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CONSTANT GAP AND MINIMUM ENERGY SUPPLY CONTROL FOR A PROPORTIONAL PNEUMATIC FLOATING VACUUM PAD

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ABSTRACT

In this paper, a new proportional pneumatic floating vacuum pad is developed and constructed. There are two features concerning this new vacuum pad. The first one is the introduced proportional solenoid, which enables the continuously variable control of the suction force output. In addition, the floating mechanism design between the vacuum pad and work-piece is the second feature, which is more preferable in real industries because it can protect the surface of the work-piece from scratching or other damages. Moreover, two control schemes are also proposed in this paper. The first one is the gap control. A pre-set constant gap is input to the controller as the command input which further drives the proportional solenoid to maintain a steady-state gap between the vacuum pad and work-piece. In the second control approach, the gap between the vacuum pad and work-piece is kept as large as possible to minimize the energy consumption. Both control schemes are successfully implemented in this study. It is expected that the newly developed prototype with two different control schemes may find some real applications in the future.

KEY WORDS

Vacuum Pad, Gap Control, Proportional Solenoid, Floating, Vacuum

NOMENCLATURE

$u(k)$: actuating signal
$\Delta u(k)$: actuating signal change
$e(k)$: error signal
K_P : gain of the proportional controller
K_I : gain of the integral controller
K_D : gain of the derivative controller
T_s : sampling time
$V(k)$: velocity signal at kth instant of sampling
$X(k)$: gap signal at kth instant of sampling
$X(k-4)$: gap signal at (k-4)th instant of sampling

INTRODUCTION

Nowadays, applications of pneumatic vacuum pad may be found in many different engineering fields, especially in the field of automatic conveyer system, automatic assembly line, semiconductor industry as well as silicon wafer factory, etc. Traditional vacuum pad generally utilizes a nozzle to produce the effect of vacuum [1, 2]. To adjust the suction force output, it is required to change manually the opening area of the nozzle. In this paper, however, a new proportional pneumatic floating vacuum pad is developed and constructed as shown in Fig. 1 [3, 4]. There are two features concerning this new vacuum pad. The first one is the introduced proportional solenoid, which enables the continuously variable suction force output. The second one is the floating (i.e. non-contacting) mechanism design, which is more preferable in real industries because it can protect the surface of the work-piece from scratching or other damages.

In this paper, two control schemes are also proposed. The first one is the gap control. A pre-set constant gap is input to the controller as the command input which further drives the proportional solenoid to maintain a steady-state gap between the vacuum pad and work-piece. A possible minor fault, however, is that the pre-set gap may not be the optimal setting. It may give rise to larger energy consumption. Therefore, a second control strategy is proposed to minimize the energy consumption. In details, the gap between the vacuum pad and work-piece is no longer a constant. Instead, the gap is kept as large as possible in order to minimize the energy consumption. It is expected that the newly developed prototype with two different control criteria may find some real applications in the future. In the following, the principles of the proportional solenoid as well as the design of the vacuum pad will be illustrated.

VACUUM PAD DESIGN USING PROPORTIONAL SOLENOID

Figure 1 shows the scheme of the developed vacuum pad. The air is guided to flow into the vacuum pad at an eccentric inlet A. After passing through the restrictor C, the air is guided to flow out of the thin film between the vacuum pad and the work-piece denoted by B. The opening area of the restrictor is automatically controlled by the proportional solenoid. The proportional solenoid (Magnet-Schultz, GRF035) is a popular electro-mechanical transducer used in the design of fluid-power proportional valves [4, 5]. It has a quite linear force/stroke relation, which is the key requirement for the design of the proportional vacuum pad. The restrictor poppet, which is subjected to a constant force in the linear working range, reaches a definite position in the vacuum pad according to Hook's law. This definite position of the poppet signifies a definite opening area of the restrictor. Furthermore, it is well-known that the relation between the output force and the input current for the proportional solenoid is linear. Consequently, the opening area of the restrictor is continuously controllable and is proportional to the input excitation current. This is exactly the basic function of the proportional vacuum pad. Other design details can be found in reference [4]. Finally, the picture of the developed prototype equipped with a gap sensor (Keyence, AS440) is shown in Fig. 2.

