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The analysis of influence of a nozzle form of the Bernoulli gripping devices on its energy efficiency

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Abstract: In the article is justified the advantages of use of Bernoulli gripping devices in the transport and loading systems of the automated production. Modeling of dynamics of air flow in a nozzle and in a radial interval between the interacting surfaces of Bernoulli gripper and object of transportation is carried out. For this purpose we use averaging on RANS equation of dynamics of viscous gas, SST-model of turbulence and γ-model of laminar and turbulent transition. Options of constructive improvement of a form of a nozzle and conditions for the analysis of energy efficiency of Bernoulli gripper are offered. As a result of numerical modeling in the program Ansys-CFX environment influence of the form of the Bernoulli gripping devices' nozzle on its carrying power and account characteristics and energy efficiency is define.

Keywords: Bernoulli gripping device, object manipulation, nozzle, radial flow, industrial robot, RANS, SST-model of turbulence.

1. Introduction

In the transport and loading systems of the automated production of broad application devices which use power effect proceeding from a screened nozzle of air flow became widely used [1-7]. The nature of interaction of air flow with cargo depends on many parameters that allows to use positive effects of this interaction for various tasks: to hold cargos by means of an aerodynamic attraction; without contact to transport cargos on a pneumatic pillow; to use reactive force and force of viscous friction for orientation of objects of transportation. The combination of these effects of interaction allows to create essentially new devices for contactless gripping, orientation and transportation of objects of production. It is easy to integrate additional functions of pneumatic control of a number of parameters of objects of transportation into these devices.

Now the greatest distribution was gained by Bernoulli gripping devices (BGP), using aerodynamic effect of an attraction (Bernoulli's effect) [1-7]. The main difference of BGD from other grippers is the lack of mechanical contact (or the minimum contact piece) with surface of the object of manipulation (OM) that is important during the work from easy deformed, fragile, heated or objects with external coverings, unstable to attrition. Now BGD are widely used in the radio-electronic industry for manipulation of semiconductor plates, solar elements and printed circuit boards [8]. Application of BGD in polygraphy at production and the subsequent use of lithographic printing forms [9] is also known, in the food industry for manipulation of cut meat [10] and vegetable [11] plates, in the textile industry [12]. There is a wide prospects of application of BGD in pharmaceutical industry.

It is most of all investigated and introduced on production BGD with cylindrical or circular nozzle and vortex grippers. For the purpose of minimization of energy consumption of Bernoulli gripping device when performing handling operations by authors of the article the method of optimization of gripper orientation in the course of manipulation was developed. The method of optimization of Bernoulli gripping device orientation when performing transport operations on a rectilinear and arc trajectory is provided in the articles [13-14]. Influence of force of front resistance of Q1, Q2 on the minimum necessary lifting force is investigated in article [15]. The description of experimental installation and the analysis of the received experimental results on application of a method of optimization of Bernoulli gripping device orientation is described in the paper [16]. Gasdynamic analysis of the Bernoulli grippers interaction with the surface of flat objects with displacement of the center of mass carried out in [17-18]. Also authors in the article [19] deals with the topical issue of reducing energy consumption for transportation of industrial objects. The energy efficiency of the process of objects manipulation with the use of the orientation optimization method while gripping with the help of different methods has been studied. The economic efficiency of the use of the optimal orientation of Bernoulli gripping device while transporting the object of manipulation in comparison to the transportation without re-orientation has been proved. Influence of parameters of a gripping system on power expenses of the industrial robot during transportation is investigated in article [20]. The dynamics of the air flow between interacting surfaces of Bernoulli-Vacuum gripping device and object of manipulation is analyzed in article [21].

The analysis of publications shows that the problem of optimization of a design of Bernoulli gripping devices is relevant and expedient, considering expansion of the sphere of their use in productions. It is insufficiently studied and demand a further research of a condition and dynamics of a gas flow in a nozzle and in a radial interval between the interacting surfaces of BGD and OM, methods of increase in energy efficiency of these devices due to optimization of their design parameters.

In this article we will consider influence of a form of a nozzle of the BGD on its operational characteristics. For the solution of an objective we use approaches of hydrodynamics computation and information technologies for imitating numerical modeling by the finite element method (FEM). FEM allows to define distributions of pressure, speeds with high precision, to receive lines of a current and other parameters of flows.

