Inverse Dynamics of the Mould Base of Blow Molding Machines

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Abstract—This paper deals with the study of devices for displacement of the mould base of blow-molding machines. The displacement of the mould in the studied case is carried out by a linear actuator, which ensures the descent of the mould base and by extension springs, which return the letter in the initial position. The aim of this paper is to study the inverse dynamics of the device for displacement of the mould base of blow-molding machines and to determine its optimum parameters for higher rate of production. In the other words, it is necessary to solve the inverse dynamic problem to find the equation of motion linking applied forces with displacements. This makes it possible to determine the stiffness coefficient of the spring to turn the mold base back to the initial position for a given time. The obtained results are illustrated by a numerical example. It is shown that applying a spring with stiffness returns the mould base of the blow molding machine into the initial position in 0.1 sec.

Keywords—Design, blow-molding machines, dynamics.

I. INTRODUCTION

THE process of using air to blow hot material was first used by the Syrians. The method has been applied by Syrian glass workers in the first century BC. They realized that a glass bulb on the end of a blow pipe could be transformed into many useful hollow forms. This was to place a tube in a container located in a blast furnace containing molten glass and removing a drop of hot rotating white liquid glass, and then blowing into a mouthpiece located at the other end of tube.

This process has been advanced in Europe to create bottles of wine. Reliefs on the walls of Egyptian royal tombs show this process. Egyptians further developed the technique of blow molding in 1700-1600 B.C. Enoch Ferngren and William Kopitke were the first people who used the Blow Molding Process [1].

In 1851, U.S. patent of S.T. Armstrong mentions the blow molding a plastic material other than glass. In the mid-1930s, ICI (Imperial Chemical Industries) proposed low-density polyethylene (LDPE) [1].

In 1950, Kautex Werke (Reinhold Hagen, Germany) proposed the first commercially available blow molding device. The design concept used in this device a rising mold technique with continuous extruded open ended prison. In 1953, high-density polyethylene (HDPE) was discovered by both Paul Hogan of the Phillips Petroleum Company in the United States and Professor Zieglar in Germany. Later,

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Professor Natta from Italy polymerized both propylene and butylene. With the creation of HDPE, an explosion of blow molded products has been occurred in both Europe and North America. In 1970, Coca-Cola tested the world's first plastic carbonated beverage bottle.

In 1970s, biaxial oriented polyethylene terephthalate (PET) was developed with introduction of the two-step process. The preform and the bottles were produced on separate machines by Cincinnati Milacron, USA. In 1977 Nisser, ASB Company (Japan), began to develop biaxial orientation of PET by means of blow molding equipment based on a one-step process. In the United States soft drink industry, the amount of plastic containers went from zero in 1977 to ten Billion in 1999 [1].

Since the 1980s, blow molding systems have reached a higher level of efficiency, using capabilities such as electromagnetically controlled stretch systems and compressed air recycling components. Improved systems that regulate the blowing process reduce scrap and automatically eliminate bottle process deviations [2].

Manufacturers of stretch blow-molding equipment propose machinery that is faster and more efficient to drive down the lifecycle costs of their equipment. In combination with advances in container material technologies, this changes the requirements of the compressed air needed to support the process. These improvements include lower pressure for forming the containers and reduced volume due to recovery capabilities [2].

Through the introduction and application of microprocessor resins, a wide range of material properties became accessible. The availability of more robust equipment and new microprocessor technologies led to the production of a range of industrial products. Then from Japan, France, and Germany, complex shapes and irregular contours were developed with the introduction of 3-D blow molding. Nowadays, even a greater amount of products is blow molded, and it is expected to be increasing.

Surf boards, bellows, fuel tanks, flower pots, automobile bumpers, walled tool cases, and cabinet panels, cigarette packs are just a few examples of the many creative design being developed.

Krones and Sidel are the two major producers of blow molding systems in the world. The Krones technology was developed in Germany, and the Sidel technology was developed in France.

Sidel recently introduced the Matrix blow molder. It is a modular blow molding system available in 200 configurations that reduce energy and material consumption as well as downtime. The system produces lightweight PET containers at

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a speed of 2,250 bottles per mold per hour.

