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Research article

FIXING PLASTIC FOOD BOTTLES SYSTEM FOR ROTARY APPARATUSES

Miorița Ungureanu[1]✉, Ioana Lucia Crăciun[1], Diana Lemian[2], Teodora Ungureanu[3]

[1]Faculty of Engineering, Technical University of Cluj-Napoca, North University Centre at Baia Mare, V. Babes St. 62A, 430083, Baia Mare, Romania
[2]Advanced Research Centre for Ambiental Quality and Building Physics, Technical University of Civil Engineering of Bucharest, 021414 Bucharest, Romania
[3]National Institute for Research and Development in Constructions, Urbanism and Sustainable Spatial Development URBAN-INCERC, 021652 Bucharest, Romania
✉miorita.ungureanu@imtech.utcluj.ro
ORCID Number: 0000-0002-5427-5857

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Abstract

This research analyses a novel *Fixing plastic food bottles system* for conveyors and the turntable of rotary apparatuses. At relatively high conveyor speeds, plastic food bottles tend to tip over or slide on the conveyor belt on which they are placed. To address this issue, we developed the *Fixing plastic food bottles system*, designed to preserve plastic food bottles in an upright orientation and ensure the spacing between subsequent bottles for accurate movement. An in-depth examination of the kinematic and dynamic characteristics of flexible transport systems reveals that inertia force and jerk (the derivative of acceleration) during initiation and cessation are the underlying causes of this phenomenon. We examined several modelling methodologies for the acceleration and deceleration of conveyors in these situations, based on numerical applications. Furthermore, we examined the impact of the fastening mechanism on plastic food bottles during initiation and cessation at different accelerations. Through the study presented in this paper, we have deepened important aspects of operation for the model created, the *Fixing plastic food bottles system*, with the goal of being practically made and used in the food industry for filling liquids such as milk, yogurt, juices, or water, as well as for capping operations.

1. Introduction

Currently, the plastic bottle clamping system that is widely used in the rotary plastic bottle processing devices is based on a worm drive at the bottles entrance on the turntable, the bottles are held in position on the turntable by two pairs of superposed ratchet wheels, which rotate together with the turntable, and for the transfer of bottles from the augers to the turntable, two profiled wheels are used, both at the entrance and at the exit (Shiba, 1975). Also, a device for separating bottles with a star wheel with a protective effect on the bottles was created (Preti *et al.*, 2010). This paper presents a new 'System for fixing plastic bottles in rotary tightness testing apparatuses' (Ungureanu *et al.,* 2020), which we continue to study and analyze with the aim of implementing it in industry.

Fixing the bottles and their behavior during transport will be an aspect studied. An optimal fixation requires the analysis of phenomena such as tangential contact that can leave traces of wear or can deform the bottle (Ostergaard *et al*., 2017).

The kinematics and dynamics of the conveyors (Feng et al., 2020; Zeng et al. 2020) and, respectively, of the fixing system are of interest to choose the optimal solution for driving them with electric motors (Umoren *et al.,* 2016; Yang *et al.* 2018). In the practice of driving conveyors, it has been concluded that driving by means of frequency converters (Jeftenić *et al.* 2009) is beneficial for the purpose of modelling the shock (jerk) that occurs when starting and stopping (Li et al. 2018; Doçi et al. 2023). The transient processes that occur when the conveyors are put into operation are influenced by the type of electric drive motor, by the size and character of the variation of the external forces (Guo et al. 2020; Francik *et al.* 2018), and in the case of non-uniform loads, a dynamic study is necessary during their operation (Hea *et al.* 2018). In the case of conveyors and fixing devices that are the subject of our study (Figure 1) there are no large or uneven loads, the transported plastic bottles have the same mass and are evenly distributed, therefore we will only analyze the phenomena that occur when starting and stopping. In these phases, the S-curve motion profile can be modelled according to various functions: trapezoidal, parabolic and cosinusoidal by means of the frequency driver (Crăciun *et al.* 2012; Ostergaard and Danjou 2017; Pop *et al.* 2019).

Thus, the present study is focused on two main directions:

- Analysis of three models of acceleration and deceleration variation, selecting the option that presents the minimum jerk;
- Analysis of stresses and deformations occurring in the bottle's body during startup and stopping.

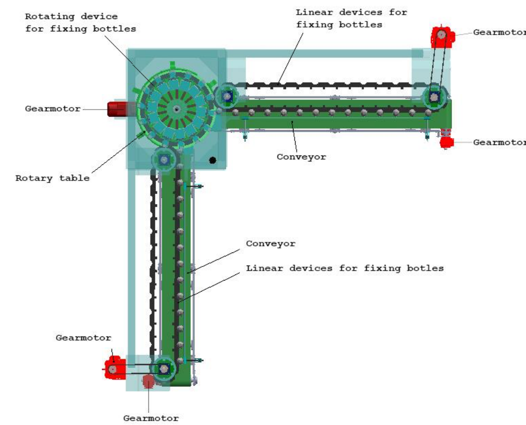

Figure 1. Plastic food bottle fixing system for rotary apparatuses

2. Description of the Proposed Plastic Food Bottle Fixing System for Rotary Devices

The system proposed by us is intended for fixing and dividing the bottles on the linear means of transport and on the turntable of the rotary devices, and according to the invention it consists of two vertical devices for fixing the bottles, one located at the entrance, and one located at the exit from the turntable. This system presents the following advantages over other systems that perform the same role (Shiba, 1975): simple construction with few moving elements; the elastomer elements ensure a flexible grip, dampening vibrations; a precise driving and transfer of the bottles; fixing devices ensure a flexible grip without deforming or damaging them due to dynamic stresses; the proposed system has a modular construction not only of the conveyors but also of the fixing devices, which allows the individual replacement of the main bottle fixing elements in case of damage or change of the processed bottles.