EXPERIMENTAL RESULTS AND DISCUSSION

Figure 3 shows the gap control block diagram for the proportional floating vacuum pad. In this study, the utilized control scheme is the PID controller, in which the optimal gains are determined by the criterion proposed by Ziegler and Nichols [6]. The discrete-time PID-controller can be formulated as

$$u(k) = u(k-1) + \Delta u(k), \tag{1}$$

$$\Delta u(k) = K_P[e(k) - e(k-1)] + K_I e(k) + K_D[e(k) - 2e(k-1) + e(k-2)], \tag{2}$$

For the first control scheme, a constant gap is input to the control system as the command input. In the second control approach, however, the gap input is not a constant. The controller tries to enlarge the gap slowly and continuously after the initial setting in order to minimize the input current to the proportional solenoid as long as the work-piece (a CD-disk) does not fall. However, the oscillation of the gap is inevitable arising from the continuously enlarged gap setting. To prevent the accidentally falling of the work-piece, therefore, the controller must assure that the oscillation of the gap is convergent. To achieve this, an upper limit for the continuously enlarged gap must be found by the controller. Practically, the incremental enlargement of the gap will be stopped by the controller if the obvious oscillation of the gap is detected. Moreover, to detect the gap oscillation precisely, the numerical derived velocity signal after the impact (shown in Fig. 5 and Fig. 6) is employed and expressed as

$$V(k) = \frac{X(k) - X(k-4)}{4T_s}. \tag{3}$$

If the absolute value of the velocity signal, $V(k)$, exceeds a pre-set bound, it signifies that the obvious oscillation of the gap is detected and the gap should no longer be enlarged by the controller. The most suitable bound for the velocity signal, however, is obtained by trial-and-error approach

In this study, the picture of the utilized experiment is shown in Fig. 4, where the generated suction force makes successfully a CD-disk adhere to the developed vacuum pad. The supply pressure is adjusted to be 2 bar and the mass of the CD-disk is approximately 16 g.

Figure 5 shows one typical experimental result using the first control scheme. The command gap input is set to be 0.5 mm. The consumed steady-state current input to the proportional solenoid is nearly 0.26 A and the steady-state error of the gap control is 0.01 mm. On the other hand, a comparative experimental result using the second control strategy is shown in Fig. 6. Obviously, the required steady-state current becomes only 0.18 A which is smaller than the aforementioned one. In addition, the gap between the vacuum pad and work-piece is oscillatory at the beginning and settles to 1.14 mm which is larger than the pre-set input gap using the first control scheme. In this case, the percentage of energy-saving is nearly 30%.

From the time response curves of the air gap thickness shown in Fig. 5 and Fig. 6, it is observed as well that the work-piece contacts the vacuum pad at the beginning. After this inevitable impact, however, the thickness of the air gap settles and reaches the steady-state value.

CONCLUSION

In this paper, a new proportional pneumatic floating vacuum pad was successfully developed and constructed. After experimental tests, three conclusions may be drawn from this research.

(1) The most important feature of the developed proportional vacuum pad is the introduction of the proportional solenoid, which can be used to generate automatically the adequate suction force output by closed-loop control technique.

(2) Two control schemes are proposed and successfully implemented in this paper. The first one is the constant gap control, which is proven to be more stable and less oscillatory. On the other hand, in the second control scheme, the gap between the vacuum pad and work-piece is kept as large as possible, which is proven to be more energy-saving but less stable. In this study, the percentage of energy-saving reaches approximately 30%.

(3) During the process of suction force output, it is observed that the work-piece contacts the vacuum pad at the beginning. After this impact, the thickness of the air gap settles and reaches the steady-state value. However, such an impact between the vacuum pad and work-piece is not allowed in some precision applications, such as the silicon wafer industry. In the future, therefore, some advanced closed-loop air gap control system should be introduced to avoid the direct contact between the vacuum pad and the work-piece.

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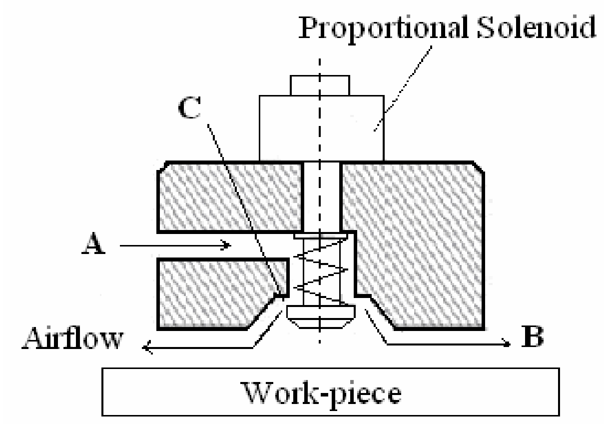

