Study on Adhesion Force Reduction and State Estimation by Piezo-transducer

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Tetsuyou Watanabe , Makoto Iwasaki, Hidekazu Matsumura, and ZhongWei Jiang

***Abstract*— Our previous paper presented a method for reducing adhesion forces by oscillation and showed the adhesion state can be checked by analyzing the data obtained by laser displacement meter. However, there are several problems in this method. 1)The end-effector must be located at the specific point where laser displacement meter can measure oscillation. 2)The adhesion state can not be checked if something blocks the light/laser or the target leaves the measuring point. 3)The total system becomes very large. To resolve these problems, this paper firstly presents a method for checking the adhesion state by piezo-transducer. Next, to achieve more precise manipulation, we propose a method to deform the end-effector by adding DC input to the piezo actuator which is also oscillated simultaneously to reduce adhesion forces. Furthermore, we find that the first mode resonance frequency shifts with the increase of the pushing force applied to the object by the end-effector. Using the shift amount, we develop a method for checking the adhesion state.**

I. Introduction

In a micro range, it is a key issue how to cope with adhesion which arises between an object and tools (see Fig.1). To resolve the problem, many methods have been developed, including the adhesion-type micro end-effector [1], the vacuum gripping tool [2], releasing by slopping and oscillating an end-effector [3]-[5], releasing by control of electrostatic force [6], and releasing strategy based on environment information [7]. However, there are still unresolved problems such as the difficulty of object control after the release [1]-[6], the difficulty of practical execution of the method [7] (since it is almost impossible to acquire all required information).

Recently, we developed a new strategy [8] (see also [9]) to cope with the adhesion force and control the object motion. By minutely oscillating the end-effector and contacting it with (bringing it near to) the object on the substrate (table), the adhesion force between the end-effector and object will become small, comparing with the force between the substrate (table) and the object (see Fig.2). Then, it is easy to remove the end-effector from the object while the object adheres to the substrate. Hereafter, ***we call this (phenomenon) relaxation of adhesion force. If the object is removed from the end-effector at any time, we say the adhesion force is relaxed enough. If it is not and the object sometimes adheres to the end-effector, we say the adhesion force is not relaxed enough***. Using this strategy, we can accurately manipulate micro object like macro manipulation. We also show whether this method is available or not can be checked by laser displacement meter. However, the use of the laser displacement meter causes several problems. 1) The end-effector must be located at the specific point where laser displacement meter can measure oscillation. 2) The adhesion state can not be checked if something blocks the light/laser or the target leaves measuring point. 3) The total system becomes very large. Furthermore, if required fine motion such as micro assembly, both adhesion force relaxation and fine tuning of grasping force are required simultaneously. In our previous paper, we move the end-effector by controlling XYZ stage. Then, one of the methods to get a finer end-effector motion is to make the resolution of the XYZ stage higher. However, practically, it is difficult to get finer motion by this way since we can not ignore errors resulted in play of the clamped end of the end-effector.

Concerning the above, this paper, firstly, presents a method to check the adhesion state by piezo sensor. By applying frequency analysis to the voltage of the piezo sensor induced by oscillation of the end-effector, we check the adhesion state. Next, we propose the method not only to relax the adhesion force but also to finely tune the pushing force applied to the object. By adding DC voltage input to the oscillated piezo actuator, we will deform the end-effector and move its tip point with fine step, relaxing the adhesion force simultaneously. In addition, we find the resonance frequency shifts with the change of the pushing force applied to the object by the end-effector. Using the shift, we develop a method to check adhesion state more accurately. Combining the above methods, we can finely tune the grasping force,

