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Quantitative study on the attachment and detachment of a passive suction cup

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ABSTRACT

To quantitatively evaluate requirements of a suction cup to achieve attachment and detachment on a wall, this paper presents the force analyses and conducts experimental verification for a common commercially available passive suction cup. The entire operation process, including the initial, pushing, attachment and detachment phases, are presented. By designing and using a test bed, optimal pushing force that ensures complete attachment of the suction cup is defined and experimentally verified. Other factors that influence the attachment and detachment of the suction cup, such as the area of the vacuum zone on the cup-wall contact surface and the internal elastic force from the elastic deformation of the suction cup, are experimentally investigated. The methods proposed in this study can be used on other types of suction cups and are valuable in guiding the design of suction-cup-based devices, such as wall-climbing robots.

1. Introduction

Suction cups are commonly adopted in the design of wall-climbing robots [1–5], since they can adhere to smooth surfaces without damaging the surface or leaving any hazardous residue. Suction cups can be generally classified into two types: active and passive. Active suction cups used in [1, 2] maintain their interior vacuum via actively actuated pumps that enable easy control of the attachment and detachment mechanism. However, to maintain attachment, energy must be continuously supplied to the pump. The presence of a pump also increases the weight of the wall-climbing robot [3]. In contrast, passive suction cups are light weight and produce only low noise levels as they do not require active pumps. However, the attachment and detachment of passive suction cups are difficult to control [4–6].

In our previous studies [7, 8], we proposed a simple method to achieve wall-climbing motion with only one actuator by adopting passive suction cups. The suction cups, fastened on an actively actuated belt, were forced to follow a designated trajectory along a guide rail, and a compliant tail is designed for balancing the payloads on the suction cups. Though experimental results on this robot have shown the potential of using passive suction cups in a wall-climbing robot, the optimal design of the guide rail is unclear. Consequently, our developed robot is sensitive to the failure of the suction cups.

Though analysis and experimental studies on diverse types of suction cups can be found in literature [9–11], a better understanding of the working process of the suction cup is required to ensure robot safety and performance. As such, the objective of this study intends is to determine the optimal working process and to quantitatively identify the main factors affecting the attachment and detachment of the suction cup.

The rest of the paper is organized as follows: Section 2 presents the operation process and a force analysis of a commercially available passive suction cup. Section 3 describes the experimental setup and procedures used in this study. Experimental results are discussed in Section 4. Finally, Section 5 concludes the present work.

2. Force analysis of a suction cup

2.1. Operation process of the suction cup

The suction cup studied, as shown in Fig. 1 (a), is a commercially available suction cup which is made of polyvinyl chloride with a Young's modulus of 4.6 Mpa. It consists of two parts: a flexible cup

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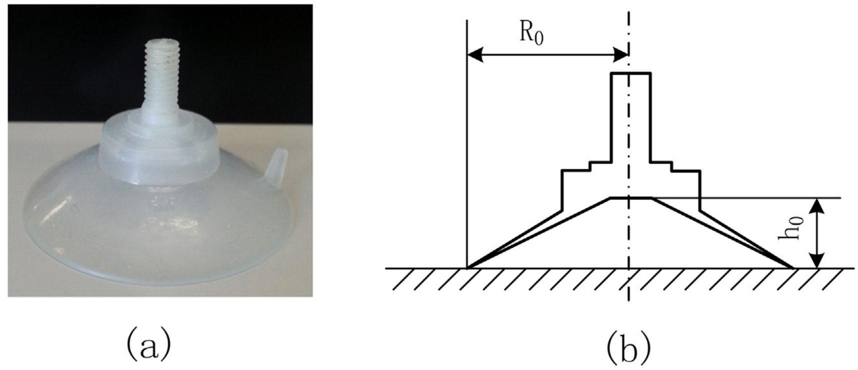

Fig. 1. Commercially available passive suction cup tested in this study. (a) Photo of the suction cup. (b) Section view of the suction cup.

and a rigid handle. The cup is the working part that is in contact with the wall, whereas the payload is exerted on its handle. The natural height and rim radius of the cup, denoted as h_0 and R_0, respectively, are illustrated in Fig. 1 (b).