The aim of fixing is to keep the bottles in a vertical position on the conveyor belt, at relatively high speed, and to transfer the bottles into categories when passing from the linear route to the circular one. The main components of the system are: a rotary bottle device for fixing and transferring bottles and two vertical devices for fixing and transferring bottles. This bottle fixing and transfer system can be used in numerous industrial applications for operations such as compliance testing of plastic food bottles; bottle filling; capping etc. The system ensures a flexible grip of plastic food bottles, thus avoiding the deformation or damage of the bottles, respectively the production of waste. The prevention of waste is an important aspect of the circular economy, a target that is considered from the concept phase.

Another advantage of the system is the fact that it ensures precise driving and transfer distribution of the bottles, which allows us to increase the productivity of the installation it serves. Increasing productivity is a key goal in the field of advanced manufacturing.

The proposed new system for securing plastic food bottles for rotary devices is shown in Figure 1 and consists of a rotating device for fixing bottles and two linear devices for fixing bottles. The linear bottle fixing devices are located above the horizontal conveyors. The conveyor together with the linear bottle fixing device ensures the entry of bottles on the rotary table, and the conveyor together with the linear device for fixing the bottles ensures the evacuation of the bottles from the rotary table. The two linear bottle fixing devices are identical and consist of two vertical drums, on which the profiled belt is mounted. On the outer side, the profiled belt is provided with grooves sized according to the shape of the bottles. The actuation of the linear device for fixing the bottles is ensured by the gearmotor. The rotary table is made up of the turntable, fixed on the vertical shaft, and the rotary device for fixing the bottles. The operation of the rotary table is carried out by the gearmotor by means of a transmission. On the shaft of the rotary table, above the turntable, the rotating device for fixing the bottles is mounted. Above the rotary table are placed the processing devices, which can be: tightness testing devices, filling devices, capping devices, etc.

The rotating device for fixing the bottles (Figure 3) consists of a metal drum on which the profiled elastomer bushing is mounted. The elastomer bushing of the drum will have the profile and pitch of the grooves identical to that of the belt of linear fixing devices, to ensure the connection between the conveyors and the rotary table, and respectively the transfer of the bottles (Figure 2). Also, in order to ensure the operation of the system, the speeds of the flexible belt conveyors, the speeds of the two linear devices and the tangential speed of the rotating device must be equal.

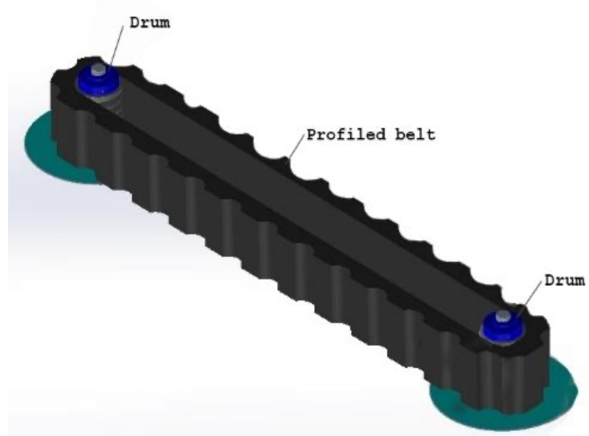

Figure 2. Linear device for fixing the bottles

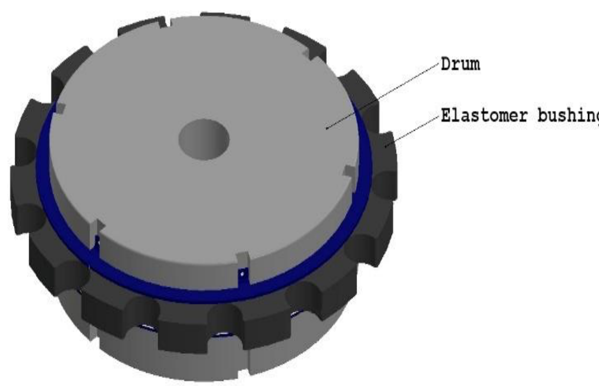

Figure 3. Rotating device for fixing the bottles

3. Materials and Methods

To develop a system that is operational for both the kinematic characteristics and the stresses encountered in extreme cases, we propose to establish an optimal control model for the electric motors driving the conveyors and the bottle securing devices. Additionally, we will conduct simulation testing of the plastic food bottle under the maximum stresses that occur due to its securing in the device.

