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Adhesive Pillar Based Air Levitation System for Contactless Manipulation of Fine Objects

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Abstract

This paper introduces the characterization study of a new actuator design -"Adhesive Pillar Based Air Levitation" (APAL) system- to manipulate fine objects in a non-destructive manner. A meso-scale polymer adhesive pillar array manages to gently contact the fine surfaces and moreover adapt variable interface geometries. Air flow, which is fed through the nozzles located across the backing layer of the pillars, levitates the target object located on the top of the pillars and ensures its contactless manipulation. Proposed approach is feasible to be used in conveying, positioning and pick/place operations of fragile objects.

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Keywords: Air levitation; non-contact handling; non-destructive manipulation.

1. Introduction

In many industries like electronics, food and textile, contact between the end-effector and the object during manipulation causes deformations on both the objects and the manipulators such as imprint generation or fractures [1]. Also in biomedical operations, it is quite easy to damage tissues due to stress intensity which makes the operations risky or impractical. To overcome these issues, some actuation systems are being used presently such as magnetic, acoustic and pneumatic levitators [2, 3, 4] or soft end-effectors [5].

The mostly used type of contactless manipulators are pneumatic systems. Present applications widely utilize the Bernoulli principle of flow and generate vacuum forces for manipulation. The tiny air jet flow, which generates the negative pressure, also constitutes an air sheet between the object and the manipulator and prevents the contact. However due to high air flow velocities and centralized bulk forces some destruction still occurs on the target objects. Other contactless manipulator types, acoustic and magnetic, has some throwbacks as having reduced target object groups. Another non-destructive manipulation approach is using soft and elastic materials to grasp objects. Adhesive pillars provide levitation of the objects with less stress and distributed contact area, but still executes the manipulation via contact, which might cause some destructions mentioned above.

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This study proposes a novel approach for non-destructive manipulation by implementing a high aspect ratio polydimethylsiloxane (PDMS) pillar array on a backing layer where air flow is fed through a pressurized chamber. Inlet air is distributed through the nozzles, which are drilled evenly along the backing layer, and impinges to the manipulated object across the pillars. The pressure generated on the impingement surface first defeats the adhesive forces (pull-off forces) between the pillar and the object following the detachment of the object in rest on the pillar tips. Then levitates and stabilizes the object at a certain height. The resulting air cushion between the surfaces provides a safe manipulation. The ability of the polymer pillar structures to adhere to the surfaces when loaded provides a more precise contact interface and distributes the load to the carrying structure. Reduced contact area due to the pillar array structure decreases the pull-off forces occurring in transition to the levitation.

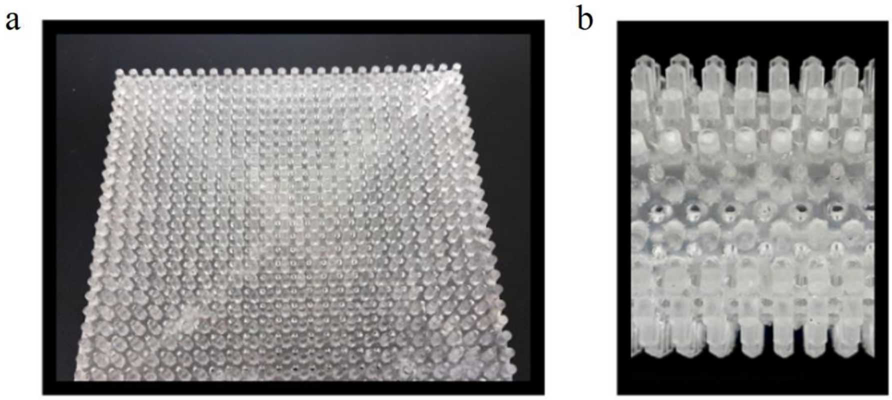

Fig. 1. A view of pillared PDMS structure. Pillar diameter: 2 mm. Aspect ratio of the pillars: 2. Nozzle diameter: 1.5 mm. Backing layer thickness: 3mm. Number of pillars: 26x26. Number of air nozzles: 25x25. (a) Flat view of the array. (b) Bended detailed view of the pillars and air nozzles.