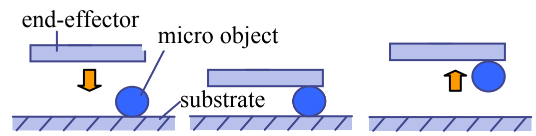

Fig. 1 Micro object adhered to end-effector

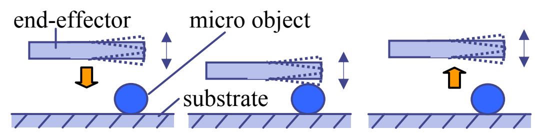

Fig. 2 Relaxation of adhesion force

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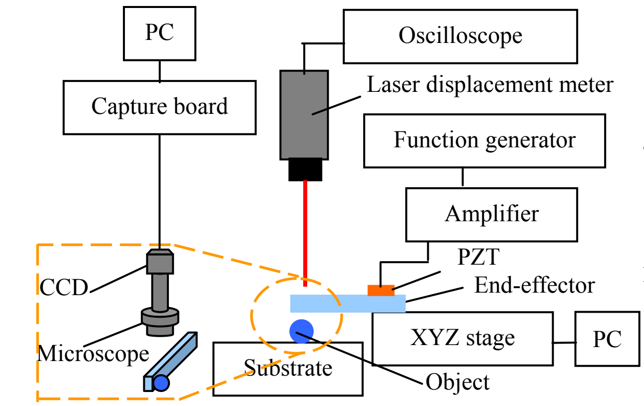

Fig. 3 Overview of the experimental setup

keeping adhesion force relaxed enough.

II. Target System

Fig. 3 shows the target system, which consists of manipulation part, image-capturing part, end-effector-oscillating part, and displacement-measuring part. For the simplicity, we assume that: (1) the manipulation is done in a planner space and a gravity force doesn't work, (2) the object is a sphere, (3) the end-effector and the substrate are made of a same material, (4) the end-effector and the substrate are grounded for preventing an extra charge at the initial state.

The manipulation part consists of end-effector, micro object, and substrate. Fig. 4 shows the overview of the end-effector and the coordinate used in this paper. The end-effector is a cantilever beams made of copper in size of 3x40x0.3[mm]. The beams are rolled copper, and any surface treatments such as grinding are not conducted. Young's modulus of copper is $1.02\mathrm{x}10^{11}$ [N/m^2], Its Poisson's ratio is 0.35, and its density is 8900 [kg/m^3]. On the end-effector, the piezocell (Fuji ceramics, Z0.2T50x50x50S-W C6) of 3x3x0.2 [mm] is bonded at the position of 1 [mm] from the clamped end for oscillating the end-effector. The surface of substrate is a copper cut bonded on an alminum board. The end-effector is attached on XYZ stage (Surugaseiki, PMZG413) which can be controlled by PC. The object is a glass sphere (Union, unibeads) with a radius of 200 [10^{-6}m]. Young's modulus of glass is $7.05\mathrm{x}10^{10}$ [N/m^2]. Its Poisson's ratio is 0.17, and its density is 2500 [kg/m^3].

The image-capturing part consists of microscope (Moritex, ML-Z07545), CCD camera (IAI, CV-S3200), Capture box (Imperx, VCE-PRO), and PC. The overview of the operation is captured by the CCD camera through the microscope and the image is sent to PC.

At the end-effector-oscillating part, the end-effector is oscillated by oscillating the piezocell (bonded on the end-effector) by the function generator (Yokogawa, FG120) through the power amplifier (NF, 4010).

At the displacement-measuring part, the tip motion of the end-effector is measured by laser displacement meter (Sony

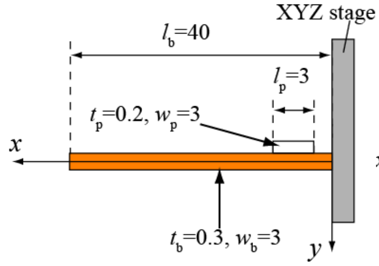

Fig. 4 End-effector and the coordinate.

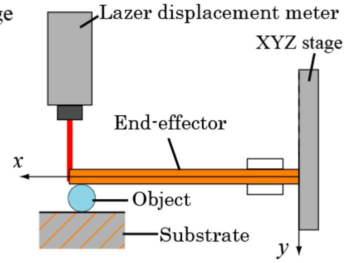

Fig. 5 View of the experiment set up from the microscope side

VL10). The measured data is sent to PC through oscilloscope (Yokogawa DL1700).