3.1. Study of system start and stop

In the case of system start-up and stop, we are interested in its kinematic study in order to create the working model of the electric encoder. Thus, the use of speed modeling in the operation of conveyors is a problem that concerns us. The kinematic parameters that influence the positioning of the glass when switching from one means of transport to another are: the value of the regime speed; acceleration value at start-up and stop and the modelling of the speed S-curve (Bebić and Ristić; Hea *et al.* 2018).

Speed variation is currently made using frequency converters that follow mathematical curves, generally named S-curves. Studies in the field of conveyors and other mechanical systems have demonstrated that S-type designs are effective, as they substantially reduce shocks in the system (Halepoto et al. 2026; Crăciun *et al.* 2017).

The S-curves used to model start and stop speeds can be generated using different variations of speed over time, the most common being the third-degree parabola and the sine (Crăciun *et al.* 2017).

In this case, the situation of a vertical bottle-fixing device with S-curves at start and stop will be analyzed for three acceleration modelling variants during acceleration and braking periods: trapezoidal, parabolic and cosine. To make a comparison between these three acceleration modelling variants, a numerical application was performed with the following data of the vertical bottle-fixing device: speed v = 0.46 m/s, acceleration a = 0.15 m/s^2, acceleration and deceleration time $t_a = t_f = 3$ s. Symmetrical curves are generated at start-up and stop, which is why we conducted the study only for start-up. Under these conditions, we will evaluate the resulting jerk as a basis for choosing the optimal modeling variant.

The equations of motion for three acceleration modeling variants are presented below.

Notations: $v_{01}(t)$-speed; a_1- acceleration; t_1-accelerating time; j_1- jerk.

3.1.1. Triangular variation of acceleration

Jerk variation:

$$j(t) = \begin{cases} j_{01} = j_1 \\ j_{12} = 0 \\ j_{23} = -j_1 \end{cases} \quad (1)$$

Acceleration variation:

$$a(t) = \begin{cases} a_{01}(t) = j_1 \cdot t \\ a_{12}(t) = a_1 \\ a_{23}(t) = a_1 - j_1(t - t_2) \end{cases} \quad (2)$$

Speed variation:

$$v(t) = \begin{cases} v_{01}(t) = j_1 \frac{t^2}{2} \\ v_{12}(t) = v_{01}(t_1) + a_1(t - t_1) \\ v_{23}(t) = v_{12}(t_2) + a_1(t - t_2) - j_1 \frac{(t-t_2)^2}{2} \end{cases} \quad (3)$$

Displacement:

$$x_{01}(t) = \frac{j_1 \cdot t^3}{6} \quad (4)$$

$$x_{12}(t) = x_{01}(t_1) + v_{01}(t_1) \cdot (t - t_1) + \frac{a_1}{2}(t - t_1)^2 - \frac{j_1}{6}(t - t_1)^3 \quad (5)$$

Boundary values:

$$a_{01}(t_1) = j_1 \cdot t_1 = a_1; \quad v_{12}(t_2) = v_{01}(t_1) + a_1(t_2 - t_1) - j_2 \frac{(t_2-t_1)^2}{2}$$

The variation curves of the kinematic parameters (jerk, acceleration and speed) were generated using MATLAB program, for v = 0.46 m/s and acceleration duration $t_a = 3$ s. The graphs obtained are shown in Figures 4, 5, and 6 and they represent the speed, acceleration, and jerk profiles over time for a parabolic variation of acceleration.

