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NEW PNEUMATIC TECHNIQUES AND APPLICATIONS

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ABSTRACT

In this paper, some new achievements of Kagawa's researches on pneumatic techniques and applications are introduced. One of them is concerned with a low noise pneumatic resistance. In regard to its basic principle, compressed air is blown out through a very thin radial slit structure to form laminar flow. By this means, aerodynamic noise caused by turbulence can be decreased to a much lower level comparing with other type resistances like orifice. The radial slit type resistance is applied to develop a new pressure regulator by making the gap thickness of radial slits adjustable, which is characterized by lower noise and less pressure fluctuation. Another proposal introduced in this paper is an unsteady mass flow generator which can continuously generate and control oscillatory flow at a frequency up to 50[Hz]. An important component of the generator is an isothermal chamber in which the essential isothermal condition is preserved. Utilizing the mass flow generator yields many practical applications, for example, the developments of air power meter. Recently, Kagawa's research interest extended to analysis and development of pneumatic non-contact handling device. A new non-contact handling method called vortex levitation by using swirling air flow is analyzed in Kagawa’s laboratory. Swirling air flow can form a parabolic negative pressure distribution to pick up a work piece and keep it stably levitate with a considerably thin gap under the device. Furthermore, it is confirmed that a work piece will vibrate while being picked up and its vibration can be damped to zero due to a damping effect.

KEY WORDS

Radial Slit Type Regulator, Low Noise, Mass Flow Generator, Air Power Meter and Vortex Levitation

FOREWORD

Pneumatic technique is widely used because of its inherent advantages like generating little heat and magnetic free, etc. Though its researches and applications had been carried out for hundreds of years, more effort is obviously needed especially as the environmental problem and energy crisis become severe recently. The author is devoted to pursue the development of new pneumatic techniques to explore the possibility for the solutions of those problems. In this paper, some new achievements are introduced with key words of low noise, energy consumption assessment and energy-saving. First, low noise radial slit type regulator is developed and proven to be able to decrease aerodynamic noise to a much lower level than the orifice type regulator while depressurizing a high pressure. Next, unsteady mass flow generator is proposed and applied to the development of air power meter. Finally, a new non-contact handling technique by using swirling air flow is introduced, which is characterized by its low air power consumption.

RADIAL SLIT TYPE REGULATOR

Usually, an orifice type regulator is widely used while depressurizing supply original pressure to a certain pressure that is often much lower than the original pressure. However, the orifice type regulator is always accompanied with problems of pressure fluctuation and considerable noise due to the turbulence flow. In order to solve those problems, a new pneumatic resistance is proposed by using radial slit structure, and is applied to develop a new pressure regulator by making the gap thickness of radial slits adjustable. In this section, the flow rate characteristics of the radial slit type regulator were investigated experimentally, and the noise level is confirmed to be decreased to approximately 40dB lower than the orifice type one[1,2].

Structure of radial slit type regulator

Figure 1 shows a schematic drawing of the variable slit structure. The slit structure consists of three elements, a disk, a guiding bar and coned disk springs. The upper part of Figure 1 shows the cross section of the structure. The upper disk consists of a flow inlet and an upper surface of the radial slit. The inner diameter of upper disk is 8.5mm. The guiding bar guides the movement of the disk. Coned disk springs are installed between the disk structures and the height of them are precisely controlled. The compressed air enters from the center of the upper disk and is exhausted outward through the radial slits. The lower part of Figure 1 shows the top view of the lower disk. The lower disk consists of a lower surface of the radial slit and a groove for holding the disc springs. The outer diameter of upper disk is 50mm, and the depth of groove is 0.5mm. The structure of the coned disk spring is shown in the right part of Figure 1. Its material is SUS304, and the spring constant is 619.5N/mm. The diameter of the coned disk spring is 8mm. The thickness is 0.3mm, and height is 0.55mm. It is located on groove of disk. The height difference of groove and coned disk spring makes the 50μm slit. The height of it is precisely controlled with a control force.

