Structural design of the working mechanism of the plastic cup stacking machine

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Abstract. The paper presents the structural design of the plastic cup stacking machine working mechanism. Based on the set requirements, a new working mechanism consisting of a cam/gear mechanism is proposed. The cam mechanism enables the change of the kinematic parameters of the working elements, and the gear mechanism provides the change of rotation direction of the output links. Based on the geometrical parameters of the cam mechanism, two principal solution of the working mechanism have been considered. Kinematic position analysis was performed and regulation characteristics have been formed. Increasing the motion range of the output shaft is approximately equal for both solutions, and the change is close to linear. However, one solution has smaller overall dimensions and more favourable values of pressure angle which makes it more efficient. The proposed solution is reliable, efficient and it has a high positioning accuracy that provides high accuracy and repeatability of movement of the output links without a time delay. The driving motor maintains a nominal number of revolution for different kinematic parameters of the machine working elements, which is a significant advantage.

1. Introduction
Thermoforming is a complex and very important industrial process in which the thermoplastic sheets or foils are processed into a new form by using heat and pressure/vacuum [1-3]. Thermoplastic materials are easily formed by heating, which makes thermoforming widely available [4]. It is the most important in the food and pharmaceutical industry for food and drug packaging, in electrical/electronic industry for enclosures and anti-static trays, in medical for radiotherapy masks, prosthetic parts, thermoplastic aligners, in automotive industry for wheel covers, wind and rain deflectors, in aircraft industry for interior trim panels and covers, in buildings for roof lights and door panels, in furniture industry for chair backs and kitchen panels, in nautics for boat hulls and dashboards, in graphic design and arts for coloring 3D printed surfaces [5-8], and in many other industries. Bearing in mind the high requirements in the food industry – productivity and flexibility of the system, special attention should be paid to the design and realization of product stacking machine.

The paper is structured as follows. The first section shows the research motivation. The second section presents the thermoforming process. Within the third section, the analysis of the conventional stacking machine has been performed and the requirements for realization are defined. The new working mechanism of the stacking machine is shown in the fourth section, kinematic position analysis has been performed and the regulation characteristics have been formed. The fifth section summarizes the paper contribution and outlooks future work.
2. Thermoforming process

The thermoforming process consists of three basic operations – foil manipulation, product forming and product manipulation [9]. Each operation is carried out on a particular module of the thermoforming machine – Figure 1. Product forming is performed on a working module of machine with a complex tool consisting of two parts – Figure 2. The upper part of the tool is immobile, and the lower one moves in accordance with the work process. When the movable part of the tool is in the lower position, the foil is retracted. The tool rises and leans the foil along the upper part of the tool. That is when product formation begins and the tool is idle. Products are separated from the foil by the tool performing the operation of separation by punching [10]. Remnants of foil are removed from the machine, while the products remain in the tool. At the end of the process, the products are taken with the appropriate mechanism from the tool or are ejected by pressure air and transported to the product manipulation module – stacking machine.

![Figure 1. Thermoforming machine: module 1 – foil manipulation, module 2 – product forming and module 3 – product manipulation.](image1)

![Figure 2. Thermoforming tool.](image2)

3. Plastic cup stacking machine

Plastic cup stacking machine presents the latest module of the thermoforming machine within which the formed products from the tool are accepted, transported and grouped for sorting and packaging. Figure 3 shows a conventional plastic cup stacking machine consisting of a mechanical system for power and motion transmission from the motor to the working elements of the machine, and a control system for changing the performance of the motor, respectively on-line change of the kinematic parameters of the working elements of machine. The drive motor (1) is coupled to the gear reducer (2) which is connected to the chain drive (3). The driven sprocket of the chain drive is attached to the

![Figure 3. Conventional plastic cup stacking machine: 1 – driving motor, 2 – gear reducer, 3 – chain drive, 4 – driving shaft, 5,6 – driving/driven sprockets, 7 – chain, 8 – panels, 9 – sensor, 10 – control box, 11 – formed products, 12 – tool, 13,14 – compressors and 15 – frame.](image3)
driving shaft (4). In addition, on the driving shaft is a fixed driving sprocket (5) that is linked to the driven sprockets (6) via chain (7). On the outside of the chain, the panels (8) that form the conveyor are attached. Sensor (9) send signals to the control box (10) which interprets them and, accordingly, performs the motor control. Formed products (11) are ejected from tool (12) by pressure air from the compressor (13) on the panels, respectively a conveyor that is inclined at an appropriate angle. Thus, the formed products – the cups, are rolling down the conveyor and falling into the holes of the panels. When the panel is positioned above the sensor – see Figure 3, the sensor detects the panel and sends the control box signal to stop the motor. The panels are then idle, and the compressor (14) ejects cups from one panel to the device located on the side or above the machine – the cycle is repeated periodically. The distance between the holes of the two adjacent panels is the working step of the machine.

