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Optimization of outer diameter of Bernoulli gripper

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ABSTRACT

A Bernoulli gripper is a pneumatic manipulator, capable of sucking and gripping. It is widely employed in automated production lines. It uses an axisymmetric radial airflow to create negative pressure that produces suction force. In this study, an important design parameter, namely, the outer diameter, is addressed both theoretically and experimentally. First, a theoretical model of the air flow between the gripper and the workpiece is created, based on which the theoretical formulas for calculating the pressure distribution and suction force are derived. It is found that the outer diameter of the gripper has a major impact on the suction force, and its design is closely related to the gap height and the supply mass flow rate. Then, the relationship between the outer diameter and the suction force and that between the gap height and the suction force are discussed, based on which a method for finding the optimal outer diameter is presented. Meanwhile, the pressure distribution is investigated in an attempt to explain the impact of the variation in the outer diameter on the flow phenomenon. Finally, the values of the optimal outer diameter for a range of supply mass flow rates are calculated and the tendency of the optimal outer diameter to change with the supply mass flow rate is revealed, which is of great importance to the design of a Bernoulli gripper.

1. Introduction

A Bernoulli gripper is a pneumatic manipulator, capable of sucking and gripping. As shown in Fig. 1, its main components are a disk and a hole in the center of the disk. On the underside of the disk, several rubber pads form an axisymmetric gap between the disk and the workpiece. Driven by the upstream pressure, the air flows through the central hole and then into the axisymmetric gap after changing direction. Because of the increase in the section area, the air slows down while flowing through the axisymmetric gap. According to Bernoulli's principle, the pressure rises as the flow velocity decreases, which means that the pressure on the inner perimeter is lower than that on the outer perimeter. Since the atmospheric pressure is acting on the outer perimeter, a subatmospheric pressure (hereafter referred to as a negative pressure) acts on the inner perimeter of the disk. The negative pressure causes an upward suction force to be exerted on the workpiece. As a result, Bernoulli grippers are widely used as a suction tool. Giesen et al. and Brun and Melkote used Bernoulli grippers to suck and carry flat workpieces [1–3], e.g., solar panels. Furthermore, Li and Kagawa built a device based on a Bernoulli gripper that could suck a silicon wafer without actually touching it [4]. In addition, the most important difference between a Bernoulli gripper and a traditional rubber vacuum cup is that the Bernoulli gripper continues to exhaust outwards while generating a negative pressure, and this exhaust flow prevents the outside air from flowing into the negative-pressure region within the inner perimeter of the disk. Therefore, even if the surface of a workpiece is very rough, the Bernoulli gripper can maintain a vacuum. This feature of a Bernoulli gripper allows not only the sucking of smooth workpieces, but also rough and irregularly shaped workpieces, such as soft and rough leather [5,6], and slices of foodstuff such as tomatoes and bread [7,8].

Because of a Bernoulli gripper's practical application value, researchers continue to work on the optimization of its design. The earliest research report on a Bernoulli gripper was presented by Welanetz and Syosset in 1956. In their report, they illustrated the mechanism whereby a Bernoulli gripper generates a negative pressure and a suction force [9]. Later, researchers installed rubber pads on the bottom of the gripper to fix the gap height between the gripper and the workpiece, so that the effect of the gap height on the suction force could be eliminated. Meanwhile, the friction force caused by the contact between the rubber pads and the workpiece prevents the workpiece from slipping or falling while being moved horizontally [2,3]. To eliminate the repulsive force resulting from the impact of the supply air flow on the workpiece in the central region, many researchers have introduced a deflector (also called

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Nomenclature

Symbol			
D	outer diameter of the tested gripper [m]	P_{0t}	total pressure at center ($r = 0$) [Pa]
d	diameter of the central air-supply hole [m]	R	gas constant (= 287) [J/(kg K)]
D_{max}	optimum outer diameter when gap height is fixed [m]	r	radial position [m]
D_{opt}	optimum outer diameter [m]	r_{edg}	radial position where $Re = 2000$ [m]
F	suction force [N]	Re	Reynolds number [–]
F_{gap}	suction force formed by gap flow [N]	T	temperature [K]
F_{jet}	repulsive force formed by jet flow [N]	u	velocity of airflow [m/s]
F_{max}	maximum suction force [N]	$\bar{u}$	average velocity [m/s]
G	supply mass flow rate [kg/s]	$\bar{u}_{d/2}$	radial average velocity at gap entrance ($r = d/2$) [m/s]
h	gap height [m]	$\bar{u}_{in}$	average velocity through central hole [m/s]
h_{max}	optimum gap height when outer diameter is fixed [m]	z	vertical position [m]
h_{opt}	optimum gap height [m]	λ	pressure loss function [–]
P	pressure [Pa]	μ	coefficient of viscosity [Pa s]
$P_{d/2}$	pressure at gap entrance ($r = d/2$) [Pa]	ρ	air density [kg/m^3]
P_{edg}	pressure where $r = r_{edg}$ [Pa]	$\rho_{d/2}$	air density at gap entrance ($r = d/2$) [kg/m^3]
P_0	atmospheric pressure [Pa]	ρ_0	air density at the center ($r = 0$) [kg/m^3]
		τ	viscous stress [N/m^2]

