under the action of gravity, even plastic deformation after a long storage time.

3.3 Friction

3.3.1 Settings

The inclination angle of the magazine is 30° , the x-dimension baffle height is 5 mm, the z-direction load exerted by the suckers is 10 mm, the position line of the suckers is at $x = 2L/5$, the dynamic friction coefficient between the cardboard and the baffles is 0.6, the dynamic friction coefficients between the cardboard and the stock are 0.2, 0.3, 0.4, 0.5, 0.6, 0.7 and 0.8 respectively.

3.3.2 Results

The x-direction displacements at $x=0$ and z-direction displacements at $x=L/5$ of the cardboard to be fed is derived through simulations. The data is dotted in a coordinate system as shown in Fig. 9. It can be seen from Fig. 9 that with the increase of the dynamic friction coefficient between the cardboard and the stock, the x-direction displacements of the cardboard to be fed decrease, while the z-direction displacements increase. It can be inferred from Figs. 6 and 7 that the maximum Von Mises stress of the cardboard rises with the increase of the z-direction displacements. Therefore, in order to ensure that the cardboard break away from the constraint of the baffles before yielding deformation, the dynamic friction coefficient between the cardboards should not be too large. On the other hand, if the friction coefficient between the cardboards is too small, it may cause the cardboard to slide down under the action of gravity, resulting in multiple feeds or disorder.

Fig. 9 Displacements when friction coefficient varies

Fig. 10 Experimental platform

4 Experiments

Experiments are carried out on the experimental platform shown in Fig. 10 to verify the above simulation methods and simulation results. The positioning module is a DTR-T series robot which realizes precise control and cooperative action of x , y and z axes to locate specific points. The displacement sensor which is installed on the z -axis mounting base of the positioning module adopts a LK-G series laser displacement sensor to measure the z -direction displacements of the observed points in the cardboard placing process. The loading module is installed on the z -axis mounting base of the positioning module and composed of power element, linear transmission element, suckers and rack. The power element is a subdivided stepping motor, the linear transmission element is a compact ball screw pair, the rack is made of aluminum parts and the SMC suckers are made of rubber. With the help of the stepping motor, z -direction loads are exerted to the cardboard step-by-step by the loading module. The clamping module is mainly composed of bottom plate and the baffles. The bottom plate is made of aluminum workpieces with good surface quality and tilted at a certain angle. The baffles are made of white transparent acrylic plate so as to be easy for visual acquisition. The pre-tightening spiral spring together with screws is installed between the baffles and the bottom plate to adjust the pressure. The computer vision module which is composed of visual acquisition components and mounting racks detects the x -direction displacements of the cardboard. During the cardboard picking process, the loading module exerts z -direction loads to the cardboard and the computer vision module

takes images of the observed side. The images are collected by the data acquisition module and then processed on PC to calculate the x -direction displacements of the observed side.

The same settings as the above ANSYS simulation process are used to carry out the experiments, and the same data processing methods as the simulations are adopted. The temperature in the experiment room is constantly kept at 24 °C by the air conditioner, the humidity in the experiment room is 60%, and the moisture content of the board is 8%. No airflow is directed to the working area of the experimental platform.

4.1 Experiments of loading

In order to compare the experiment results and simulation results more intuitively, they are dotted in the same coordinate system. When the x -dimension baffle height of the clamping module is 5 mm, the dynamic friction coefficient between the cardboard and the baffles of the clamping module is 0.6, the dynamic friction coefficient between the cardboard and the stock is 0.3, the clamping module is inclined at an angle of 30°, the distance between the position line of the suckers and the side of the cardboard with zero abscissa is $L/2$, the experiment results and simulation results are shown in Fig. 11a and b. When the inclination angle of the clamping module is 30°, the x -dimension baffle height of the clamping module is 5 mm, the z -direction load exerted by the suckers of the loading module is 10 mm, the position line of the suckers is at $x = 2L/5$, the dynamic friction coefficient between the cardboard and the baffles of the clamping module is 0.6,

Fig. 11 Comparison of experiment results and simulation results

the dynamic friction coefficients between the cardboard and the stock are 0.2, 0.3, 0.4, 0.5, 0.6, 0.7 and 0.8 respectively which are achieved by using the corresponding cardboards, the experiment results and simulation results are shown in Fig. 11 c and d. It can be seen that the experiment results are very close to the simulation results.