2. Methodology

The principle of work of BGD consists in the following. Compressed air through nozzle 1 of the the Bernoulli gripping device (Figure 1) via nozzle 2 by radius rn follows into the camera between its face surface and the surface of OM 3. At the same time on r_n radius, at $h_c<r_n/2$, the stream experiences the biggest narrowing. In the place of the biggest narrowing, with excessive pressures of food of gripper by compressed air more than 30 kPa, the stream reaches critical speed, equal to acoustic speed for these conditions. As a result of further increase in the area of radial stream, its supersonic speed grows, and the static pressure upon surface of OM decreases to size smaller than atmospheric.

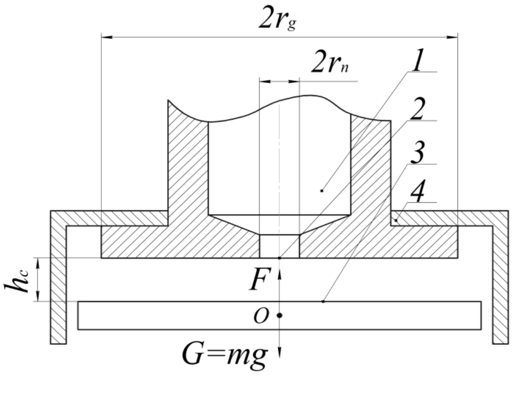


Figure 1. Constructive scheme of BGD.

At some distance from the center of nozzle there is hard braking of supersonic stream, to the subsequent its transition in subsonic that is followed by formation of pressure jump. As a result of further of times expansions the speed of subsonic stream falls, and static pressure in spacing slowly increases up to the size of atmospheric pa. Action of depression on surface of OM leads to its levitation. Side offset of OM prevent thrust blocks 4.

Key parameters which influence the most on power and account characteristics of the BGD are an air pressure in camera 1, nozzle radius r_n, outer radius of capture r_g and distance of h_c from edge of a nozzle to OM.

The mathematical model of course of air in radial interval between the interacting surfaces of BGD and OM is based on Navier-Stokes's (Reynolds averaged Navier-Stokes equations) equations (RANS) average according to Reynolds [22, 23]. For carrying out modeling the SST-model of turbulence [24] and γ-model of laminar and turbulent transition are used [25].

γ-model of laminar and turbulent transition is described by one differential equation for intermittency coefficient γ:

$$\frac{\partial(\rho\gamma)}{\partial t}+\frac{\partial(\rho V_j\gamma)}{\partial x_j}=P_\gamma-E_\gamma+\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\gamma}\right)\frac{\partial\gamma}{\partial x_j}\right] \tag{1}$$

where ρ - air density; t – time; x – coordinate; V – vector of air velocity; P_γ, E_γ - respectively generative and dissipation members of managing directors of laminar and turbulent transition; μ - molecular dynamic viscosity of gas; μ_t - turbulent dynamic viscosity of gas; $\sigma_\gamma=1.0$ - model constant.

In γ-model of transition use the modified equations of the SST-model:

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_j}(\rho V_j k)=\tilde{P}_k+P_k^{\lim}-\tilde{D}_k+\frac{\partial}{\partial x_j}\left((\mu+\sigma_k\mu_t)\frac{\partial k}{\partial x_j}\right) \tag{2}$$

$$\frac{\partial}{\partial t}(\rho\omega)+\frac{\partial}{\partial x_j}(\rho V_j\omega)=\alpha\frac{P_k}{v_t}-D_\omega+Cd_\omega+\frac{\partial}{\partial x_j}\left((\mu+\sigma_\omega\mu_t)\frac{\partial\omega}{\partial x_j}\right) \tag{3}$$

$$\tilde{P}_k=\gamma P_k \tag{4}$$

$$\tilde{D}_k=\max(\gamma,0.1)\cdot D_k \tag{5}$$

$$\mu_t=p\frac{a_1\cdot k}{\max(a_1\cdot\omega,F_2\cdot S)} \tag{6}$$

$$S_{ij}=\frac{1}{2}\left(\frac{\partial V_i}{\partial x_j}+\frac{\partial V_j}{\partial x_i}\right);\quad S^2=2S_{ij}S_{ij} \tag{7}$$

where k - kinetic turbulent energy; ω - the specific speed of dissipation of kinetic energy of turbulence; P_k, D_k - original generation and dissipation of the SST model; $P_k^{\lim}$ - the additional part, which provides the correct gain of turbulent viscosity in transitional area at very low level of turbulent viscosity of the running stream; v_t - turbulent kinematic viscosity of gas; σ_k, α, a_1 - empirical constants of model.