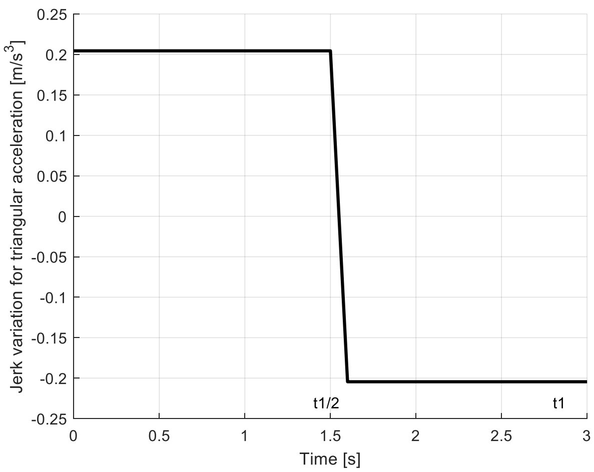

Figure 4. Jerk variation for triangular acceleration

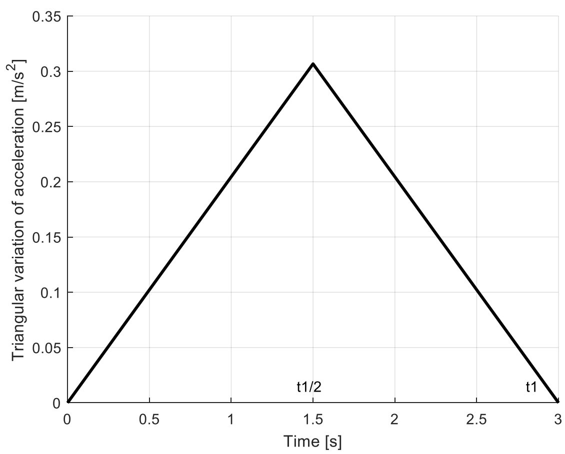

Figure 5. Triangular variation of acceleration

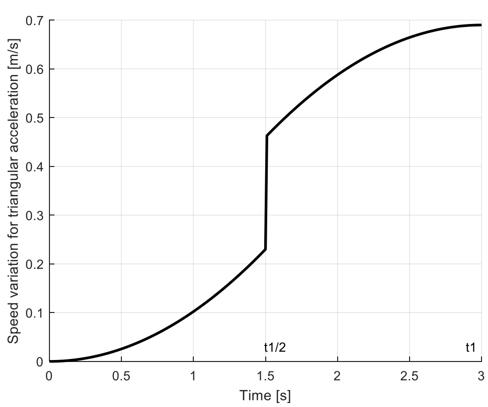

Figure 6. Speed variation for triangular acceleration

3.1.2. Parabolic variation of acceleration

Jerk variation:

$$j_{01} = j_1 - \frac{2j_1}{t_1}t \qquad (6)$$

Acceleration variation:

$$a_{01} = j_1 t - \frac{j_1}{t_1}t^2 \qquad (7)$$

Speed variation:

$$v_{01} = j_1\frac{t^2}{2} - \frac{j_1}{t_1}\frac{t^3}{3} \qquad (8)$$

Displacement:

$$x_{01}(t_1) = j_1\frac{t_1^3}{6} - j_1\frac{t_1^4}{12t_1} = j_1\frac{t_1^3}{12} \qquad (9)$$

Boundary values: $a_{01}(t_1) = 0$; $j_{01}(t_1) = -j_1\ m/s^3$; $j_{01}(t_1/2) = 0$; $a_{01}(t_1/2) = a_1\ m/s^2$.

After running the numerical simulation in MATLAB with a speed of v=0.46m/s and time parameters t_a=t_f=3s, the graphs in Figures 7, 8, and 9 were obtained. These show the speed, acceleration, and jerk profiles over time for a parabolic variation of acceleration.

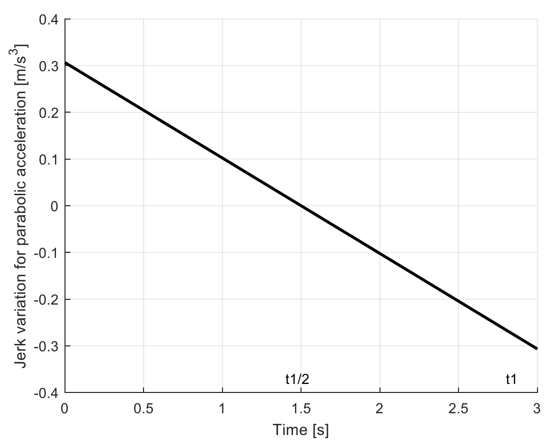

Figure 7. Jerk variation for parabolic acceleration

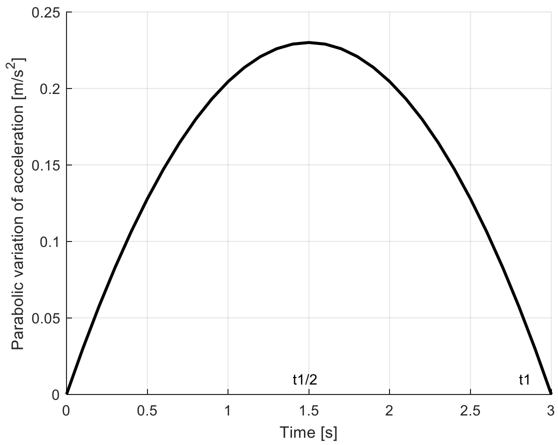

Figure 8. Parabolic variation of acceleration

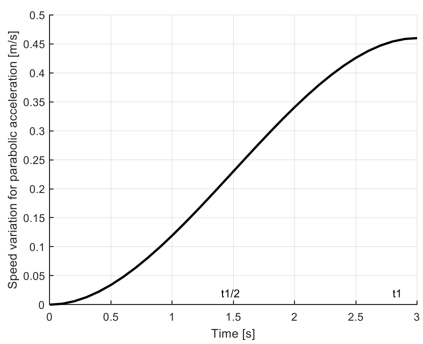

Figure 9. Speed variation for parabolic acceleration

3.1.3. Cosinusoidal variation of acceleration

Jerk variation

$$j_{01}(t) = j_1 sin\ \frac{2j_1}{a_1}\ t = j_1 sin\ \frac{2\pi}{t_1}\ t \quad (10)$$

Acceleration variation:

$$a_{01}(t) = \frac{a_1}{2}(1 - cos\ \frac{2j_1}{a_1}\ t) = \frac{a_1}{2}(1 - cos\ \frac{2\pi}{t_1}\ t) \quad (11)$$

Speed variation:

$$v_{01}(t) = \frac{a_1}{2}(t - \frac{a_1}{2j_1} sin\ \frac{2j_1}{a_1}\ t) = \frac{a_1}{2}(t - \frac{t_1}{2\pi} sin\ \frac{2\pi}{t_1}\ t) \quad (12)$$

Displacement:

$$x_{01}(t) = \frac{a_1}{2}\left(\frac{t^2}{2} + \frac{t_1^2}{4\pi^2} cos\ \frac{2\pi}{t_1}\ t - \frac{t_1^2}{4\pi^2}\right) \quad (13)$$

Boundary values: $j_{01}(t_1/4) = j_1$; $a_{01}\left(\frac{t_1}{2}\right) = a_1$; $a_{01}(t_1) = 0$; $v_{01}(t_1) = v_1$.