By observing the machine, disadvantages are noticed. The basic is insufficient reliability of the control system that is not able to detect the panel every time and stop it exactly in the position of cup ejection. Therefore, it is not possible to achieve high positioning accuracy and repeatability of movements, which is essential for functionality of the machine, i.e. undisturbed process cycle. In addition, the machine should work with products of different shapes and sizes, whereby using panels with different holes for accepting formed products. Due to the different panel width, the working step of machine are changed, which requires the change of the kinematic parameters of the working elements. Existing system for motor control and on-line change of kinematic parameters of working elements is not reliable enough, precise and efficient, wherefore has been reconstructed.

4. Working mechanism

Figure 4 shows the new mechanical system of the plastic cup stacking machine – working mechanism, which solves the existing problems without electronic control system. It is based on two mechanisms that are interconnected. The first one is a cam mechanism that enables the change of the kinematic parameters of the working elements, and the second one is a gear mechanism that provides the change of rotation direction of the machine output links. The driving motor (1) is coupled with a gear reducer (2) and a chain drive (3). Driven sprocket of the chain drive and cam (5) are attached to the driving shaft (4). Constant between the cam and the follower (6) is provided by the torsion spring (6a). The follower is attached to the outer race of the one-way clutch (7), while the inner race of the one-way clutch is fixed to the shaft (8) – a common link of the cam/gear mechanism. Driving/driven gear pair (9,10) transmits the motion from the cam mechanism to the driven shaft (11). On the shaft ends are attached the driving sprockets (12) – output links, which through driven sprockets (13) and chain (14), move the panels (15). Screw/nut mechanism (17) enables the axial cam movement respectively adjusting the working step of machine. In this way, the transmission of power and motion from the
motor to the working elements of the machine is carried out. The proposed solution has a small number of movable parts and is easy to manufacture and assemble. By adequate selection of the cam profile, a very fine regulation of the kinematic parameters of the working elements can be achieved. The driving motor has always a nominal angular velocity for different kinematic parameters of the working elements, which is a significant feature.

4.1. Kinematic position analysis

Figure 5 shows the kinematic scheme of working mechanism respectively cam/gear mechanism. The cam mechanism, which enables the change of kinematic parameters of working elements, consists of input links – shaft (4) and cam (5), operating links – follower (6) i outer race of the one-way clutch (7), and output links – inner race of the one-way clutch (7) and shaft (8). The input links of the cam mechanism are coupled with a screw/nut mechanism (17) which allows an axial cam motion along the shaft. In this way, the working step of machine changes. Depending on the position of the cam on the shaft, the follower has a larger or smaller oscillation angle, resulting in certain kinematic effects. The gear mechanism, which provides the change of rotation direction of the output links, consists of the input links – shaft (8) and gear (9), and output links – gear (10), shaft (11) and sprockets (12). The common link of the cam/gear mechanism is shaft (8).

Figure 6 shows the cam – an irregularly frustum of a cone, with basic geometric parameters. The plane that cuts off the top of the cone is parallel to the base of the cone. One generating line of cone t-t is horizontal. In addition, for each plane cross section that is parallel to the base, a circle is obtained as a cross curve. The circle centers form the line s-s which with the horizontal constructs the angle $\delta$. This angle represents the geometric characteristic of the cam mechanism. The radii of the smaller and larger base of the cone are $\rho_0,\rho_2$. The follower is flat and with the cam creates a linear contact. The cam performs a continuous, and follower an oscillatory rotational motion. The follower is rigidly attached to the outer race of the one way clutch (3a) – Figure 7. Therefore, shaft 8 produces intermittent rotary motion in the same direction. Although the cam is spatial, the contact between the cam and the follower is realized in one plane as shown in Figure 6 – plane V. Therefore, the mechanism can be considered as a planar.