The generative member in the equation (1) looks like:

$$P_\gamma = F_{length} \rho S \gamma (1-\gamma) F_{onset} \tag{8}$$

where F_{length} is empirical correlation which controls length of the transitional area (accept F_{length} = 100); F_{onset} is the function controlling the provision of the beginning of transition.

Dissipation member which is responsible for arelaminarization:

$$E_\gamma = c_{a2} \rho \Omega \gamma F_{turb} (c_{e2} \gamma - 1) \tag{9}$$

where c_{a2}=0.06, c_{e2}=50 – empirical constants; $\Omega = \sqrt{2\Omega_{i,j}\Omega_{i,j}}$ - invariant of the tensor of vorticity; $F_{turb} = e^{-\left(\frac{R_T}{2}\right)^4}$; $R_T = \frac{\rho k}{\mu \omega}$.

The provision of the beginning of process of laminar and turbulent transition is controlled by the following functions:

$$F_{onset1} = \frac{\mathrm{Re}_v}{2.2\,\mathrm{Re}_{\theta c}}, \quad \mathrm{Re}_v = \frac{\rho d_\omega^2 S}{\mu}; \tag{10}$$

$$F_{onset2} = \min(F_{onset1}, 2.0); \tag{11}$$

$$F_{onset3} = \max\left(1 - \left(\frac{R_T}{3.5}\right)^3, 0\right); \tag{12}$$

$$F_{onset} = \max(F_{onset2} - F_{onset3}, 0); \tag{13}$$

where d_ω - distance to the next wall.

The value of a critical Reynolds number of an impulse loss $\mathrm{Re}_{\theta c}$ is calculated with the help of an algebraic ratio with use of local variables [25]:

$$\mathrm{Re}_{\theta c} = f(TU_L, \lambda_{\theta L}). \tag{14}$$

Generation of P_k is counted by means of a formula Kato-Launder:

$$P_k = \mu_t S \Omega. \tag{15}$$

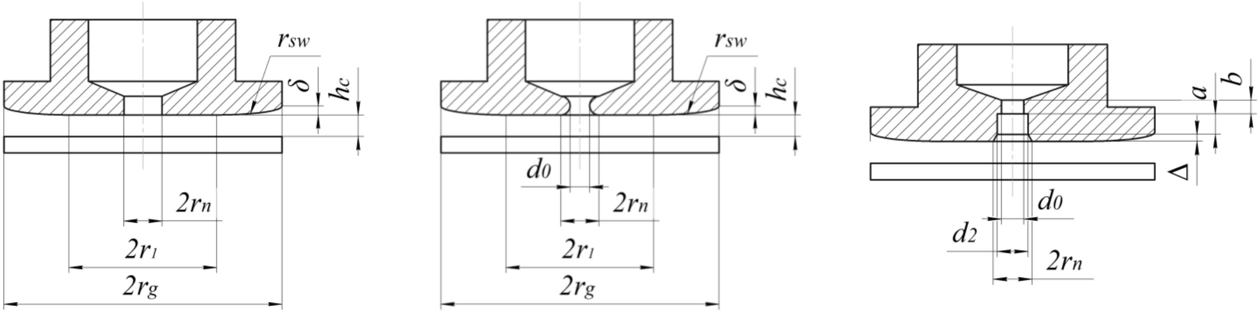
The additional member $P_k^{\lim}$ is defined as follows:

$$P_k^{\lim} = 5C_k \max(\gamma - 0.2, 0)(1-\gamma) F_{on}^{\lim} \max(3C_{SEP}\mu - \mu_t, 0) S\Omega;$$
$$C_k = 1.0, \quad C_{SEP} = 1.0; \tag{16}$$

$$F_{on}^{\lim} = \min\left(\max\left(\frac{\mathrm{Re}_V}{2.2 \cdot \mathrm{Re}_{\theta c}^{\lim}} - 1,\ 0\right), 3\right); \quad \mathrm{Re}_{\theta c}^{\lim} = 1100. \tag{17}$$