After running the numerical simulation in MATLAB with a speed of v=0.46m/s and time parameters t_a=t_f=3s, the graphs in Figures 10, 11, and 12 were obtained. These show the speed, acceleration, and jerk profiles over time for a parabolic variation of acceleration.

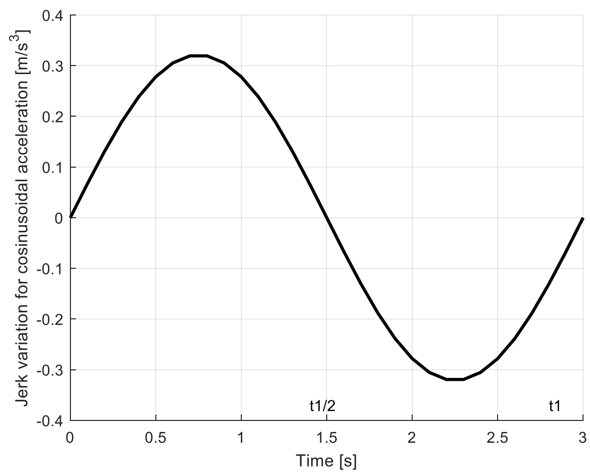

Figure 10. Jerk variation for cosinusoidal acceleration

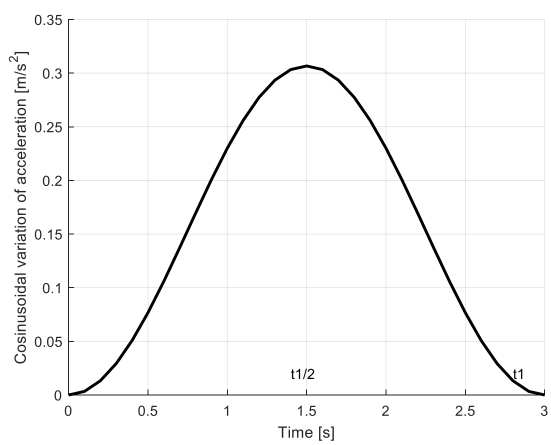

Figure 11. Cosinusoidal variation of acceleration

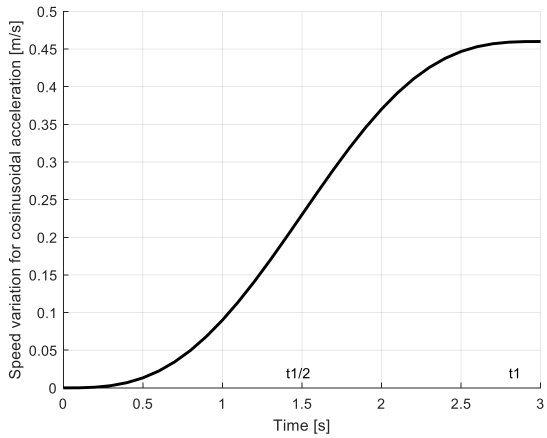

Figure 12. Speed variation for cosinusoidal acceleration

3.1.4. Data analysis

Substituting the numerical values for speed and time in equations 1-13 and performing the calculations we obtained the numerical maximum values for acceleration and jerk of the three modeling variants of the kinematic parameters as can be seen in Table 1, it resulted that the most advantageous modeling is the one with triangular, acceleration because in this case the shock induced in the system is minimal.

Table 1. Maximum values of acceleration and jerk for triangular, parabolic and cosinusoidal variation of acceleration

Acceleration/ Jerk	Triangular	Parabolic	Cosinusoidal
a_1	0.30 m/s^2	0.20 m/s^2	0.30 m/s^2
j_1	0.20 m/s^3	0.30 m/s^3	0.320 m/s^3

3.2. Finite Element Analysis of Stresses and Deformations in Food Plastic Bottles during Startup and Shutdown the Conveyors

Fixing bottles and their behavior during transportation requires analysis of phenomena such as: tangential contact, which can leave wear marks or deform the glass (Ostergaard and Danjou, 2017; Ekinci *et al.* 2022). A simulation of the stresses that occur in the glass when fixed with the help of devices allows us to predict potential deformations of the glass during startup or shutdown. Based on simulating the operating conditions in a mechanical system, the verification of its components is carried out, identifying possible shortcomings, and gaining detailed knowledge of the phenomena, which will later allow us to take constructive measures for necessary improvements (Caban *et al.* 2019; Andras at al. 2021).