2. Fabrication

Molding technique is used to produce pillar arrays. A master template is made out of polytetrafluoroethylene (PTFE) due to its low friction feature which is sufficient to pull out the high aspect ratio polymer array without destruction. The PTFE replica is formed by drilling holes for pillar formation. PDMS solution (Dow Corning Slygard 184) is vacuumed before and after the casting, in order to supply the complete penetration of the liquid to the high aspect ratio holes in the replica. Backing layer thickness is adjusted at 3 mm, as thick enough not to rip and thin enough to avoid unnecessary energy loss of the air flow. Dried polymer structure is gently pulled off from the template and an acrylic glass supporting layer of 3 mm is fixed beneath the backing layer to avoid the bending of the substructure due to the pressurized air. This integrated structure is then again drilled in between the pillars to open the air nozzles. An acrylic glass feeding room is built to supply air inlet to the nozzles. Structure joints are designed in such a manner that they allow the modularity of the polymer top layer for different experiments and avoids any air leakage. For this purpose, a double side adhesive is applied between the 3 mm supporting layer of the top structure and the open edges of the feeding room.

3. Experiments and Results

3.1. Pull-off force measurement

Before the levitation of the target object via pressured air flow, there would be a finite contact area between the pillar tips and the object surface. As the pillar material, PDMS, has an elastic and adhesive structure, a deformation occurs under the stress generated by the object weight on the pillar tips. After the air pressure is generated on the impingement surface and starts to lift the object with drag forces, adhesive forces constitutes a recalling force, which is known as the “pull-off force” in contact mechanics. These forces effect the dynamics of the structure till the end of the detachment.

To analyze this the JKR (Johnson, Kendall, Roberts) model is used. According to this model the equation which gives the pull-off force between flat object surface and the round elastic pillar tip is as below Eq.1 [6].

$$F_{pu} = \frac{3}{4} \times \pi \times \omega_{Ad} \times d_{pc} \tag{1}$$

Work of adhesion is a parameter which is determined by the pair potential of the contacting material and it is bounded to these materials' surface free energies. Here, a silicon based material is chosen to demonstrate the experiments and the theoretical calculations. The work of adhesion value for PDMS-Silica pair is reported between 40-60 mJ/m^2 [10]. The equivalent work of adhesion is calculated as 55, 3 mJ/m^2 from the pull-off experiments (Figure 2).

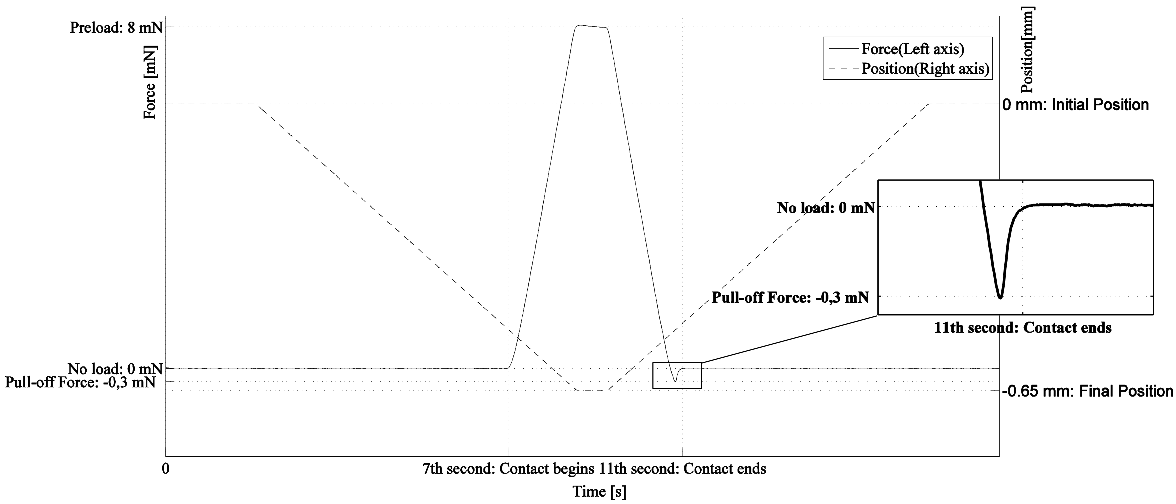

Fig. 2. Pull-off force observation on a single pillar. At the contact zone which is represented with vertical dotted lines, force increases with the increasing displacement and decreases with the decreasing displacement. At the end of the contact zone the pull-off force is detected.

3.2. Pressure transmission experiment

Compared with a conventional distributed air levitator (Fig. 3. a, c), in the proposed design (Fig. 3 b) air flow rushes out from the air nozzles much before impinging the target object surface at rest position. This air release occurs at a level lower than the impingement surface, as lower as the length of the pillars. Within this area the air flow is guided by the pillars.