III. Estimation of Adhsion State by PZT

A. *Adhesion force relaxation by oscillation*

Here, we introduce the method [8] for relaxing adhesion force by oscillation. In the target system, the effect of capillary force among adhesion forces is the largest. Here, we relax such kind of adhesion force by oscillation. By minutely oscillating the end-effector bringing it near to the object, and contacting it with the object on the substrate, the adhesion force between the end-effector and the object is relaxed. However, this method can not be always available. If the pushing force is large, the effect of the oscillation decreases, and the adhesion force is not relaxed enough. Therefore, adhesion state has to be checked. Here, we show the method for the check. Fig. 5 shows the experimental set up. We set y direction so that y can be orthogonal to the long side of the end-effector as shown in Fig. 4. We move the oscillated end-effector by moving the clamped end by XYZ stage, along y positive direction with the step of 1 [μm] from y(x=0)=-1 to y(x=0)=4 [μm]. Let y(x=0) (the origin) when the end-effector firstly contacts with the object be 0. At the initial state (y(x=0)=-1), the end-effector does not contact with the object. At y(x=0)=0, the end-effector contacts with the object. At y(x=0) ≥ 0, the end-effector pushes the object. y(x=0) corresponds to the magnitude of the pushing force. We measure the oscillation of the end-effector by the laser displacement meter. The input signal for the oscillation is sine curve whose amplitude is 10 [V], and whose frequency is 4th mode frequency (this mode is selected so that enough large kinetic energy can be got while the amplitude is small enough not to disturb the manipulation). The left figures of Fig. 6 shows the data obtained by applying FFT to the measured oscillation. The horizontal axis denotes the frequency and the vertical axis denotes the power spectrum density. At y(x=0)=-1 [μm] (before contact), only inputted 4th mode frequency was observed as shown in Fig. 6 (a). At y(x=0)=0~3 [μm], not only inputted 4th mode frequency but also lower mode frequencies (see the round marks at Fig. 6 (b)) were observed. Fig. 6 (b) shows the typical result. At this range, the adhesion force is thought to be relaxed enough since it was observed that the object did not adhere to the end-effector at any time when moving the end-effector along

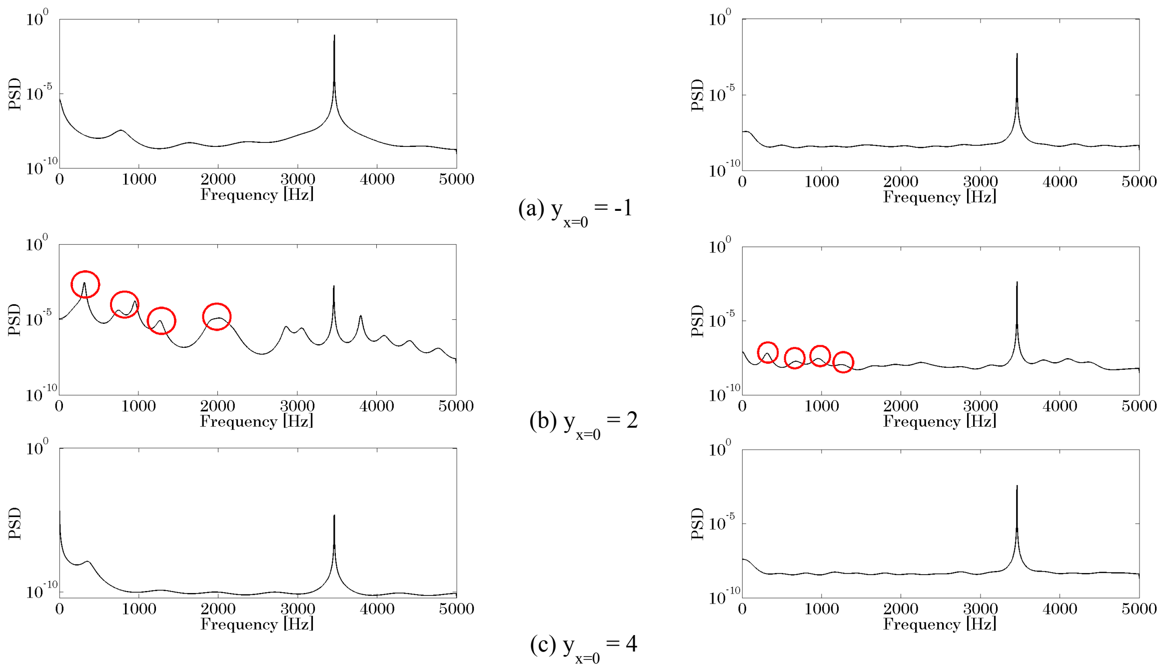

Fig. 6 Experimental results. The left column shows the results obtained by applying FFT to the measured oscillation by laser displacement meter and the right column shows the results obtained by applying FFT to the measured oscillation by the PZT sensor.