Electrical consumption is reduced about 50 percent versus that of a conventional oven because it requires fewer heating modules and lamps, according to the Sidel's customer service. The system uses installed power more efficiently, resulting in reduced preform heating time. Moreover, air consumption is reduced, resulting in compressed air savings of up to 30 percent.

The system is developed to reduce air consumption during the blow molding process. Instead of releasing compressed air into the atmosphere, the system reuses it to feed the pre-blow circuit and the pneumatic system. The extra air is used in the low-pressure circuit of the plant. As a result, the blow molder produces low-pressure compressed air that can be reused for downstream operations. The system also recuperates the high-pressure air needed for the next blowing cycle.

Sidel recently supported Midwest Coca-Cola Bottling Co., Eagan, MN, reduce blowing air pressure by more than 50 percent in its blow molding operation. The company manufactures bottles and distributes Coca-Cola products throughout the Midwest, and it used Sidel's Eco Booster service to reduce blowing air pressure and oven electricity across four of its lines.

Sidel's Eco Booster service studies a line to identify potential opportunities for savings. Measurement implementations are installed that record the consumption of all utilities (air, water, electricity and carbon dioxide) by machines. They can even provide information about the activity of an entire plant. Along with measuring consumption and calculating energy costs per bottle produced, the improved systems help to determine the correlation between consumption levels and production procedures. This information helps beverage producers to support initiatives for reducing waste.

In most of the cases, each unit of blow-molding machines consists of two half-moulds and a mould base, mutually mobile through actuating means controlled by the fixed cams (Fig. 1). Such a kinematics is typical for these machines and is approved by a large number of manufacturers.

However, in the course of evolution of blow-molding machines, new solutions were developed. In the inventions [3]-[6], several devices were developed, in which the half-moulds are connected with the mould base by the auxiliary linkages: (i) planar articulated dyads [3]; (ii) cam mechanism [4], [5]; (iii) spatial linkage [6] (Fig. 4). In these solutions, the rectilinear translation of the mould base is actuated by the half-moulds and in such a manner the best synchronization is achieved.

Another known design solution, which consists in accumulation of the energy of springs during the descent of the mould base and its restitution for return the mould base in the initial position, has been also developed. Such a solution allows one to carry out the displacements of the mould base by minimum expenditure of energy.

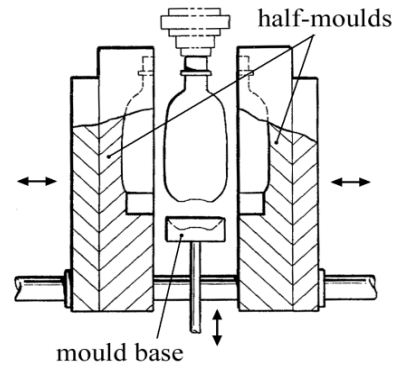Firstly, let us consider the design concept.

Fig. 1 The half-moulds and the mould base displacements in the typical blow-molding machines
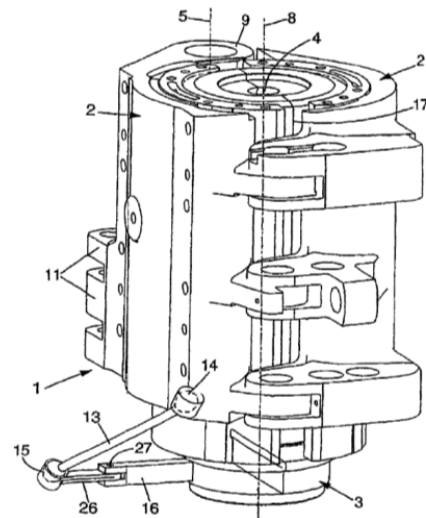

Fig. 2 Device for blow-molding or stretch blow molding of thermoplastic materials containers [6]

II. DEVICE FOR DISPLACEMENT OF THE MOULD BASE OF BLOW-MOLDING MACHINES

The suggested solution consists of a linear actuator and two springs connected with the mould base and the central console of the half-moulds (Fig. 2). The operating procedure of this device is the following: the actuator mounted between the central console and the mould base executes a descent of the mould base. During this time, the springs extend by means of the actuator. During the descent, the gravitational and inertia forces of the mould base are driving forces, i.e. they help the actuator to descent the mould base. At the final position of the mould base, the springs are maximally extended and they have the maximal potential energy. This energy can be used for returning the mould base to its initial position. Thus, the advantage of this system consists in the accumulation of the energy of springs during its descent and the restitution of the spring's energy for return to the initial position.