the "core" or "cone mill" in articles by Giesen et al. and Brun and Melkote, respectively) [1,3,5] in the center of the gripper. Another function of such a deflector is to increase the velocity of the air flow when it enters the gap, so that the deceleration of the air flow is enhanced and, therefore, the suction force is increased. In addition, Petterson et al. designed a Bernoulli gripper capable of sucking 3D objects [8]. They replaced the disk with a deformable surface that can conform to the surface of a range of 3D objects. The deformable surface forms a gap on the curved surface and thus generates a negative pressure distribution. This innovative design greatly extends the application range of the Bernoulli gripper.

According to our literature review, there is no study that addresses another design element, namely, the outer diameter. Therefore, in this study, we set out to examine the role of the outer diameter both theoretically and experimentally.

2. Theoretical modeling

As shown in Fig. 1, the force created by a Bernoulli gripper and applied to a workpiece can be divided into two parts: the first part, denoted by F_{jet}, is the repulsive force of the jet flow from the central air-supply hole, caused by the effect of the high-speed air flow striking the surface of the workpiece. Another part, denoted by F_{gap}, is the suction force caused by the negative pressure distribution formed by the gap flow. Regarding the latter, some researchers have used the momentum equation for an ideal fluid to describe the pressure distribution $P(r)$ and to calculate F_{gap}, as given by the following equations [5,7,8]:

$$P = P_0 + \frac{G^2}{8\pi^2 h^2 \rho}\left(\frac{4}{D^2} - \frac{1}{r^2}\right) \tag{1}$$

$$F_{gap} = \frac{G^2}{8\pi h^2 \rho}\left(2\ln\frac{D}{d} + \frac{d^2}{D^2} - 1\right) \tag{2}$$

where P_0 is the atmospheric pressure, G is the supply mass flow rate, h is the height of the gap between the gripper and the workpiece, ρ is the density of air, D is the outer diameter of the gripper, r is the radial position, and d is the diameter of the air-supply hole. The above equations lead to two conclusions: (1) F_{gap} becomes infinite when h becomes very small; (2) F_{gap} also becomes infinite when the outer diameter of gripper D becomes very large. Obviously, neither of these conclusions can be true, because the viscous effect, which plays an important role in the gap flow, has been neglected. Welanetz and Syosset, Takenaka et al., Savage, Jackson and Symmons, Moller, and Waltham et al. took the viscosity of air into consideration, but neglected the compressibility of air [9–14], which means that their models become invalid when the Mach number exceeds 0.3. Based on the above-mentioned studies, Li and Kagawa theoretically separated the inertial effect (i.e., the deceleration of the air flow) and the viscous effect, and compared their effects on the suction force. Meanwhile, they provided considerable supporting data on the pressure distribution and force [4]. These efforts produced an F–h curve, representing the relationship between the suction force and the gap height, which is convex rather than monotonic, as shown in Fig. 2(a). Therefore, there is a maximum suction force F_{max}, and the corresponding gap height is denoted by h_{max}; however, the experimental results for the pressure distribution shown in Fig. 2(b) indicate that when $h = h_{max}$ (i.e., $F = F_{max}$), the absolute value of the negative pressure is not maximum. Li and Kagawa indicated that, when $h < h_{max}$, both the inertial and viscous effects are enhanced as the gap height decreases. This enhancing of the inertial effect is reflected in the increase in the absolute value of the negative pressure in the small-radius region, while the enhancing of the viscous effect is reflected in the increase in the absolute value of the positive pressure in the large-radius region. However, the enhanced amplitude of the viscous effect is larger than that of the inertial effect [4]. Therefore, as a whole, the reduction in the gap height reduces the suction force. It is thus possible to speculate that a reduction in the outer diameter of the gripper may reduce the positive pressure in the large-radius region

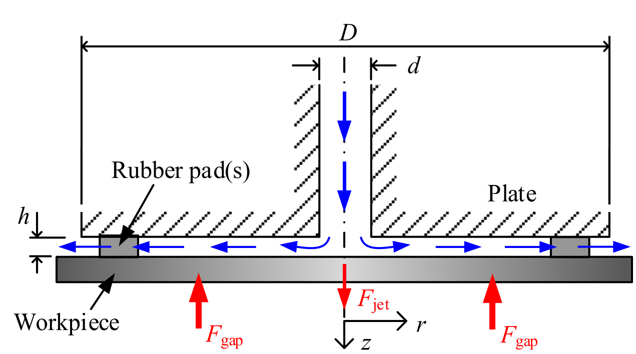

Fig. 1. Schematic of a Bernoulli gripper.