3. Results and discussions

The attractions of an object of manipulation by Bernoulli gripper are connected with a formation of object of depression zone on the surface. However, opposite to a nozzle the zone of the excessive pressure which is using the force on OM repellent is formed and leads to decrease in loading capacity of the BGD. Minimization of this force requires special profiling of a nozzle of the BGD. For this purpose, except a cylindrical nozzle, two cases of special configuration are considered, presented on Figure 2. Diameter of a bottleneck of the rounded-off or step nozzle should be chosen from a condition that the area of its section $\pi d_0^2/4$ was on 30... 50% are more than the area of critical section $S^* = 2\pi r_n h_c$.



a) b) c)

Figure 2. Options of design snuffled the JGD: a) cylindrical nozzle; b) rounded nozzle; c) stepped nozzle with a conic facet.

Unlike Figure 1 instead of a flat active surface of BGD the combination of a flat and toroidal surface is used. Such profiling of an active surface of the BGD will allow to reduce losses of energy of a flow by viscous friction in radial an interval and to increase extent of expansion of air flow. As a result, the size of a supersonic zone of depression will increase by surfaces of OM and depression size in a subsonic zone, will increase power characteristics of BGD on 50...70%. Generally attraction force power of Bernoulli gripping of an object of manipulation is defined by integration of distribution of depression $(p_a - p_r)$ in radial an interval:

$$F = 2\pi\int_0^{r_g}(p_a - p_r)\,rdr. \tag{18}$$

where p_r – an absolute air pressure in the radial gap of the radius r.

For definition of distribution of pressure upon surfaces of object of manipulation numerical modeling of the BGD with such geometrical parameters is carried out: external BGD radius r_g=30 mm, nozzle radius r_n=3 mm, diameter of the smallest section round and stepped of nozzle of d_0=2.5 mm, height of radial interval of h_c=0.2 mm, width round ache facets δ=0.3 mm, radius r_1=12 mm. For a stepped nozzle: d_2=4 mm, Δ=0.4 mm, a=3.6 mm, b=2 mm.

Numerical modeling was carried out in the environment of computing hydro-gas dynamics by Ansys-CFX with use of SST of γ-model of turbulence. For carrying out calculations means this program environments in settlement area have constructed unstructured final and differential grid. The total number of knots in settlement area makes 3 million. Knots of grid are united in volume elements (tetrahedrons and prisms). Total number of volume elements of grid it is equal to 7 million. The total number of tetrahedrons makes 3 million. As material are used air as ideal gas from libraries of the program. Boundary conditions for model of air flow are presented on Figure 3.

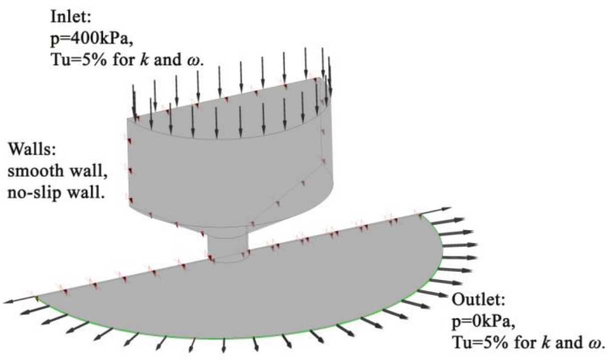


Figure 3. Extreme conditions for air flow model.

By the results of the executed calculations with use decisive the sonicTurbFoam module (for turbulent streams of the compressed gases moving with sound and supersonic speeds) schedules of distribution of pressure upon surfaces of OM have been constructed (Figure 4).