Finite element analysis is a technical analysis that allows us to predict the performance of a structure or mechanism under load during service or an overload caused by extreme conditions (Monkova *et al*. 2024; Ojoa and Shittub, 2023; Keawjaroen and Suvanjumrat, 2017).

Most of them plastic bottles used in the food industry are made from polyethylene terephthalate (PET) and high-density polyethylene (HDPE) (Ekinci *et al.,* 2022; Suvanjumrat and Puttapitukporn, 2011). Polyethylene terephthalate (PET) has lower mechanical strength properties compared to high-density polyethylene (HDPE), which is why in our study we simulated the mechanical stresses on bottles made of polyethylene terephthalate (PET) (Suvanjumrat and Puttapitukporn, 2011; Benyathiar et al. 2022).

Polyethylene terephthalate, coded as PET, PETE, is a thermoplastic polymer resin of the polyesters. From a structural point of view, PET can exist both as amorphous and as semi-crystalline. Crystallinity and its physical and mechanical properties are dependent on processing conditions in the manufacture of bottles. (Demirel *et al.,* 2011).

3.2.1. Data analysis

An important issue to ensure a flexible grip of the bottle in the profiled belt is establishing the contact pressure between the profiled belt and the bottle. Related to this, we have studied the total deformation and the equivalent stress, realized in a simulation software, following the application of the force that appears as a result of the displacement of the 0.5 l bottle from PET material, on the linear device, for the speed differed speeds and for differed acceleration or deceleration to the start or to braking at the linear device. PET material, on the linear device, for the speed differed speeds and for differed acceleration or deceleration corresponding to the start or to braking at the linear device. The values of the speeds and of the accelerations are presented in Table 1.

The calculation of mechanical stresses and deformations was performed for the moment of system startup, that is, during acceleration until a constant speed is reached. During braking, the deceleration process is symmetric, and the stresses will be the same but in the opposite direction.

The simulation was performed for the three acceleration modeling variants presented in section 3.1, namely for the triangular variation of acceleration, the parabolic variation of acceleration, and the cosine variation of acceleration. For the analysis of stresses and deformations occurring during startup and braking, the following assumptions were made: a) the surface on which the inertial force acts is considered to be half of the contact area between the profiled band and the glass; b) the deformation of the rubber was not taken into consideration.