y negative direction (the direction of getting away from the object). At *y*(x=0)=4 [μm], only inputted 4th mode frequency was observed as shown in Fig. 6 (c). It is thought that the pushing force was large and then the effect of oscillation decreased. At this range. the adhesion force is not relaxed enough since it was observed that the object adheres to the endeffector sometimes when the end-effector moves along *y* negative direction. Summarizing, Fig. 6 indicates that we can estimate whether adhesion force is relaxed enough or not by checking the excitation of the lower mode frequencies.

B. Estimation of adhesion state by PZT

To resolve the problems in the case when using laser displacement meter as mentioned above, we propose the method to estimate adhesion state by PZT.

Fig. 7 shows the proposed system. PZT for sensing (hereafter, we call PZT sensor) is bonded on the end-effector in addition to PZT for actuating (hereafter, we call PZT actuator). We bonded PZT sensor on the very opposite side of PZT actuator so that the influence of entity of the PZT sensor on the end-effector oscillation can be small. We oscillate the end-effector by oscillating the PZT actuator through the power amplifier. The voltage at the PZT sensor is induced by the oscillation. We measure the voltage by oscilloscope. The measured data is sent to PC.

We did experiment to show the validity of the proposed measuring system. In order to check whether the adhesion force is relaxed enough or not, based on the results of the previous section III.A, we will check the excitation of lower mode peak frequencies in the oscillation (voltage) induced at the PZT sensor.

Similarly with the experiment of the previous section III.A, we moved the oscillated end-effector along *y* positive

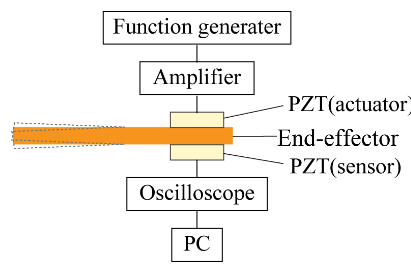

Fig. 7 Overview of the hybrid actuator and sensor system

direction with the step of 1 [μm] from y(x=0)=-1 to y(x=0)=4 [μm] (see Fig.5). The input signal for the oscillation was the same as the previous case. We measured and analyzed the voltage of the PZT sensor induced by the oscillation of the end-effector.

The right figures of Fig. 6 show the data obtained by applying FFT to the induced voltage at the PZT sensor. Similarly with the previous results, At *y*(x=0)=-1 [μm] (before contact), only inputted 4th mode frequency was observed. At *y*(x=0)=0~3 [μm], not only inputted 4th mode frequency but also lower mode frequencies were observed (Fig. 6 (b) shows the typical result). At this range, the adhesion force was relaxed enough. The difference from the previous case in section III A is the followings. 1) 3rd mode frequency (around 2000 [Hz]) was observed at the previous case, while it wasn't observed at this case. 2) The magnitudes of power spectrum densities for lower mode peak frequencies in the previous case were larger than those in this case. These are thought to be due to the bonded position of the PZT sensor. The collocation of PZTs causes that the PZT sensor has low gain in the induced voltage. At *y*(x=0)=4 [μm], only inputted 4th mode frequency was observed. At this range. the adhesion force was not relaxed enough. Summarizing, these results

