MATHEMATİCAL MODEL OF VORTEX VACUUM ROBOT GRİPPER TO DETERMİNE İTS CARRYİNG CAPACİTY

Yegana Novruz Aliyeva, Sakina Mammad Abbasova
Azerbaijan State Oil and Industry University, Baku, Azerbaijan:
yegane.aliyeva.1969@mail.ru, abbasovasakina@rambler.ru
https://orcid.org/0000-0002-4211-9806, https://orcid.org/0000-0002-9213-5273

Abstract. Analysis of the quality and reliability of the results of boundary layer formation depending on the parameters of gas flow calculation, separation of the device connection model into finite elements was carried out in ANSYS FLUENT environment using the finite element method.

The results of calculations on the obtained analytical dependencies show high convergence with the calculations obtained by more complex modeling in the Ansys Fluent environment. They also include items with different surface shapes to provide gripping of items with different surface shapes while generating the technologically necessary gripping force. When manipulating different types of objects, stringent requirements are placed on the handle to ensure the safety of the surfaces it interacts with. Sometimes it is necessary to equip robots with interchangeable grippers to meet the requirements of the gripper.

Keywords: *Ansys Fluent, manipulation, vacuum grip, vortex, finite elements*.

Introduction

The ability of industrial robots to perform the tasks of gripping objects, holding them securely during transfer and accurately positioning them at given positions has required the creation of a large number of different gripping devices.

When calculating and designing the gripping device of the considered type, the dimensions of the vacuum chamber and the carrying capacity of the device, determined by the mass of manipulation objects and the dynamics of the gripping device movement together with the object, are set as initial parameters. Consideration of the conditions of equilibrium of all forces allows us to determine the carrying capacity of the vacuum gripping device. At first, the bearing capacity is determined in the absence of motion, when only gravity and lifting force of the gripper act on the gripped object with a flat, horizontally oriented surface. This means that the gap is stabilized so that the lifting force of the gripper slightly exceeds the gravitational force acting on the object [1].

Main part

The object must be in equilibrium when they act together; this condition imposes constraints on the masses of the objects to be carried on the one hand, and on the other hand, on the dynamic forces acting on the objects during the transfer. The force distributions lead to the conclusion that bending of the grasped object occurs, and this may be important for the determination of the strength conditions. Also, for very thin objects in the form of sheets, deformations, in particular creases, can be significant, leading to significant changes in clearances. In relation to the forces of gravity and the forces of inertia, factors such as center of mass displacements and angular orientation of the gripping device are also important.

Vortex motion of gases in the considered problems always has nonstationarity, which is accompanied by significant pressure pulsations, gas flow regimes are turbulent. However, in the simplified theory only constant, stationary components of velocities and pressures are considered.

The curve (Figure 1) shows that in the region from the axis to a certain radius the flow rotates with almost constant angular velocity $w \approx 19 (1/s)$. In vortex theory, this zone rotating with w=const is called a forced vortex [2]. In the peripheral region of the chamber the angular velocity decreases sharply with increasing radius, and near the wall in the boundary layer it drops to zero. The law of velocity variation in this region, especially in cross-sections close to the nozzle cross-section, approaches the law of potential fluid flow. In the theory of vortex effect this flow is called free vortex.

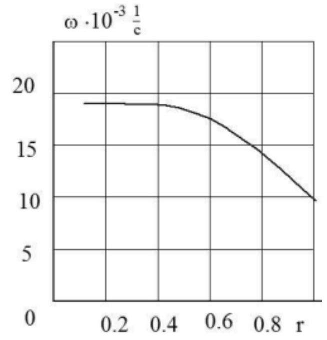

Fig. 1. Distribution of angular velocity of the rotating gas mass in the nozzle section of a vortex tube with a diameter of 30 mm along the relative radius r=r1/R

The second component of the problem solved in the course of research is the problem of destruction of the jet exiting the nozzle, which ends the channel of compressed gas supply. The velocity V of flow from the nozzle for the pre-critical regime, when it is less than the speed of sound $V<V^*$ is determined by the expression

$$V = \sqrt{\frac{2P}{\rho}} \tag{1}$$

and in the subcritical regime the velocity remains constant and equal to the speed of sound V*.