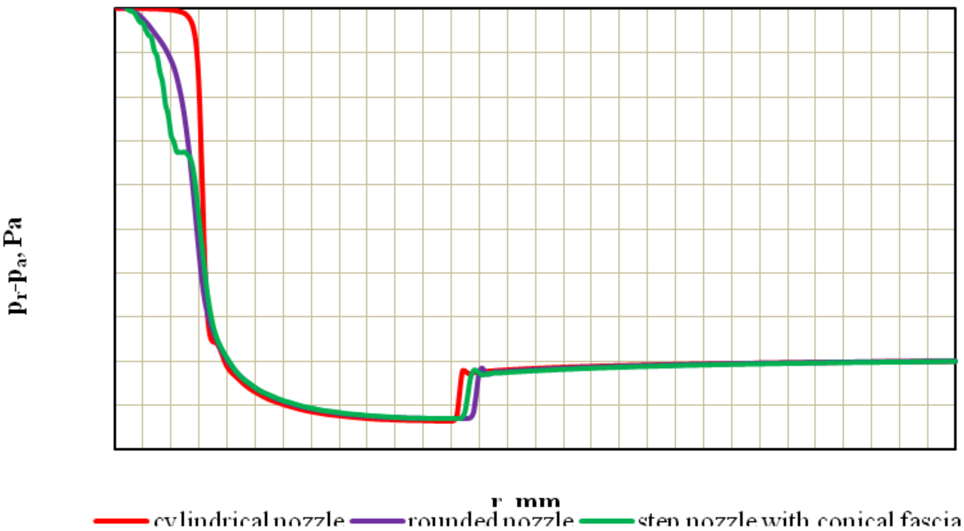


Figure 4. Schedules of distribution of pressure upon surfaces of object of manipulation for various options of design of BGD.

The fluid value of a radial interval h_c has more significant effect on distribution of pressure upon surfaces of an object of manipulation and resultant loading capacity of the BGD and also on a consumption of compressed air. For identification of nature of this influence modeling of dynamics of a flow for number of fixed values of radial gaps is carried out. Thus, here is obtained data on distribution of pressure upon surfaces of OM and a consumption of compressed air for various options of design of BGD at various values of radial gaps. It is carried out calculations of force of an attraction of an object of manipulation of Bernoulli gripper. Results of modeling and additional calculations are presented on Figure 5, 6.

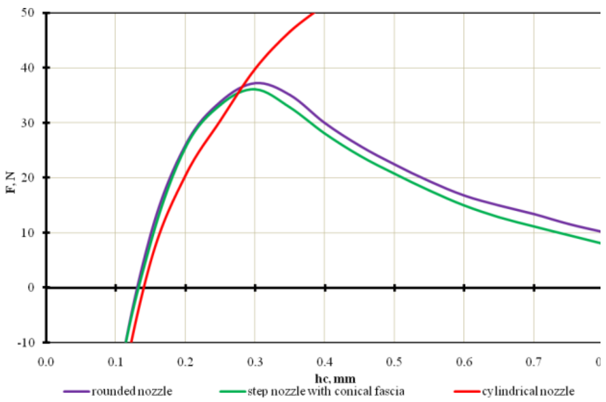


Figure 5. Dependence of the attraction force of an object of manipulation on the magnitude of the radial gap

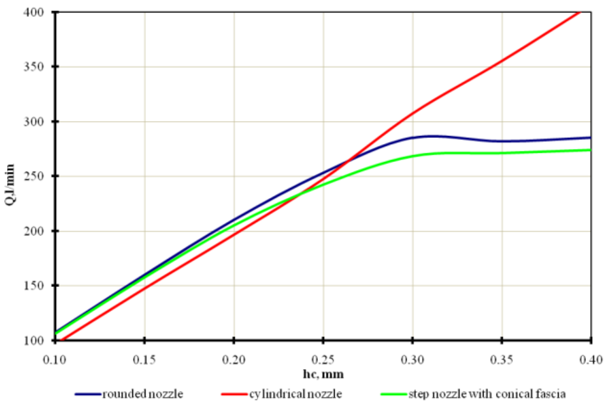


Figure 6. The dependence of the volumetric flow of compressed air on the size of the radial gap

The analysis of Figure 6, 7 proves the efficiency of the use of BGD with rounded and stepped nozzles in the range of radial gaps h_c=0.15...0.25 mm.