The picture and the structure of newly developed regulator are shown in Figure 2. In this study, we produced a new regulator which has four layers of slit as shown in the right side of Figure 2. The compressed air with supply pressure *Ps* enters from the center of the disks and is exhausted to atmosphere pressure through the slits. The pneumatic cylinder is set up below the disk, and its piston is connected with the disk. The control pressure *Pc* is supplied to the cylinder, and the cylinder moves the disk. Therefore, the gap thickness of slits is controlled with the pneumatic cylinder by changing the control pressure. The gap thickness of slit is measured by a microscope.

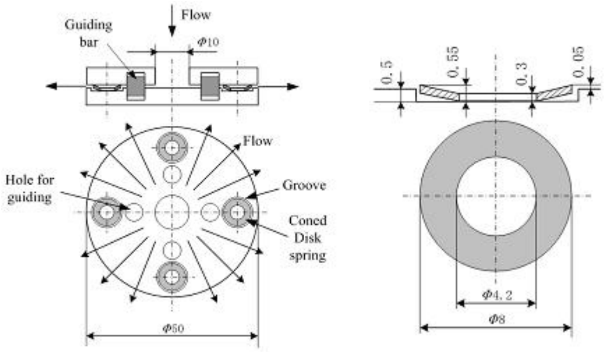

Figure 1 Adjustable radial slit

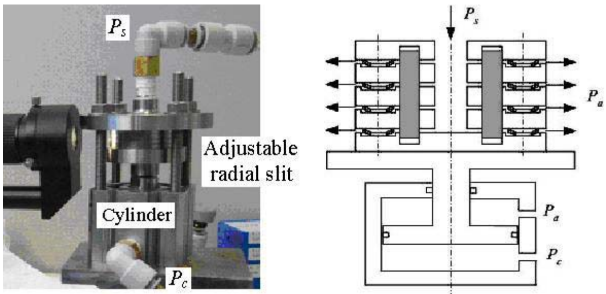

Figure 2 Radial slit type regulator

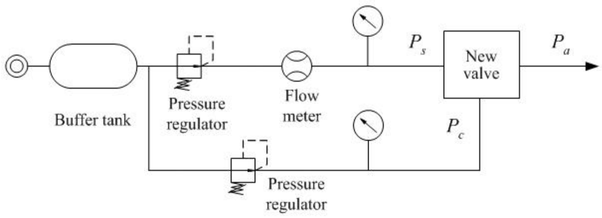

Figure 3 Experimental apparatus for flow characteristics

Flow rate characteristics

The flow characteristics were measured experimentally using the experimental apparatus shown in Figure 3. Buffer tank and two regulators are set up on the upstream side. Supply and control pressures were regulated by each regulator. The pressure and the flow rate were measured using a bourdon tube pressure gauge and a float-type area flow meter, respectively. The measured flow characteristic is shown in Figure 4. The supply pressure is set constant at 500kPa. The control pressure was increased from atmospheric pressure to 700kPa and then decreased to atmospheric pressure. The triangular symbols show the increased process of the control pressure and the rectangular show the decreased process.

When the control pressure was increased to 300kPa, the flow rate was decreased from 216Nl/min to 24Nl/min.

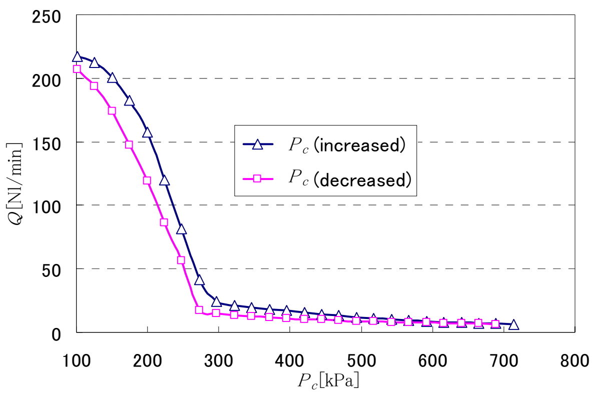

Figure 4 Flow rate characteristics

The flow rate decreased at a rate of 1Nl/min in 1kPa, and a change of flow rate was large in this range. When the control pressure is beyond 300kPa, the flow rate decreased at a rate of 0.04Nl/min in 1kPa. In this range, a change of flow rate was small. The flow rate at 700kPa was close to 0Nl/min. When the control