Let us consider the use of compressed air as a working gas. At pressure in the compressed air line P =0.5 MPa, the flow from the pipeline with a diameter of 2 mm is subcritical [3].

After the air flows into the chamber, it expands with a pressure drop to approximately atmospheric pressure (from 0.5 MPa to 0.1 MPa, i.e. 5 times). If the pipeline directly enters the chamber, the expansion occurs uniformly in all directions. To obtain directional expansion tangential to the vortex, a nozzle is used. A nozzle is a nozzle in which the potential energy of compressed gas is converted into kinetic energy; along the nozzle axis, the velocity of the moving air increases to the critical velocity and the pressure decreases. The absolute pressure decreases toward the nozzle outlet section, and the velocity can increase substantially, resulting in an increase in the angular velocity of the rotating air mass in the chamber.

The problems of aerodynamics of the processes occurring in a vortex vacuum gripping device are rather complicated. The mathematical model of these processes is built on the basis of nonlinear partial differential equations of Navier-Stokes under certain boundary conditions. The theory of vortex aerodynamics occupies a significant place in classical monographs on the mechanics of liquids and gases. The theory of vortices in cylindrical chambers has also been developed, but predominantly in relation to technological installations designed for air purification with particulate matter extraction and/or in relation to cooling [5-7].

Such problems are predominantly solved by numerical finite element method. As a result of mathematical modeling, the laws of stationary distribution of velocities and pressures in the vortex chamber after the jets exit from the nozzles were determined. However, first of all, it is necessary to have a convenient for practical use engineering technique for analyzing processes and determining parameters on the basis of rather simple calculation formulas.

Calculation of velocity and pressure distributions in a cylindrical chamber is carried out under the assumption that rotation of a significant part of the gas volume occurs around a fixed vertical axis in the absence of rotational slippage of cylindrical air layers relative to each other, i.e., it is assumed that the velocity distribution is the same as in a solid body when it rotates with angular velocity ω around a fixed axis (Fig. 2). In this case, the velocities at all points are orthogonal to the radii, i.e., they are directed along the tangents to the concentric circles

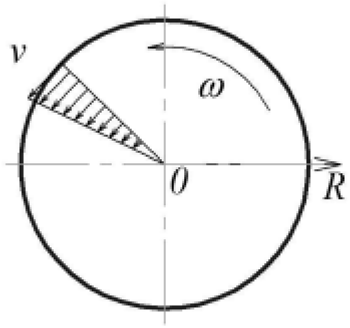

Fig. 2. Distribution of tangential gas velocity in the chamber along the radius

The volume of the gas mass rotating with angular velocity w in the cylindrical volume is bounded by the cylindrical wall of the chamber of radius R. Obviously, under such assumptions, the friction forces of cylindrical layers against each other are absent, and there is no energy dissipation in a significant part of the vortex chamber volume. It can be assumed that friction forces and energy loss occur only at the walls in thin boundary layers, the study of which represents an independent problem solved in a number of works [3].

$$b = R\left(\frac{1}{\sqrt{Re}}\right), \tag{2}$$

where R is the characteristic dimension (we can consider that it is the chamber radius), and Re is the Reynolds number, which is expressed by the relation

$$Re = \frac{\rho V R}{\mu} \tag{3}$$

where ρ is the air density, V is the vortex velocity (average), μ is the dynamic viscosity coefficient. In this work, the boundary layers, the thickness of which, estimated by the above formulas for typical chamber parameters, as applied to vacuum vortex gripping devices, is of the order of 0.1R, is small, and therefore, the influence of boundary layers on the pressure (rarefaction) distribution and the values of the gripping device lifting force for the steady-state mode can be neglected. The fact that the boundary layer thickness is small is confirmed by the results of computer modeling using the finite element method. It is also assumed that the distribution of velocities and pressures does not change along the height of the chamber. However, it is necessary to take into account the compressibility of the gas, i.e., the dependence of the density ρ on the pressure p varying along the radius. In accordance with the adopted model, the tangential velocity V(r) at radius r is determined by the expression