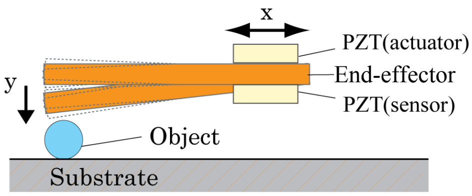

Fig. 8 Displacement induced by DC input

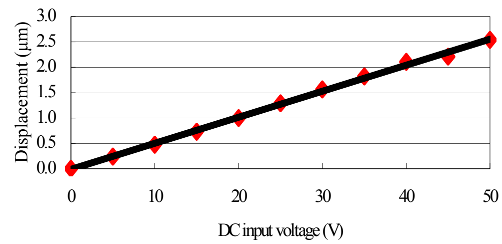

Fig. 9 The relation between DC input voltage and tip displacement

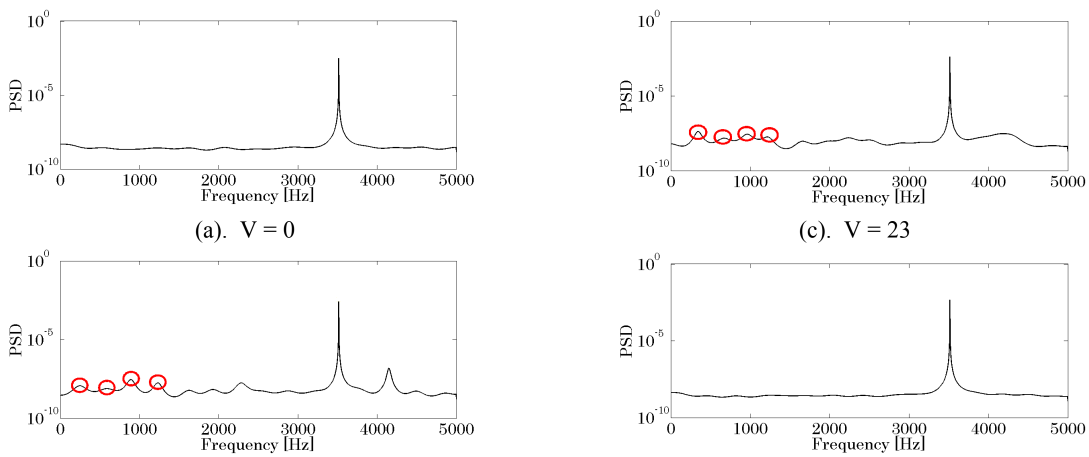

Fig. 10 Experimental results obtained by applying FFT to the induced voltage at the PZT sensor when adding the combined input of the DC and the AC inputs to the PZT actuator.

indicate that we can estimate whether adhesion force is relaxed enough or not by the PZT sensor.

IV. Fine Tuning of Grasping Force by PZT and Ashesion State Control

To achieve both adhesion force relaxation and fine tuning of grasping force simultaneously, we develop a method of adding DC input voltage to the PZT actuator. In addition, we develop a method for adhesion state estimation, based on the shift of lower mode peak frequency which causes due to the change of grasping/pushing force.

A. Tuning of grasping force by adding DC voltage

When adding DC voltage to PZT, a constant amount of distortion arises in a specified direction. Based on this phenomenon, we will change the force applied to the object by adding DC voltage to the PZT actuator as shown in Fig. 8. When adding DC voltage to the PZT, PZT stretches in x direction(see Fig. 8). Due to the stretch, the tip position ($x=l_b$) of the end-effector displaces in y direction. We measure the tip displacement of the end-effector by laser displacement meter when adding DC voltage to the PZT actuator. Fig. 9 shows the results. The horizontal axis denotes the input voltage and the vertical axis denotes the displacement. From Fig. 9, it can be seen that the tip position can be changed with the step of about 0.05 [μm], by increasing the input DC voltage with the step of 1 [V]. Comparing with the case when using XYZ stage to move the end-effector (the resolution is 1 [μm] at our experimental set up), we can move the end-effector more precisely and continuously. Also, we do not have to consider the error due to the play of the clamped end of the end-effector.

Next, we try to achieve both adhesion force relaxation and fine tuning of the pushing force applied to object simultaneously. We add the combined input of AC voltage input for oscillation and DC voltage input for fine motion to the PZT actuator. We did experience to see the validity of this approach. We apply FFT to the voltage of the PZT sensor induced by the oscillation. Using the data of power spectrum density, we will check adhesion state. The input signal for the oscillation was sine curve whose amplitude was 10 [V], and whose frequency was 4th mode resonance frequency. Firstly, we set the input voltage for moving the end-effector was 0 [V]. Then, by increasing the voltage with the step of 1 [V], we brought the end-effector near to the object and contacted it with the object. When the DC input was 7 [V], the end-effector firstly contacted with the object. We increased the DC input until adhesion force was not relaxed enough.