The aim of this study is to develop the dynamic model of the mould base displacements, which allows returning the mould base in the initial position, i.e. it is necessary to determine such parameters of the system, which allows one to return the mould base in the initial position for given time.

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If the moving forces are small, the mould base will be late. If the moving forces are very large, the mould base will be returned in the initial position rapidly. However, in this case, the more powerful linear actuator will be used for the descent of the mould base. So, there is an optimal solution which must be found.
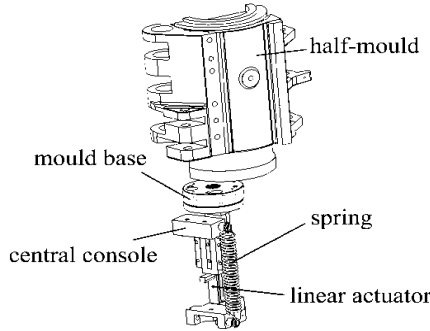

Fig. 3 Schematics of the device for displacements of the mould base

For this purpose, let us consider the equation of motion of the device given in Fig. 3.

III. DYNAMICS OF THE DEVICE FOR DISPLACEMENT OF THE MOULD BASE OF BLOW-MOLDING MACHINES

The equation of motion of the device can be written as [7]:

$$\left(\frac{m}{k}\right)\ddot{z} + \left(\frac{\beta}{k}\right)\dot{z} + z = -\frac{F_g - kz_{max}}{k} \qquad (1)$$

where, m is the mass of the mould base, k is the stiffness coefficient of springs (it is recommended to use two springs in order to keep the symmetry), β is the coefficient of the viscosity friction, F_g is the gravitational force of the mould base, z is the co-ordinate of the mould base relative to its end position, z_{max} is the maximum extension of the spring, $\dot{z} = dz/dt$ is the velocity of the mould base, and $\ddot{z} = d\dot{z}/dt$ is its acceleration. In this equation, the unknown is z.

Introducing $z_1 = z + (F - kz_{max})/k$ and taking into account that $\ddot{z}_1 = z$, $\dot{z}_1 = \dot{z}$, we obtain the following differential equation:

$$T_2^2 \ddot{z}_1 + T_1 \dot{z}_1 + z_1 = 0 \qquad (2)$$

where $T_1 = \beta/k$ and $T_2^2 = m/k$.

The characteristic equation of this one is the following:

$$T_2^2 r^2 + T_1 r + 1 = 0 \qquad (3)$$

and the roots are the followings:

$$r_{1,2} = -\frac{T_1}{2T_2^2} \pm \frac{\sqrt{T_1^2 - 4T_2^2}}{2T_2^2} \qquad (4)$$

Thus, there are three possible solutions [8]:

1) $T_1^2 > 4T_2^2$ or $|T_1| > |2T_2|$. In this case, this is quadratic equation of aperiodic type and roots are the followings:

$$r_1 = -\frac{T_1}{2T_2^2} + \frac{\sqrt{T_1^2 - 4T_2^2}}{2T_2^2} \qquad (5)$$

$$r_2 = -\frac{T_1}{2T_2^2} - \frac{\sqrt{T_1^2 - 4T_2^2}}{2T_2^2} \qquad (6)$$

2) $T_1 = 2T_2$, we have

$$r = r_1 = r_2 = -1 \qquad (7)$$

3) $|T_1| < |2T_2|$. In this case, this is an equation of oscillatory type and the roots are the followings:

$$r_{1,2} = -\frac{T_1}{2T_2^2} \pm j\vartheta, \text{ with } \vartheta = \frac{\sqrt{4T_2^2 - T_1^2}}{2T_2^2}, \quad j = \sqrt{-1} \qquad (8)$$

The considered problem corresponds to the third case and the solution is the following:

$$z = e^{-\gamma t}(C_1 \cos \lambda t + C_2 \sin \lambda t) + \zeta \qquad (9)$$

where $\gamma = \frac{\xi}{T_2}$, $\lambda = \sqrt{\frac{1 - \xi^2}{T_2}}$, $\zeta = z_{max} - \frac{F}{k}$, $\xi = \frac{T_1}{2T_2}$,

$(r_{1,2} = -\gamma \pm j\vartheta)$.