$$V(r) = \omega r = \frac{V_0 r}{R}, \tag{4}$$

where ω is the angular velocity and V_0 is the linear velocity at the wall (actually at the boundary with the boundary layer). The value $V_0 = V\tau(R)$ of the tangential air velocity at the chamber wall is ultimately determined by the kinetic momentum of air jets from nozzles, i.e., the product of the nozzle flow velocity (in the problems under consideration, it is the sound velocity Vkr, i.e., close to 360 m/s) by the mass flow rate [8]. However, recalculation to the velocity V_0 is difficult; it is only clear that at a constant flow rate of incoming compressed air through the nozzles, the velocity V_0 (practically - averaged over the height) is smaller the greater the height of the chamber. It is further assumed that the velocity distribution in the chamber does not depend on the coordinate z along the chamber axis. Accordingly, it is assumed that the absolute pressure in the gas p(r) and its density ρ(r) depend only on the radius r. It is assumed that the temperature is constant throughout the volume, so the process is isothermal; then the density is proportional to the pressure

$$\frac{\rho(r)}{\rho(R)} = \frac{p(r)}{p(R)} \tag{5}$$

It is also possible to assume that the process is isoentropic, then the above relation must be changed. In the further derivation of the formulas, the pressure p(R) and density ρ(R) at the wall are assumed to be known. To derive the pressure distribution along the radius, consider a thin layer between two cylinders of radii r and (r+dr), respectively. As the gas rotates, a distributed radial volume load ρω 2r from centrifugal forces acts on each layer, and as a consequence the pressure and, respectively, the density ρ change. On a positive increment dr of radius r there is a positive increment of pressure dp(r)

$$dp(r) = \rho(r)\,\omega^2 r\,dr \tag{6}$$

Using the relation (5) relating pressure to density, we obtain instead (6):

$$\frac{dp(r)}{p(r)} = \frac{\rho(R)\omega^2 r}{p(R)} \tag{7}$$

Integrating over the variable r in the range from an arbitrary value of r to the boundary r=R, we obtain

$$\ln(r) = \frac{\rho(R)\omega^2 r^2}{2p(R)} + C \tag{8}$$

where C is an arbitrary constant. After its definition from the boundary condition p(R) at r=R, we finally obtain an expression for the relative change of the degree of rarefaction along the radius r:

$$\frac{p(r)}{p(R)} = \exp\left[-\frac{\rho(R)\omega^2 (R^2 - r^2)}{2p(R)}\right] \tag{9}$$

Thus, the formula of pressure variation along the radius coincides with the formula of Gaussian distribution, the center of which is shifted relative to zero (r = 0) to the edge. At the center on the chamber axis (i.e., at r = 0), the minimum pressure value is obtained:

$$\frac{p(0)}{p(R)} = \exp\left[-\frac{\rho(R)\omega^2 R^2}{2p(R)}\right] = \exp\left[-\frac{\rho(R)V^2 R}{2p(R)}\right] \tag{10}$$

This expression defines the maximum rarefaction. The exponent in expression (10) is the exponent of the exponent, which is the ratio of the velocity head at the chamber wall (at r = R) to the static pressure also at the wall:

$$F_в = 2\pi \int_0^R \left(p(r) - p_0\right) r\,dr \tag{11}$$

The integral within (0, R) is not expressed through elementary functions, but is expressed through the integral of probabilities or must be calculated numerically. The determination of the pressure drop (from p(R) to atmospheric p_0) at the exit (at r = R), i.e., when air exits the chamber through the annular slit, is an independent problem, the solution of which can be found in the monograph [9]. However, if the annular width of the slit is assumed to be small, the radial component of the flow velocity from the slit can be determined from the energy conservation condition

$$\frac{\rho(R)V_r^2(R)}{2} \approx [p(R) - p_0] = \Delta p \tag{12}$$

Relations (10) and (12) are two equations with respect to two unknowns Vr(R) and p(R). When solving them, it is necessary to set different values of the gap z. The assumption often made that the pressure p(R) can be considered close to atmospheric pressure (p(R) ≈ 0.1 MPa) is not justified, and this pressure value must be found from the conditions of equality of flow rate through the slot and gas inflow through the nozzles.