Using the method of an equivalent mechanism, the cam mechanism is represented by an equivalent lever mechanism – Figure 8, where: $a$ – the distance between the supports $O_1,O_2$ respectively the axial distance between the shaft of the cam and the follower, $r$ – the length of crank respectively the distance between the axis of cam rotation $O_1$ and the center of the cam curve A, $\rho$ – length of the link AB respectively the radius of the curvature of the cam and $b$ – the length of the segment $O_2B_1$. Depending on the geometric parameters, two variant solutions of the cam mechanism

Figure 5. Kinematic scheme of the working mechanism: 4 – driving shaft, 5 – cam, 6 – flat follower, 7 – one-way clutch, 8 – shaft, 9,10 – driving/driven gear, 11 – driving shaft, 12 – driving sprockets and 17 – screw/nut mechanism.

Figure 6. Cam with basic geometric parameters.
are possible – the first one shown in Figure 8 for $b < \rho$, and the second one in Figure 10 for $b > \rho$. In the first case, for $b < \rho$, the angle of the follower $\psi$ is determined as:

$$\psi_{(b<\rho)} = \psi_1 + \psi_2 + \frac{\pi}{2} \quad (1)$$

where:

$$\tan \psi_1 = \frac{O_1A \sin \varphi}{O_1A \cos \varphi + O_1O_2} = \frac{r \sin \varphi}{r \cos \varphi + a} \quad (2)$$

$$\tan \psi_2 = \frac{AC}{O_2C} \quad (3)$$

The parameters based on which the angle $\psi_2$ is determined are:

$$AC = \rho - b \quad (4)$$

$$O_2C^2 = O_2A^2 - AC^2 \quad (5)$$

where:

$$O_2A = \sqrt{O_2A^2 + O_2O_1^2 - 2O_2A \cdot O_2O_1 \cos (180^\circ - \varphi)} = \sqrt{r^2 + a^2 + 2ra \cos \varphi} \quad (6)$$

Inserting eqs. (4) and (6) in eq. (5), gives the distance between the point $O_2$ and $C$ as:

$$O_2C^2 = a^2 + r^2 + 2ra \cos \varphi - (\rho - b)^2 \quad (7)$$

Inserting eqs. (4) and (7) in eq. (3), gives the angle $\psi_2$ as:

$$\tan \psi_2 = \frac{\rho - b}{\sqrt{a^2 + r^2 + 2ra \cos \varphi - (\rho - b)^2}} \quad (8)$$

Finally, based on eqs. (2) and (8) the angle of the follower is obtained:

$$\psi_{(b<\rho)} = \arctan \frac{r \sin \varphi}{r \cos \varphi + a} + \arctan \frac{\rho - b}{\sqrt{a^2 + r^2 + 2ra \cos \varphi - (\rho - b)^2}} + \frac{\pi}{2} \quad (9)$$

In similar way, the angle of the follower $\psi$ for $b > \rho$ is defined as:
By differentiating eqs. (9) and (10), angular velocities and angular accelerations of the output links of the cam mechanism can be obtained. The difference of angles $\psi_{\text{max}}$ and $\psi_{\text{min}}$ represents the amplitude of the oscillatory motion of the follower respectively the rotation angle of the inner race of a one-way clutch that is directly proportional to the working step of the machine – Figures 11 and 12.

Now the angle $\Delta \psi$ is defined for $b<\rho$ and $b>\rho$:

$$
\Delta \psi_{(b<\rho)} = \psi_{\text{max}} - \psi_{\text{min}} = \left(\frac{\pi}{2} + \arcsin \frac{OC_{\text{max}}}{O_1O_2}\right) - \arccos \frac{OC_{\text{min}}}{O_1O_2} = \left(\frac{\pi}{2} + \arcsin \frac{r + \rho - b}{a}\right) - \arccos \frac{\rho - r}{a}
$$

(11)

and:

$$
\Delta \psi_{(b>\rho)} = \psi_{\text{max}} - \psi_{\text{min}} = \arccos \frac{OC_{\text{max}}}{O_1O_2} - \arccos \frac{OC_{\text{min}}}{O_1O_2} = \arccos \frac{b - (\rho + r)}{a} - \arccos \frac{b - (\rho - r)}{a}
$$