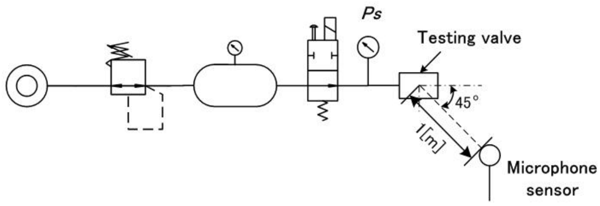

Figure .5 Experimental pneumatic circuit

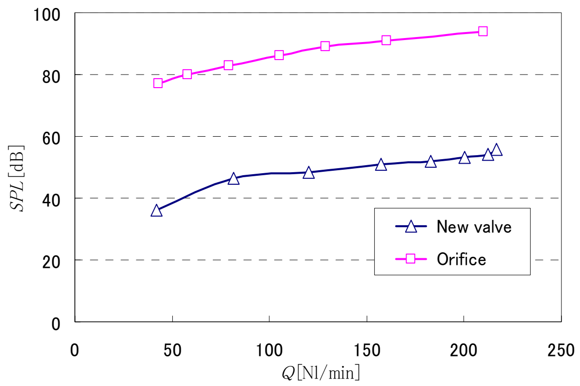

Figure .6 Comparison of noise level between orifice type regulator and radial slit type regulator

pressure is decreased to atmospheric pressure, the flow rate is smaller compared with the increased process. This is considered to be caused by the hysteresis of the pneumatic cylinder and the coned disk springs.

Noise level

The noise level of the valve was measured using a microphone sensor. The background noise level of the room is at 30dB. Microphone was placed in the room at an angle of 45 degree from the center axis of the regulator as shown in Figure 5. The distance from the regulator to the microphone was 1.0m. The noise levels of the orifice and the newly developed regulator with the variable slit structure were compared. The experimental results are shown in Figure 6. The horizontal axis is flow rate, and the vertical axis is the noise level. We confirmed in advance that the flow characteristics of the orifice and the new regulator were approximately the same. The results indicated that the noise level decreased approximately 40dB in the new valve.

UNSTEADY MASS FLOW GENERATOR

There is no effective method to calibrate the dynamic characteristics of gaseous flow meters due to a fact that the density of those fluids changes largely with respect to both pressure and temperature. This section describes the development of an unsteady mass flow generator for gases. The generator mainly consists of an isothermal chamber and two spool-type servo valves. The heat transfer area within the isothermal chamber is made sufficiently large by stuffing the copper wool materials to ensure that the essential isothermal conditions are preserved [3]. The calibration of the dynamic characteristics of the gaseous flow meters and the internal flows within such meters are achieved using the generator. Experimental tests reveal that the generator can control oscillatory flows at a frequency of up to 50 Hz with an uncertainty of 5.5%. In addition, the generator can generate flows for more than 30 min[4,5].