For a detailed analysis of the energy efficiency of the BGD in a static mode, when the object of manipulation is already gripped and occupies a fixed position, it is expedient to use the K_{ef} [N/W], which characterizes the ratio of the magnitude of the force of attraction F to the power consumption E

$$K_{ef} = F/E \qquad (19)$$

$$E = p_a Q \ln\left(p_0 / p_a \right), [26] \qquad (20)$$

where Q is the volume of air flow, brought to normal conditions; p_0 - excessive pressure of the BGD power supply.

The results of calculating the K_{ef} by the formulas (19, 20) and Figure 5, 6 is shown in Figure 7.

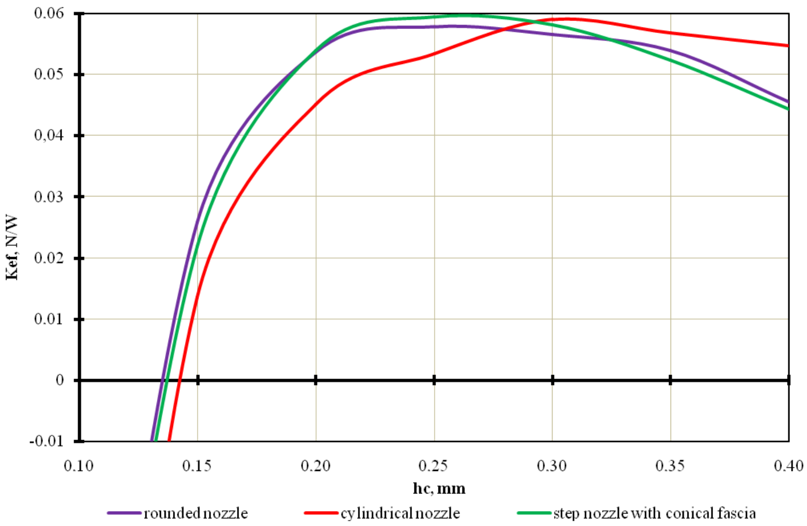


Figure 7. Dependence of K_{ef} on the magnitude of the radial gap for the BGD with different nozzle forms.

Thus, JGD with stepped nozzle and conical fissure reaches the highest energy efficiency in the range of radials hc=0.2...0.3 mm, the gripper with a rounded-off nozzle - at hc<0.2 mm, and a gripper with a cylindrical nozzle - at hc>0.3 mm. However, BGD with a cylindrical nozzle at hc>0.3 mm is inappropriate to operate due to the significant increase in the cost of compressed air. In addition, the highest stability of contactless holding of Bernoulli grippers of objects of manipulation is achieved when the equilibrium position of the trapped object corresponds to radial gaps hc=0.15...0.25 mm [17, 18].

Therefore, in order to increase energy efficiency of the BGD, it is necessary to minimize the energy loss of the air flow at the inlet to the nozzle, when the flow of the radial gap between the active surfaces of the gripper and the object held by it and the loss of the viscous friction in the radial gap is minimized.

4. Conclusions

The mathematical dependences for numerical simulation of the air flow dynamics in the nozzle of the Bernoulli gripping device and in the radial gap between its active surface and the surface of the object of manipulation are presented.

The variants of improvement of the shape of the Bernoulli nozzle gripping devices of industrial robots are offered. It is established that when using the Bernoulli gripper of a rounded or stepped nozzle with a tapered facet in the construction, the excess pressure on the surface of the object of manipulation in the area opposite the nozzle is reduced and the width of the supersonic zone of dilution increases. This allows you to increase the lifting capacity of the Bernoulli gripper by an average of 26%.

The dependences for calculating the energy efficiency of Bernoulli grippers in static mode are presented. It has been found that jet nozzles with rounded nozzle achieve the highest energy efficiency at radial intervals smaller than 0.2 mm, and grippers with a stepped nozzle and conical faces - in the range 0.2...0.3 mm. The highest stability of contactless gripping by Bernoulli grippers of objects of manipulation is achieved when the equilibrium position of the gripped object corresponds to radial gaps of 0.15...0.25 mm.

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