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Effect of supply flow rate on performance of pneumatic non-contact gripper using vortex flow

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ABSTRACT

The vortex gripper is a new kind of non-contact gripper, which generates negative pressure by blowing compressed air into a vortex cup through two tangential nozzles. It can provide an adequate suction force for handling a workpiece without contact. This gripper can avoid the disadvantages of traditional gripping devices, such as inducing mechanical scratches, local stress concentration, frictional static electricity, and blots on the workpiece. In this study, we experimentally and theoretically investigated the effect of supply flow rate on the performance of the vortex gripper. First, we proposed three performance indexes for evaluating the properties of the vortex gripper: the maximum force, suspension region, and suspension stiffness. Then, we obtained a series of *F*–*h* (i.e., the suction force against the spacing between the gripper and the workpiece) curves at different supply flow rates and the pressure distributions at the surface of the workpiece for different values of spacing *h*. Based on the experimental data, we analyzed the effect of the supply flow rate on the maximum force, and by nondimensionalization of the *F*–*h* curves, the changes in the suspension region were assessed. Furthermore, we proposed an additive method of pressure distribution and deduced a simplified theoretical formula for suspension stiffness. In addition, from the perspective of the suspension stability of the workpiece, we evaluated the physical significance of the slope of the *F*–*h* curves after nondimensionalization. The findings of this study could help researchers to comprehend the operation of the vortex gripper and provide guidance for implementing the vortex gripper in practical applications.

1. Introduction

On automatic production lines, the workpiece frequently needs to be gripped and transported. Thus Fantoni et al. provided a review of grippers and robotic hands in automated production processes [1]. Mechanical paws and rubber suction cups are the most commonly used end-effectors, but because they have to make contact with the workpiece, they may cause some damage to it. For instance, they may induce mechanical scratches, local stress concentration, frictional static electricity, or blots on the workpiece. Such damage is usually fatal to precision workpieces such as LCD glass substrates, and silicon wafers [2,3]. Furthermore, in the food and pharmaceutical industries, contact between the end-effector and the workpiece may cause contamination, reducing the quality of the products. In addition, usually they need control strategies which are sometimes very complicated. In order to solve these problems, researchers have developed a variety of noncontact handling devices. For instance, Rawal et al. developed a noncontact end effector for handling of bakery products [4]; Li and Kagawa proposed a noncontact gripper using swirl vanes [5]; Ozcelik et al. designed a noncontact end-effector for handling of garments and evaluated the results of handling various materials [6,7]; Davis et al. developed an end effector based on the Bernoulli principle for handling sliced fruit and vegetables [8]. Among them, the pneumatic non-contact gripper, which uses air as the force transmission medium, is widely used. It does not produce a magnetic field or need feedback control. In addition, it has a simple construction and is easy to maintain.

The vortex gripper, a new kind of non-contact gripper, was proposed recently. It generates negative pressure and suction force by using a high-speed vortex airflow and can grip the workpiece without any contact. Compared with traditional pneumatic non-contact grippers (e.g., Bernoulli gripper [8,9]), the vortex gripper has the advantage of low gas consumption. As a result, many related researches have been carried out and reported in recent years. In 2008, Li et al. experimentally investigated the fundamental characteristics of the vortex gripper, namely the pressure distribution and the suction force [10]. They deduced that there exists a very small space under the vortex gripper in which the suction force is

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positively associated with the spacing between the gripper and the workpiece, i.e., the slope of the *F*–*h* curve is positive. Thus, the workpiece can be stably suspended at a certain distance under the gripper. In another research, Li et al. analyzed the velocity and pressure fields inside the vortex gripper in detail using numerical fluid dynamics calculations, which revealed the relationship between flow velocity and pressure distribution [11]. Iio et al. observed the form of the vortex flow in an underwater environment [12]. Moreover, Wu et al. obtained experimental data of velocity distribution using visual equipment and the particle image velocimetry (PIV) method and proposed several empirical formulae for the velocity distribution of vortex flow [13].

However, all these researches were focused on the description and analysis of the physical phenomena. There have been no studies on the operation parameters of the vortex gripper, which are more important from the user's point of view. In particular, the supply flow rate of the compressed air is a significant operation parameter, as it is the only parameter that users can adjust because others (e.g., the design parameters) have been determined already. Therefore, it is important to understand how the performance of the vortex gripper changes as the supply flow rate varies. Based on these considerations, we experimentally and theoretically studied the effect of supply flow rate on the performance of the vortex gripper. We first proposed three performance indexes for evaluating the characteristics of the vortex gripper, and then we analyzed the effect of the supply flow rate on each of these performance indexes. Table 1 is the nomenclature of the alphabetic characters that we used in this paper.