As shown in Fig. 2, once the suction cup is in contact with the wall, a margin on the cup-wall contact surface is covered by the suction cup. This margin is known as the cover zone. Interior of the cover zone beneath the inner cavity of the suction cup is defined as the vacuum zone Ω_v, whereas the exterior zone is the contact zone Ω_c. Areas of the vacuum zone and the contact zone are called the vacuum area and the contact area, denoted as A_v and A_c, respectively.

The typical operations of a suction cup can be divided into four phases, i.e., the initial phase, the pushing phase, the attached phase and the detached phase, as shown in Fig. 3. In the initial phase, the suction cup is in contact with the wall surface without any payload. Once an external pushing force is applied to the handle of the suction cup, the cup enters the pushing phase, wherein the cup deforms and the air inside the cup is squeezed out. Once the pushing force reaches its peak value, the cup enters the attached phase. In this phase, the suction cup adheres to the contact surface and acquires a new force balance under the gauge pressure force and the external payload force. Note that the external payload force can be a pushing force or a pulling force, according to its acting direction. If the direction of the payload force is towards the wall, it is a pushing force. If the payload force is a pulling force and exceeds the maximum air pressure force (namely the detachment force), the suction cup detaches from the surface and then enters detached phase.

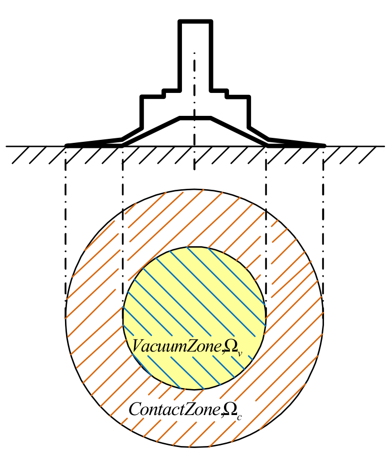

Fig. 2. Schematic diagram of the vacuum zone and the contact zone on the cup-wall contact surface.

To provide sufficient payload capability for a suction-cup-equipped wall-climbing robot, the interior air in the suction cup should be sufficiently squeezed out during the pressing phase. As the pushing force increases, more air is expelled from the suction cup until the rigid part of the suction cup reaches the contact surface. In other words, the suction cup becomes completely attached. Once the suction cup is completely attached, further deformation of the cup and air expulsion are not possible, regardless of the extent of the pushing force. In such circumstances, as the volume of the squeezed air reaches its maximum value, the detachment force required to detach the cup from surface is maximized. The maximum detachment force is known as the potential detachment force. The minimal pushing force (also called the optimal pushing force) required for the suction cup to reach its potential detachment force is a critical characteristics of the suction cup. In the following section, we conduct force analysis and experimental studies on the optimal pushing force and the potential detachment force.

2.2. Forces acting on the suction cup

To analyze the relationship of the payload force and the gauge pressure force, the force equilibrium conditions in the pushing and attached phase are examined. Furthermore, in both phases, only the direction of the payload force is different, and therefore, general forms of the force equilibrium equations are presented in this study.

Fig. 4 (a) shows the force equilibrium condition of the suction cup on the wall under an external payload force **F**. For the sake of simplicity, only the forces in the y direction are analyzed in the current stage. As the weight of the suction cup is sufficiently small, it can be safely ignored in our analysis. Therefore, the forces acting on the suction cup include the atmospheric pressure force, the internal air pressure force consisting of the internal contact air pressure force and the internal cavity air pressure force, the normal force, the payload force and the internal elastic force (the internal force between the contact and cavity sections of the cup). In this analysis, the internal contact pressure force is ignored. As the force is generated by the internal contact pressure on interspace of contact area, it is small enough to be ignored.

When only considering the normal force, the resultant distribution of the normal force on the cup-wall contact surface (**N**), can be expressed as follows:

$$\mathbf{N} = \oint_{\Omega_c} \hat{\mathbf{y}} \sigma_{Nc} dA, \tag{1}$$

where Ω_c is the interior contact surface that is in contact with the attached surface, dA is an infinitesimal area on the contact zone of