Figure 1 Scheme of the developed proportional floating vacuum pad

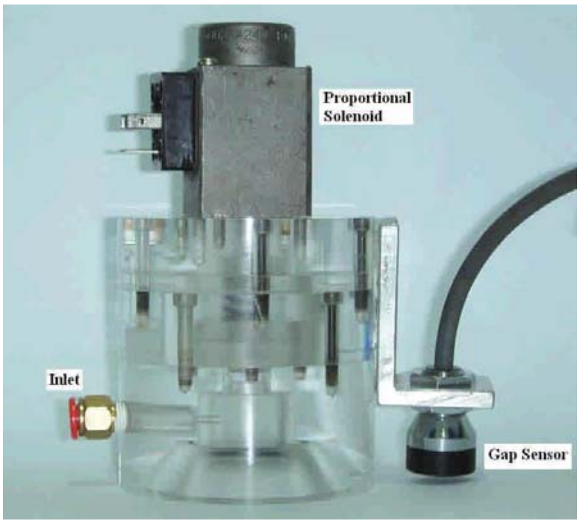

Figure 2 Prototype of the developed proportional floating vacuum pad

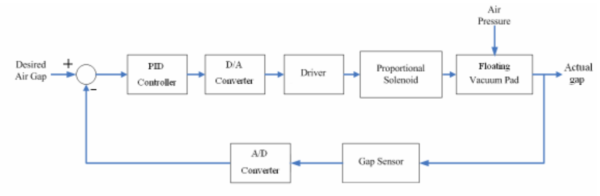

Figure 3 Block diagram of the gap control for the proportional vacuum pad

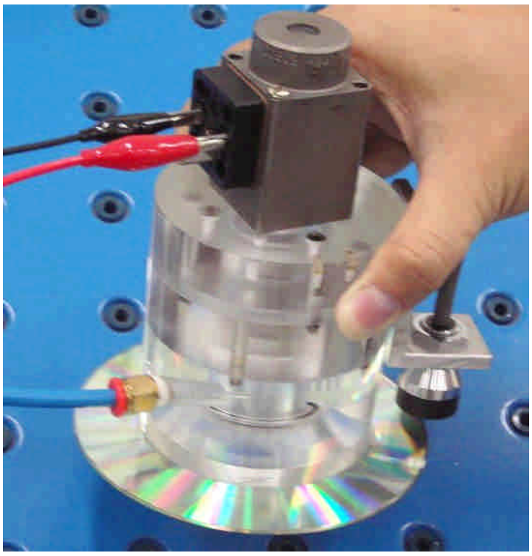

Figure 4 Experimental example showing the developed vacuum pad with a sucked CD-disk

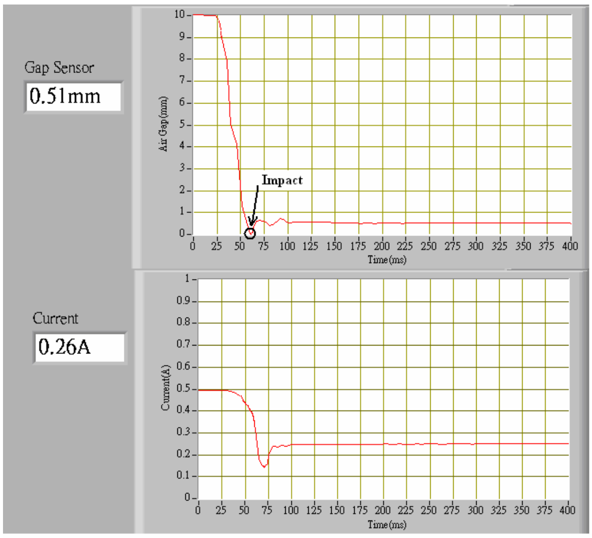

Figure 5 Experimental results using the first control scheme

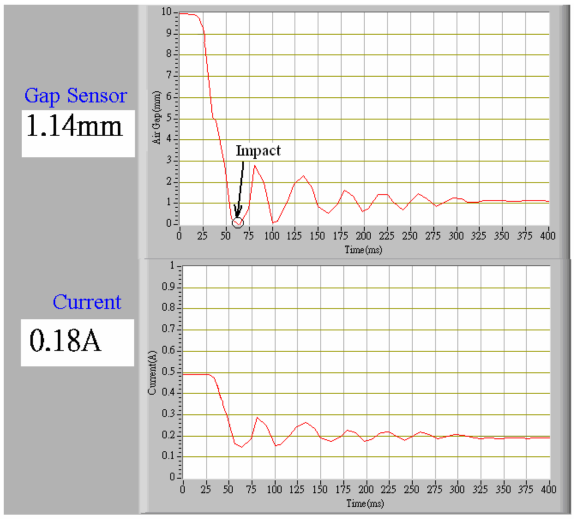

Figure 6 Experimental results using the second control scheme

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