4.2 Experiments of cardboard picking

In order to further verify the results of the simulations and experiments above, the experiments of cardboard picking are carried out on the above experimental platform.

(1) x-dimension baffle height

4.2.1 Settings

The position line of the suckers is at $x=L/2$, the inclination angle of the clamping module is 30° , the dynamic friction coefficient between the cardboard and the baffles is 0.6, the dynamic friction coefficient between the cardboard and the stock is 0.3, the x-dimension baffle heights are 10 mm, 20 mm, 25 mm and 35 mm respectively.

4.2.2 Results

The picking operation is repeated 200 times respectively, the results of the operation are defined as picking-out (success, damage, disorder and multiple feeds) and not-picking-out, as shown in Fig. 12. It can be seen that the ratio of picking-out increases with the decrease of the x-dimension baffle heights when they are less than 25 mm, but the ratio of disorder and multiple feeds increases slightly too. The reason is that small x-dimension baffle heights are beneficial to absorption of the cardboards, at the same time, they will cause larger z-direction displacements, even lead to plastic deformation. The ratio of picking-out is very low and the ratio of damage is very high when the x-dimension baffle heights are greater than 25 mm. The reason is that the maximum stress exceeds its yield stress when the cardboard breaks away from the constraint of the baffles.

(2) Friction

4.2.3 Settings

The position line of the suckers is at $x=L/2$, the inclination angle of the clamping module is 30° , the x-dimension

Fig. 12 Results of the operation when the x-dimension baffle heights vary

baffle height is 5 mm, the dynamic friction coefficient between the cardboard and the baffles is 0.6, the dynamic friction coefficients between the cardboard and the stock are 0.2, 0.4, 0.6 and 0.8 respectively which are achieved by using the corresponding cardboards.

4.2.4 Results

The picking operation is repeated 200 times respectively, the results of the operation are defined as picking-out (further divided into success, damage, disorder, multiple feeds) and not-picking-out, as shown in Fig. 13. It can be seen that the ratio of picking-out increases with the decrease of the dynamic friction coefficients, but the ratio of disorder and multiple feeds increases slightly too. The reason is that small dynamic friction coefficients are conducive to the cardboard to break away from the constraint of the baffles, at the same time, they will cause the cardboard to slide under the action of gravity, resulting in disorder and multiple feeds. On the other hand, the ratio of picking-out decreases and the ratio of damage rises greatly with the increase of the dynamic friction coefficients. The reason is that the maximum stress exceeds

its yield stress when the cardboard breaks away from the constraint of the baffles.

5 Discussions

Biancolini [2], Hua [4], Luong [6] and Li [8] adopted Finite Element Method and experiments to study the yielding behavior of corrugated paper packages too, which is of some reference value from the perspective of research method for this paper. Wen [3], Wang [7] and Guo [9] tested the mechanical behavior of different paperboards, it inspired the experiment design of this paper. Moreover, the research results of the cited literature focus on the mechanical features of fiber-based material such as different paperboards. However, in this paper it studies the mechanical behavior of the cardboard during the specific vacuum picking process, considering the main variables of the system. The results reveal the role of baffle height, back pressure and friction in cardboard vacuum picking system, which is of some practical value for the implementation of vacuum picking board sheets from in-feed magazines on many types of packaging machinery.

Fig. 13 Results of the operation when the dynamic friction coefficients vary

6 Conclusions

Baffle height, back pressure and friction between sheets are all thought to be critical in successful operation of vacuum picking of sheet board. The cardboard whose stiffness and elasticity are limited is chosen as an example, and the variables in the vacuum picking system are evaluated through simulations and experiments. It is found that x-dimension baffle height, magazine inclination angle and dynamic friction coefficient interact with each other in successful operation of cardboard picking. This study is of some practical value for the design of vacuum picking of board sheets from in-feed magazines on many types of packaging machinery.

However, there are some limitations too. The automatic picking system of the lining plate which plays the role of shape retention and tension maintenance in the pantyhose packaging is studied, so only simple cardboard sheets are used in this paper. However, for the transferability of the results to wider applications, it should be noted that corrugated paperboards with incisions are more widely used in packaging field, so the pick and pull system for the paperboards with incisions still needs to be further studied in the future.

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Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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