(12)
4.2. The working step of machine

During the operation of the machine, the minimum value of angle between the follower and the horizontal axis is the angle $\psi_{\text{min}}$, and its value is constant. The value of the angle $\psi_{\text{max}}$ is variable and depends on the position of the cam at the contact place with the follower – Figure 13. By moving the cam along the shaft, the diameter of the cam is changed $d=2\rho$ at the contact place with follower – Figure 14. The axial displacement of the cam is provided by a screw/nut mechanism. The initial position will be when the follower is in contact with the circle of the smallest radius $\rho$ on the cam. The radius of the circle at the contact place with the follower changes according to the equation:

$$\rho_1 - \rho_0 = \frac{\Delta L \tan \delta}{2}$$  \hspace{1cm} (13)

where: $\Delta L$ – position change of the cam along the shaft, and $\delta$ – inclination angle of the cone.

![Figure 13](image13.png) \hspace{1cm} ![Figure 14](image14.png)

**Figure 13.** Change of angle $\psi_{\text{max}}$ depending on $\rho$. \hspace{1cm} **Figure 14.** Change of cam diameter depending on its position on the shaft.

Based on eqs. (11) and (12), the regulation characteristics that represent the dependence $\Delta \psi(\Delta L)$ are shown – Figure 15 for $b<\rho$ and Figure 16 for $b>\rho$. The input parameters are: $R=100$ mm, $a=700$ mm, $\rho_0=200$ mm, $b_1=50$ mm, $b_2=650$ mm, $\delta=2^\circ$ and $\Delta L=0\div50$ mm. For the given range of change position of the cam, rotation angle $\Delta \psi$ of the output shaft changes at an interval of approximately $13\div29^\circ$ for $b<\rho$, respectively approximately $22\div37^\circ$ for $b>\rho$. The increase of the motion range of the output shaft in both cases is approximately equal to $15^\circ$. In addition, the change is close to linear, which is very favourable. The variant solution of the cam mechanism for $b<\rho$ has less overall dimensions and more favourable values of the pressure angle, which makes it more efficient than the variant for $b>\rho$.

![Figure 15](image15.png) \hspace{1cm} ![Figure 16](image16.png)

**Figure 15.** Regulation characteristics for $b<\rho$. \hspace{1cm} **Figure 16.** Regulation characteristics for $b>\rho$. 
5. Conclusion
The paper presents the structural design of the working mechanism of the plastic cup stacking machine. Several problems were detected while operating the machine. The control system cannot always detect the panel and stop it exactly in the position for ejecting formed products. In addition, the machine should work with products of different shapes and dimensions, which requires a change in the kinematic parameters of the working elements. The existing control system for motor control and the change of the kinematic parameters of the machine's working elements is not sufficiently reliable, flexible and efficient, wherefore it has been reconstructed.

Based on the set requirements, a working mechanism that solves the noticed problems without control system is proposed. It consists of a cam mechanism that enables the change of the kinematic parameters of the working elements, and the gear mechanism that provides the change of rotation direction of the machine's output links. Depending on the geometric parameters of the cam mechanism, two variants of the working mechanism were considered – the first one for $b<\rho$, and the second one for $b>\rho$. Kinematic position analysis has been performed and, based on that, the regulation characteristics have been formed. The increase of the motion range of the output shaft is approximately equal for both solutions, and the change is close to linear, which is significant. The variant solution for $b<\rho$ has smaller overall dimensions and more favorable of pressure angle values, so it is more efficient than the variant for $b>\rho$.

By adequate selection of the cam profile, a very fine regulation of the kinematic parameters of the machine's working elements can be achieved. The proposed solution is reliable, efficient and it has a high positioning accuracy that provides high positioning accuracy and repeatability of movement of the output links without time delay – sensitive sensors and expensive electronics that can cancel for any reason do not exist. In addition, it has a high degree of flexibility, because it enables working with products of different shapes and dimensions. It should be noted that the driving motor for different kinematic parameters of the working elements, has always a nominal number of revolution, which is a significant advantage. Further work will examine the influence of the geometric parameters of the working mechanism on the kinematic-dynamic performance of the machine, which requires optimal synthesis.

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