Fig. 10 shows the results obtained by applying frequency analysis to the induced voltage at the PZT sensor. The horizontal axis denotes the frequency and the vertical axis denotes the power spectrum density. At V=0 (~6) [V] (before contact), only inputted 4th mode frequency was observed, similarly with the result of Fig. 6 (a) (see Fig. 10 (a)). At V= 7

~23 [V], not only inputted 4th mode frequency but also lower mode frequencies were observed, similarly with the result of Fig. 6 (b) (see Fig. 10 (b) and (c)). Comparing Fig. 10 (b) with Fig. 10 (c), it can be seen that the peak frequency shifts with the increase of the DC input voltage. From the section III, this range can be regarded as the range where adhesion force is relaxed enough. Then, we did experiment in which at this range, we moved the end-effector along *y* negative direction (the direction of getting away from the object) 10 times. In all cases, the end-effector was removed from the object while the object adhered to the object. It indicates that at this range, the adhesion force is relaxed enough. At V=24 [V], only inputted 4th mode frequency was observed, similarly with the result of Fig. 6 (c) (see Fig. 10 (d)). At this range, relaxing adhesion force is not enough, and we observed that the object sometimes adhered to the end-effector when moving the end-effector along *y* negative direction.

Summarizing, we reveal that 1) we can displace the end-effector tip, relaxing the adhesion force simultaneously, by the combined input of the DC and the AC inputs; 2) The adhesion state can be estimated by checking the excitation of lower mode frequencies.

B. Adhesion state estimation based on peak frequency shift

From the results shown in Fig. 10 (b)~(d), It can be seen that the lower mode peak frequencies shift with the change of pushing force applied to the object by the end-effector. Then, we will judge the adhesion state (whether the adhesion force is relaxed enough or not) by this shift. Among the lower mode peak frequencies, we focus on the 1st mode frequency (the lowest peak frequency) since its shift can be most easily detected.

We did experiment to observe the shift of the peak. We took the same way as the section IV.A. The input signal for the oscillation was sine curve whose amplitude was 10 [V], and whose frequency was 4th mode resonance frequency. Firstly, we set the input voltage for moving the end-effector was 0 [V]. Then, by increasing the voltage with the step of 1 [V], we brought the end-effector near to the object and contacted it with the object. When the DC input was 7 [V], the end-effector firstly contacted with the object. We increased the DC input until adhesion force was not relaxed enough. We applied frequency analysis to the measured voltage of the PZT sensor (induced by oscillation), and observed the shift of the target peak frequency.

Fig. 11 shows the results. The horizontal axis denotes the frequency and the vertical axis denotes the power spectrum density. V=0 is a typical result before contact with the object. The target peak did not appear. Note that in this case, only inputted 4th mode frequency was observed. At V= 7 ~23[V], it can be seen that the target peak frequency shifts from 250 [Hz] to 350 [Hz] with the increase of the DC input voltage (which corresponds to increase of the pushing force). Note that in this range, not only inputted 4th mode frequency but also lower mode frequencies were observed, and the adhesion

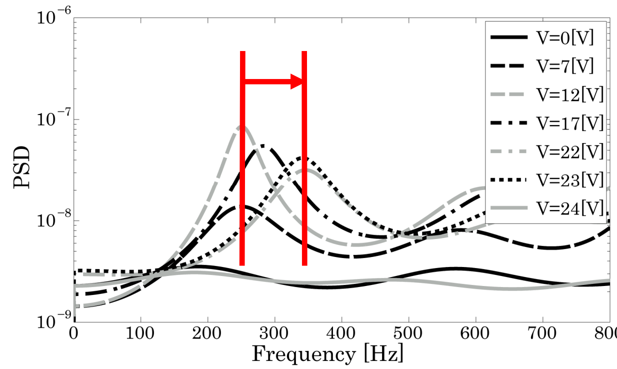

Fig. 11 Shift of target peak frequency

Table 1 Difference from reference point

	Difference (Hz)
Maximum difference	140
Minimum difference	100

force was relaxed enough. At V=24 [V], the target peak frequency did not appear. Note that in this case, only inputted 4th mode frequency was observed and the adhesion force was not relaxed enough.