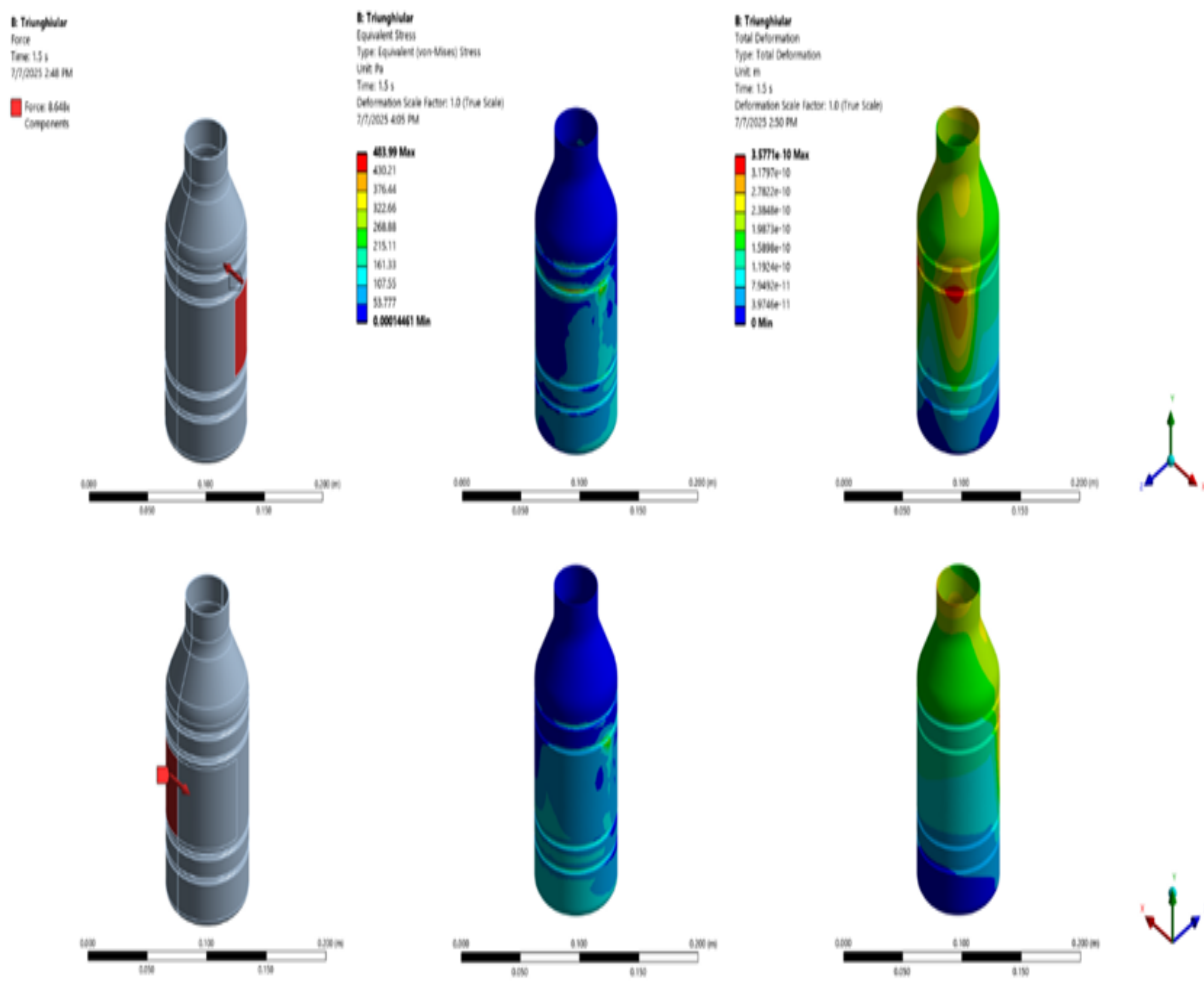

Figure 13. Stresses and deformations of PET glass for the triangular acceleration modeling

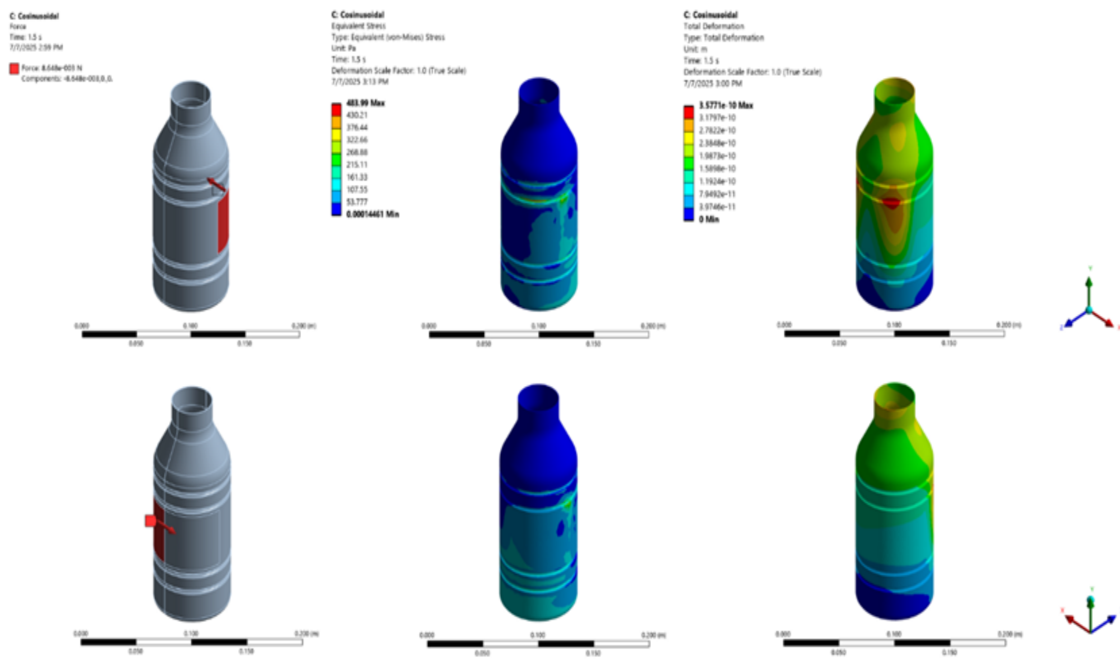

Figure 14. Stresses and deformations of PET glass for the parabolic acceleration modeling