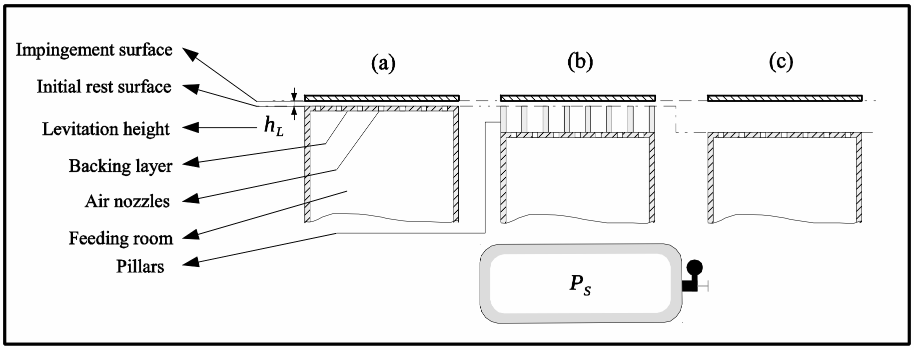

Fig. 3. (a) Construction-a, complete guidance via nozzles; (b) construction-b, partial guidance via pillars; (c) construction-c no guidance.

Supplying the same pressure to the three systems represented in Fig. 3, pressures transferred to the impingement surface are measured and compared. While the comparison between impingement pressures a and b gives the pillar effect for equal levitation heights, comparison between b and c gives the pillar effect for equal heights between the backing layer and the impingement layer. The experiment results are demonstrated in Fig. 4.

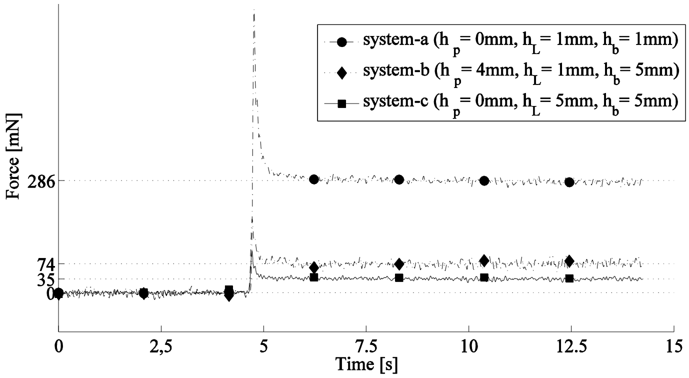

Fig. 4. Impingement force measurements. Number of the pillars: 26x26, number of the nozzles: 25x25, pillar diameter: 2mm, pillar aspect ratio: 2, nozzle diameter: 1.5 mm, nozzle length: 6mm, air supply pressure: 6 bar. Indices for "h" parameter are; "p" for pillar, "L" for levitation and "b" for backing layer.

The impingement surface forces for system a, b, and c are measured as; 286 mN, 74 mN and 35 mN respectively. The pressure values for the same are calculated as, 53 Pa, 14 Pa and 6.5 Pa. As there is no distance between the object rest level and air release level in system-a, there won't be any pressure loss due to lack of guidance. To degree the loss effects of the three system at a scale "0" to "1", it is obvious that system-a would take the value "0". As the system-c doesn't have any structure to guide the flow, it would take the value "1". So the pressure loss ratio (PLR) value for a pillared system is derived as in the Eq. 2 below. The pressure generated by the system-b is approximately 2 times of the pressure generated by the system-c.

$$PLR = 1 - \frac{P_{im}^{b} - P_{im}^{c}}{P_{im}^{a} - P_{im}^{c}} = 1 - \frac{F_{im}^{b} - F_{im}^{c}}{F_{im}^{a} - F_{im}^{c}} = 0.85 \tag{2}$$

The construction for the experiment is selected as the stiffest pillar array to observe the maximum air guidance. Thus the study shows the minimum pressure loss ratio (PLR) can be achieved with an APAL system is "0.85" in a scale of "0" to "1" (Fig. 5).

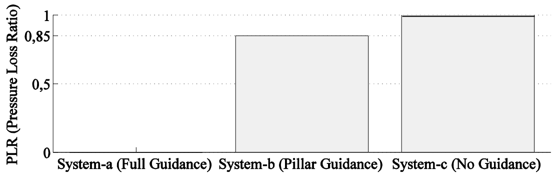

Fig. 5. Air guidance coefficients on a 0 to 1 scale.

4. Conclusion

With the proposed study, the basic limitations of the designed system are observed and analyzed. Fabrication of various construction of the designed system reveal the manufacturing limitation and risks of the design. With the pull-off force experiment the equivalent work of adhesion is verified. The pressure transmission experiment gave the pressure loss degree as 0.85 for the stiffest APAL system. The pressure generation at the same impingement height from the backing layer, pillared system generates approximately 2 times of the pressure generated by the system with the flat backing layer.

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