Then, we will find the range of the target peak frequency where the adhesion force is relaxed enough. First, we set the reference peak frequency is the target peak frequency in the case when the end-effector firstly contacts with the object. Next, we calculate the maximum difference between the reference peak frequency and the target peak frequency at the range where the target peak frequency appears. We did the experiments to calculate the difference 5 times. Table 1 shows the results which show the maximum and minimum differences. To realize the manipulation in which the end-effector can be removed from the object at any time, let the minimum difference (100Hz) be the threshold. If the difference from the reference peak frequency is smaller than the threshold, the target peak frequency will appear at any time. It indicates that adhesion force is relaxed enough. If the difference is larger than the threshold, it cannot be guaranteed that the target peak frequency will appear. Then, it cannot be guaranteed that the adhesion force will be relaxed enough. By controlling the pushing force applied to the object so that the difference from the reference peak frequency can be smaller than the threshold, we can keep the adhesion force relaxed.

We did experiments of keeping the difference from the reference peak frequency smaller than the threshold. We observed that the lower mode frequencies were excited in all cases. It indicates that the adhesion force was relaxed enough in all cases, and the validity of this method were shown.

We summarize the above method and express it as the flow chart shown in Fig. 12. Here is the procedure of the method.

1. By adding the combined voltage input of DC and AC inputs to the PZT actuator, we bring the end-effector near to the object and contact it with the object.

2. We apply frequency analysis to the measured voltage of the PZT sensor.
3. We judge whether or not the end-effector contacts with the object by checking whether or not the lower mode frequencies are excited. If judging the end-effector does not contact with the object, we go back to 1.
4. Let the lowest mode peak frequency in the case when the end-effector firstly contacts with the object be the reference frequency.
5. We control the pushing force applied to the object by controlling the DC input voltage.
6. We apply frequency analysis to the measured voltage of the PZT sensor.
7. We calculate the difference between the reference frequency and the lowest mode peak frequency.
8. If the difference is smaller than the threshold, we judge that the end-effector can push the object more. If it is not, we judge that the end-effector cannot push the object any more. We go back to 5.

V. Conclusion

In our previous paper [8], we proposed a method for reducing adhesion force by oscillation. We also showed that the available range of the method can be checked by analyzing the data obtained by applying FFT to the measured oscillation by laser displacement meter. However, the use of laser displacement meter causes several problems. 1) The end-effector must be located at the specific point where laser displacement meter can measure oscillation. 2) If something blocks the light/laser or the target leaves the measuring point, we can not check adhesion state. 3) The total system becomes very large. Considering the above, in this paper, we have developed the method to check adhesion state by PZT instead of laser displacement meter. By the proposed method, we can check adhesion state at any time of the operation. The validity of this method has been shown by the experiments.

Next, to pursue to realize more precise manipulation, we have developed a method to finely control the pushing force applied to the object by end-effector (grasping force), simultaneously relaxing the adhesion force relaxed enough. It has been done by adding the combined input of the DC input voltage for control of the pushing force and the AC input voltage for oscillation for relaxing adhesion force. In addition, we have focused on the shift of the lower mode frequencies which arises due to the change of the pushing force, and developed a method to check adhesion state more accurately. By combining these method, we can finely tune the pushing force applied to the object, simultaneously keeping the adhesion force relaxed enough.

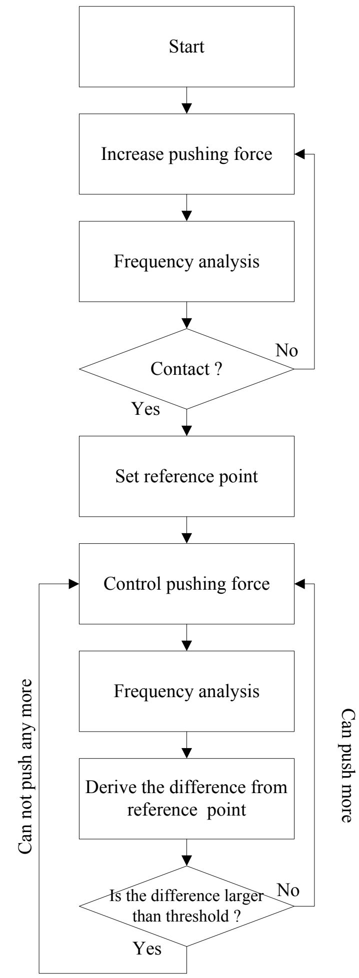

Fig. 12 Method to keep adhesion force relaxed enough

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