Further, we need to use the condition of air mass constancy in the chamber, i.e., the equality of air flow rates through n nozzles with inner diameter d and flowing out through the gap between the chamber edge and the object surface. This condition has the form:

$$\frac{\pi n d^2 \rho^* V^*}{4} = 2V_r(R)\pi R z \rho(R) \tag{13}$$

where V* and ρ* are respectively velocity and density in front of the gap. Hence, at n=2 the expression for the gap is obtained:

$$z = \frac{d^2 \rho^* V^*}{4R\,\rho_0\,V_r} \tag{14}$$

At d=2 mm, assuming that V(R)/V* = 0.5, we obtain z = 0.6 mm. Note that in the absence of stops positioning the object, the constant value of the gap cannot be set, it is obtained as a result of using the obtained solution of the problem. However, in another case, when the position of the object relative to the camera is set by setting the stops, and this unambiguously determines the width of the slot, we can be guided by this value. When the gripping device is supplied from the compressed air network, the velocity of flow from the nozzle is close to the speed of sound V* ≈ 340 m/s, and the density ρ* ≈ 5 kg/m3 . After substituting (13) into (12), we obtain the following dependences of overpressure Δp = [p(R) - p0] and radial velocity Vr(R) on the gap z:

$$V_r(R) = \frac{nd^2 \rho^* V^*}{8Rz\rho(R)} \tag{15}$$

$$\Delta p = \frac{n^2 d^4 \rho^{*2} V^{*2}}{128 R^2 z^2 \rho(R)} \tag{16}$$

For the case of a gripper with two nozzles of 2 mm diameter connected to a standard compressed air network with a pressure of 0.5 MPa we have:

$$\Delta p = \frac{0.281}{R^2 z^2 \rho(R)} \tag{17}$$

These formulas are valid only for the range of variation of the gap z for which the vortex is conserved. The results of calculations according to formulas (10) and (12) are presented in the form of graphs depicting the dependences of the ratio of the rarefaction index in the center on the vortex velocity at the wall, shown in Figure 3.

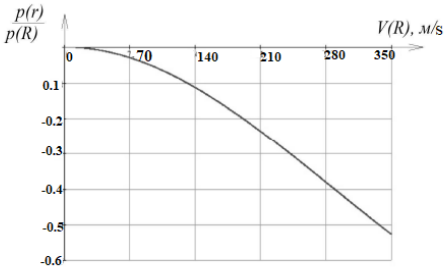

Fig. 3. Dependence of the rarefaction index on the velocity at the chamber wall

It can be seen that the rarefaction index p(0)/p(R)= 0.5 is achieved at very high velocity V * ≈ 300 m/s, close to sonic velocity. At substantially lower subsonic velocities, instead of (9) for the distribution of the degree of rarefaction, it is reasonable to limit ourselves to the first two terms of the decomposition into a step series,then approximately

$$\frac{p(r)}{p(R)} \approx 1 - \frac{\rho(R)\omega^2(R^2 - r^2)}{2p(R)} \tag{18}$$

and in the center, at r=0

$$\frac{p(0)}{p(R)} \approx 1 - \frac{\rho(R)V^2(R)}{2p(R)} \tag{19}$$

Using the approximate expression (17), the lifting force Fc, can be found as an integral over the area:

$$\begin{aligned} F_в &= 2\pi\int_0^R (p(r) - p_0)rdr = 2\pi\int_0^R \left[p(R) - \frac{\rho(R)\omega^2(R^2 - r^2)}{2} - p_0 \right] rdr = \\ &= -\frac{\pi}{4}R^4\rho(R)\omega^2 + \pi R^2 p(R) - \pi R^2 p_0 \end{aligned} \tag{20}$$

If we take the chamber radius R=0,025m, r(R) =1kg/m3 as the air density under normal conditions (atmospheric pressure), and the pressure at the periphery of the vortex chamber to be equal to p(R)=0,1MPa, we obtain the value of the lifting force: Fv = 72N.

As a result of numerical calculations without the above simplification, the specified value of the force F is obtained:

$$F_в = 2\pi\int_0^R \left(\exp\left[-\frac{\rho(R)\omega^2 R^2}{2p(R)} \right] - p_0 \right) rdr = 58\ H \tag{21}$$