Differentiating (9), we obtain the velocity of displacements:

$$\dot{z} = e^{-\gamma t}(-\lambda C_1 \sin \lambda t + \lambda C_2 \cos \lambda t) - \gamma e^{-\gamma t}(C_1 \cos \lambda t + C_2 \sin \lambda t) \qquad (10)$$

Taking into account that, in the end position of the mould base the initial conditions are $z_{(t=t_0)} = 0$ and $\dot{z}_{(t=t_0)} = 0$, we obtain:

$$C_1 + \zeta = 0 \qquad (11)$$

$$\lambda C_2 - \gamma C_1 = 0 \qquad (12)$$

from which

$$C_1 = -\zeta \qquad (13)$$

$$C_2 = -\frac{\zeta \gamma}{\lambda} \qquad (14)$$

Thus, we obtain the following equation of motion:

$$z = -\zeta e^{-\gamma t}(\cos \lambda t + \frac{\gamma}{\lambda}\sin \lambda t) + \zeta \qquad (15)$$

Let us carry out numerical simulations according to the obtained equation of motion.

IV. NUMERICAL SIMULATION AND OBTAINED RESULTS

For development of highly productive blow-molding machines, it is necessary to increase the mechanism velocities and, as a result, it is necessary to carry out very fast displacements of the mould base. Taking into account the present productivity of the blow-molding machines, it is selected for the simulation $t \in [0; 0.1s]$, i.e. it is necessary that the mould base can be returned in the initial position within 0.1 s.
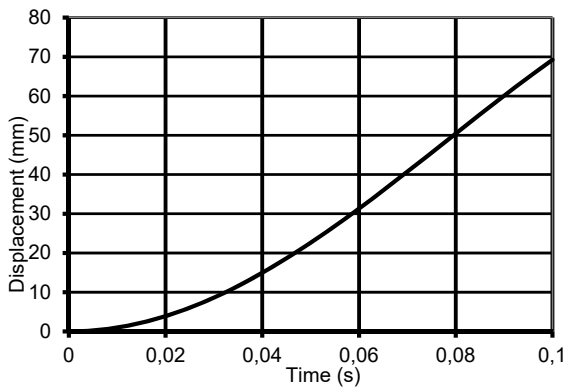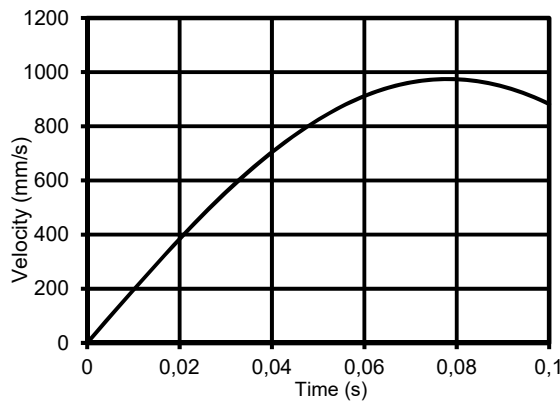

Fig. 4 Displacement of the mould base

Fig. 5 Velocity of the mould base

For numerical simulations, the following parameters have been selected: $m = 15kg$, $\beta = 0.015\,Ns/mm$, $z_{max} = 70mm$. According to the obtained equation of motion, Figs. 4 and 5 show the displacements and velocities of the mould base for the springs with $k = 7N/mm$, which allows one to carry out the return of the mould base for 0.1 s.

It should be noted that, at the end of the motion, the speed of the mould base becomes to reduce, which is very favorable for damping of the movement.

V. CONCLUSION

In this paper, a device for displacement of the mould base of blow-molding machines is studied. Originality of such a device is the accumulation of the energy of elastic forces during the descent of the mould base, which carried out by a linear actuator and its restitution for return the mould base in the initial position. The dynamic model of the device is developed, which allows the determination of the optimum parameters of the device for displacements of the mould base of blow-molding machines taking into account requirements of the productivity. A numerical example, which takes into account the mentioned productivity of the blow-molding machines, illustrates the proposed study.

The obtained results might be integrated in the design concepts of new generation of blow-molding machines.

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