2. Proposed performance indexes for vortex gripper

2.1. Principle of vortex gripper

As shown in Fig. 1, the basic structure of the vortex gripper includes a cylindrical vortex chamber and two tangential nozzles, which are processed on the circular wall of the chamber. Compressed air blows into the vortex chamber through the tangential nozzles and forms a high-speed vortex flow along the internal face of the chamber. Similar to a tornado, the centrifugal force produced by the vortex flow pushes the air in the center towards the peripheral region of the chamber, and thus a negative pressure zone with rarefied air is created at the center. As a result, a suction force will be applied on a workpiece placed under the gripper, which can then be picked up. In addition, as compressed air is constantly supplied through the nozzles into the vortex chamber, the airflow will continually vent through the gap between the gripper and the workpiece. This exhaust flow ensures that there will be no contact between the gripper and the workpiece.

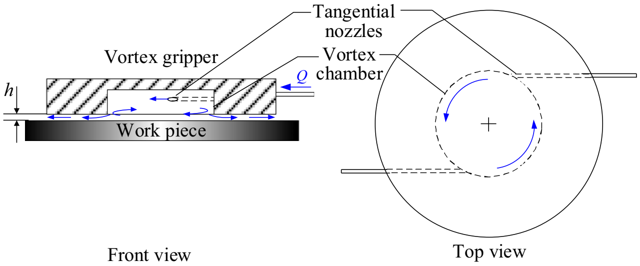

Fig. 1. Schematic of vortex gripper.

Table 1
Nomenclature.

Symbol	Quantity	SI Unit
d	Diameter of tangential nozzles	mm
F	Suction force	N
$F_{\max}$	Maximum force	N
g	Acceleration due to gravity	m/s^2
h	Spacing between gripper and workpiece	mm
h_B	Spacing at stable suspension position	mm
h_C	Diameter of tangential nozzles	mm
$h_{\max}$	Optimum spacing	mm
H	Height of vortex chamber	mm
H_1	Height of upper part of vortex chamber	mm
H_2	Height of lower part of vortex chamber	mm
k_B	Suspension stiffness	N/mm
k'_B	Suspension stiffness after nondimensionalization	mm^{-1}
L	Distance between nozzle and central point	mm
m	Mass of workpiece	kg
p	Pressure	Pa
p_1	Pressure distribution dominated by vortex flow	Pa
p_2	Pressure distribution dominated by gap flow	Pa
Q	Supply flow rate	L/min (ANR)
r, z	Cylindrical coordinates	–
R_1	Radius of vortex chamber	mm
R_2	Radius of annular skirt	mm
u_a	Circumferential velocity	m/s
u_r	Radial velocity	m/s
$\overline{u_r}$	The average radial velocity	m/s
ρ	Air density	kg/m^3
η	Gripping coefficient	–
μ	Coefficient of viscosity	Pa·s

2.2. Performance indexes

To study the application of the vortex gripper in non-contact handling, we propose three performance indexes based on the suction force characteristic curve (*F*–*h* curve): maximum force, suspension region, and suspension stiffness. In this section, we elaborate on the definition and physical meaning of these three indexes.

(1) Maximum force

The study by Li et al. [10] reported that the suction force *F* changes when the spacing between the vortex gripper and workpiece, *h*, changes. Fig. 2 shows a typical *F*–*h* curve for a given supply condition. When *h* is small, the gripper generates a repulsive force on the workpiece. As *h* increases, the repulsive force reduces to zero, and then a suction force is generated. After the suction force reaches a maximum, it decreases gradually. The maximum of the curve, marked by A, corresponds to the maximum suction force $F_{\max}$, which is generated at the spacing of $h_{\max}$. Therefore, the gripper can pick up a workpiece whose weight is less than $F_{\max}$, that is,

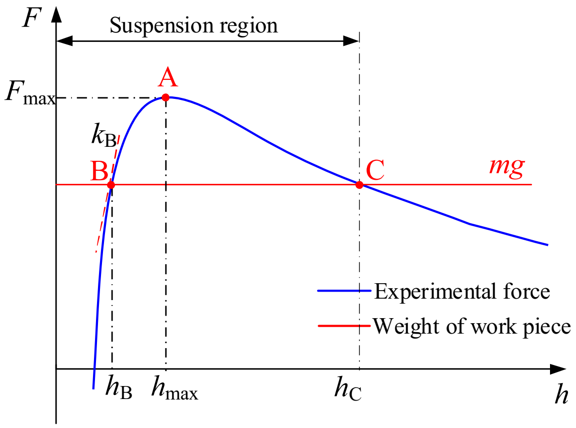

Fig. 2. The definition of performance index.