Thus, the error of calculation by the simplified formula (19) compared to the calculation of the integral (20) by numerical methods (Runge-Kutty) is about 20%. To be fair, it should be noted that if the first three terms in the power series expansion of formula (9) are retained, the expression for the force will take the form:

$$\begin{aligned} F_в &= 2\pi\int_0^R (p(r) - p_0)rdr = 2\pi\int_0^R \left[p(R) - \frac{\rho(R)\omega^2(R^2 - r^2)}{2} + \frac{\rho(R)^2\omega^4(R^2 - r^2)^2}{4} - p_0 \right] rdr = \\ &\pi p(R)R^2 - \pi p_0 R^2 - \frac{\pi R^4\omega^2\rho(R)}{4} + \frac{\pi R^6\omega^4(\rho(R))^2}{24} = 56H \end{aligned}$$

In this case, the value of force F will be equal to 56 N, and the calculation error will be 4%. The question of velocity distribution in the boundary layer at the chamber wall remains open. Obviously, this velocity depends on the number of nozzles and, most importantly, on their diameters. It can be expected that the velocity distribution along the height will be significantly different from the uniform one; it can be assumed that, other things being equal, the velocity distribution will also depend on the geometrical dimensions of the chamber, namely, on the height or volume of the chamber [10,11]. The greater the height, the greater the volume of gas will be driven into rotational motion, the lower the velocities will be and the lower the degree of rarefaction will be. In full-scale experimental studies, it is easier to measure the pressure (rarefaction) or the forces themselves rather than the velocities.

Mathematical modeling of aerodynamics in the vortex chamber is presented below. The results of numerical calculations performed by the finite element method of pressure distribution (reduction with respect o atmospheric pressure) in the working chamber of the gripper are presented in Figure 4, Diagram 2.

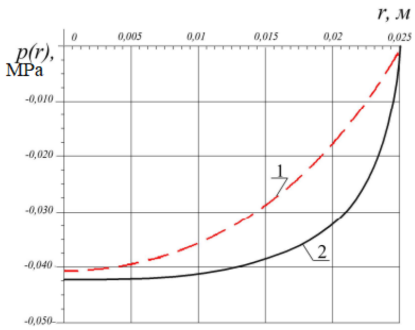

Fig. 4. Graph of pressure change along the radius of the vortex chamber, calculated analytically - 1 and in ANSYS Fluent – 2

Figure 4, graph 1 shows the analytically obtained graph of pressure distribution in the working chamber of the gripper. Figures 4 show that the analytical solution is close enough to the numerical one. The analytically obtained approximate solution allows to carry out simplified express-calculations, which is necessary at the initial stages of design of the gripping device of the considered type. To solve the problem of parametric optimization of the gripping device it is advisable to use numerical simulation of the processes occurring in the vortex chamber of the vacuum vortex gripping device[5, p. 215-240]. From the results of the calculations it follows that the level of rarefaction, which was achieved in the calculations of the vortex chamber with a diameter of 50 mm, is 0.04MPa, and the vortex gripping device with a chamber diameter of 150 mm was able to statically hold an object with a mass of 29kg. Characteristics of two variants of the device with different chamber diameters are presented in table.

Characteristics of vacuum vortex non-contact grippers

Vacuum chamber diameter, mm	50	150
Nozzle diameter, mm	2	3
Maximum design mass of the load held statically, kg	7.8	29
Compressed gas flow rate, l/min	210	622
Supply pressure, MPa	0.6	0.6
Vortex velocity at the periphery of the vacuum chamber, m/s	320	310

The obtained characteristics of vacuum gripping devices allow using these gripping devices for solving many practical problems, including manipulation tasks in robotic technological systems.

The above dependences (19-20) can be used in the design of a vacuum vortex chamber. Designing a vacuum vortex chamber for a gripping device provides a reasonable choice of its geometric parameters and nozzle parameters, as well as compressed air pressure. The main geometrical parameters are: diameter D, height h of the chamber, nozzle diameter and their number, width of the vacuum chamber body side above the annular gap between the gripping device and the object to be carried. Compressed air can be supplied from an independent pump or from a central line; in the second case, it should be taken into account that the actual pressure can be much lower than the industry standard pressure (e.g. 0.4 MPa).

Conclusions

In the course of the research, it is shown that there is a stable equilibrium position during object holding along with the unstable equilibrium position. Moreover, the system "gripper-object of holding" passes the unstable equilibrium position at the moment of gripping the manipulation object and determines the distance from which the gripping process begins.

Mathematical models of vortex gripping devices designed for automation of technological processes and operations requiring limited impact on the manipulation object have been developed.

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