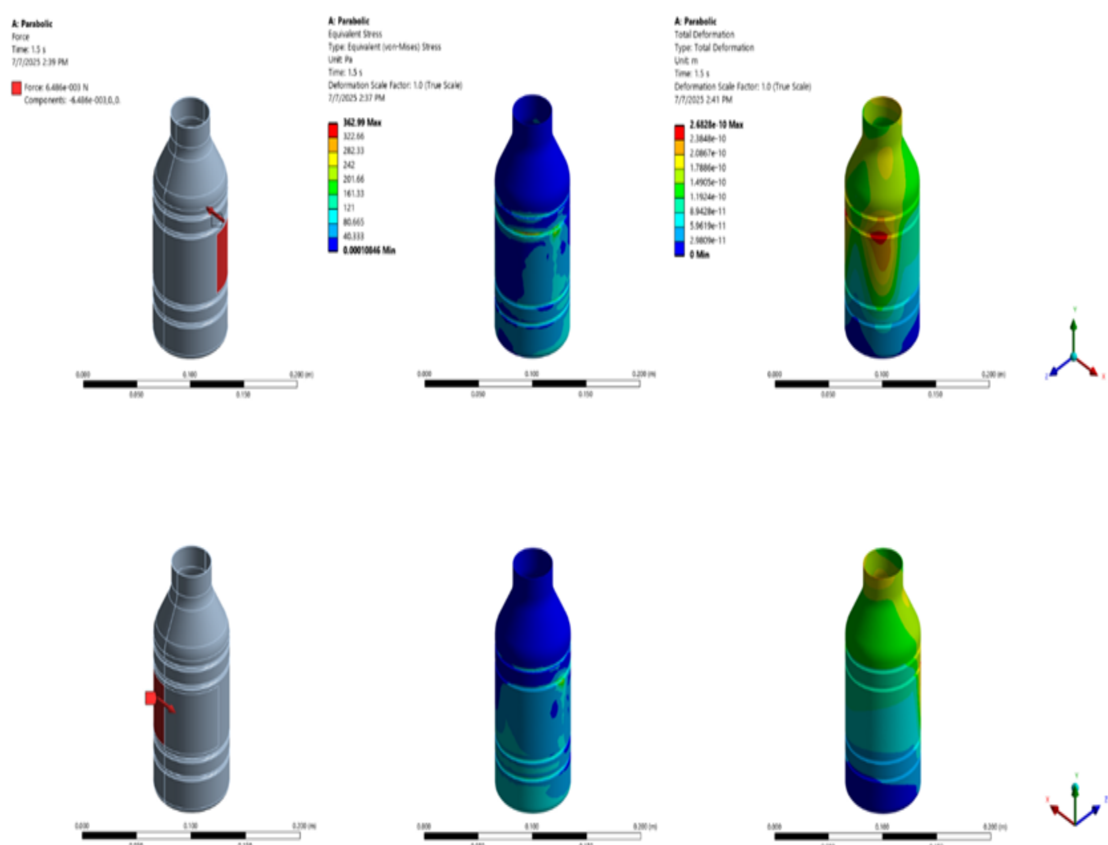

Figure 15. Stresses and deformations of PET glass for the cosine acceleration modeling

The stresses and deformations in the PET material glass for the load values occurring during startup and shutdown under the action of the fixing device were analyzed using the finite element modeling tool in the ANSYS program for all three cases of acceleration modeling (triangular, parabolic, and cosine), with imposed values for speed and time being v=0.46 m/s and time t_a=t_f=3s. The results of the simulation are shown in Figures 13, 14 and 15.

3.2.2. Results and discussions

The prediction of a proper fixation of the glass without it being damaged is based on the condition that the maximum yield stress of the design does not exceed the specified material property. The stresses that result in the glass for the three loading cases analyzed and presented in Figures 13-15 are below the PET material's limit. For the triangular variation of acceleration, the highest stress, the von Mises stress value of 483.99 Pa for the PET glass material, is lower than the PET material's yield limit of 55 MPa. For the parabolic variation of acceleration, the highest stress, the von Mises stress value of 362.99 Pa for the PET glass material, is lower than the PET material's yield limit of 55 MPa. For the cosine variation of acceleration, the highest stress, the von Mises stress value of 483.99 Pa for the PET glass material, is lower than the PET material's yield limit of 55 MPa. Thus, it can be concluded that the deformation of the glass due to inertial force is reversible for all three acceleration modeling cases. The deformations of the PET glass in all three simulation cases are very small. It can be observed that the smallest deformation value results from the parabolic acceleration modeling, with slightly higher values in the triangular and cosine acceleration models.

4. Conclusions

The plastic food bottle clamping system presented in this study is suitable for relatively high operational speeds and this offers several comparative advantages over other systems fulfilling the same function, such as those based on a worm drive at the bottles' entrance on the turntable (Shiba, 1975) and systems using a star-wheel bottle separator with a protective effect (Preti et al., 2010). Specifically, the system has a simpler construction with few moving elements, dampens vibrations, and ensures precise guidance and transfer of bottles. The clamping devices provide flexible gripping without deforming or damaging the bottles under dynamic loads. The modular design of the clamping devices allows individual replacement of the main clamping elements in case of damage or when processing bottles of different sizes.

To demonstrate the functionality of the newly created plastic food bottle clamping system, numerical simulation in MATLAB and using FEA analysis in ANSYS were performed in a virtual environment. After numerical analysis in MATLAB it resulted that to minimize shocks during startup and, respectively, during the shutdown of the belts, vertical clamping devices for the bottles, and the turntable, an "S" curve velocity model and a triangular acceleration and deceleration model are proposed. Moreover, for acceleration modeling scenarios, we analyzed the impact of the clamping mechanism on plastic food bottles during start-up and stop at different accelerations through finite element analysis of stresses and deformations in polyethylene terephthalate (PET) bottles. In all cases, stresses remained well below the material's allowable limits, and the resulting deformations were within acceptable values.

In conclusion a triangular acceleration and deceleration model are proposed, because, for this type of modeling, the shock induced in the system is minimal, and the glass deformation due to inertial force is reversible.

For the usual operating high speed of conveyors, according to the simulations conducted in this study, it results that the glass deformation due to inertial force is minimal and reversible, and the stresses of PET bottles are within admissible limits of the material. In conclusion, the plastic food bottle clamping system is suitable for use in the food industry, for example, in the process of filling bottles, capping, or in the process of manufacturing plastic food bottles when testing them for leakage.

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