Principle

The unsteady mass flow is generated using an isothermal chamber and two servo valves, as shown in Figure 7. The state equation for compressible fluids in a chamber can be written as

$$PV = WR\theta \tag{1}$$

The following equation can be derived by differentiating Equ.1, if the chamber volume is constant:

$$V\frac{P_c}{dt} = (G_{in} - G_{out})R\overline{\theta} + WR\frac{d\overline{\theta}}{dt} \tag{2}$$

Here, the mass flow rate G_{in} is charged through the servo valve installed in the upstream of the isothermal chamber. The controlled mass flow G_{out}, which is the generated flow, is discharged through the servo valve installed in the downstream of the isothermal chamber. The generated flow G_{out} is given by the following equation by transforming Equ.2:

$$G_{out} = G_{in} - \frac{V}{R\overline{\theta}}\frac{dP_c}{dt} + \frac{W}{\overline{\theta}}\frac{d\overline{\theta}}{dt} \tag{3}$$

If the state of the air in the chamber during charge or

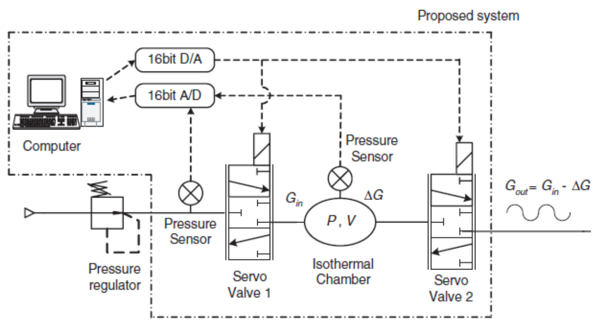

Figure .7 Sketch of the unsteady mass flow generator

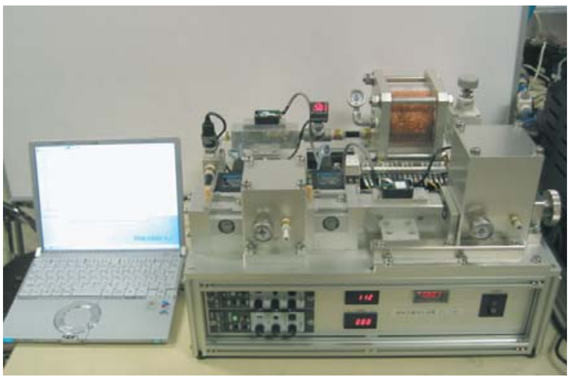
Figure .8 Photograph of the mass flow generator

discharge remains isothermal, the generated mass flow rate can be obtained from Equ.3 as

$$G_{out} = G_{in} - \frac{V}{R\overline{\theta}}\frac{dP_c}{dt} = G_{in} - \Delta G \qquad (4)$$

Since the condition remains isothermal, the average temperature in the chamber $\overline{\theta}$ is equal to the room temperature θ_a[3]. Equ.4 indicates that if the volume of the chamber V and the room temperature θ_a are known, then the generated mass flow rate can be controlled by the pressure difference in the isothermal chamber and the inlet mass flow rate. The inlet mass flow rate is controlled by servo valve 1, as shown in Figure 7, and the pressure change in the isothermal chamber is controlled by servo valve 2.

Apparatus

A schematic diagram and a photograph of the developed generator are shown in Figure 7 and 8, respectively. The apparatus consists of an isothermal chamber, two spool-type servo valves, two pressure sensors and a personal computer. Servo valve 1 controls the charged mass flow rate to the isothermal chamber, and servo valve 2 controls the generated unsteady flow from the chamber. A laminar flow meter having a high-speed response was arranged on the downstream side of the mass flow generator, as shown in Figure 9, and was used to verify the generated unsteady mass flow[6].

Experimental results

The target oscillatory mass flow rate is given as a sine wave. The low-pass filter was used for the processing of the measured data. The cut-off frequency of the filter was set at three times the frequency of the phenomenon. Figure 10 shows an experimental result at a frequency of 50Hz. In the Figure, the dashed line shows the target flow rate, the solid line shows the generated flow rate using the unsteady mass flow generator and the short-dotted line indicates the measured flow rate using the laminar flow meter. From Figure 10, it could be confirmed that the target flow rate and the generated flow rate show good agreement. And the flow is generated continuously for 30min. These results show that the maximum error between the target mass flow rate and the generated mass flow rate is less than approximately 5%.

Figure 11 shows a triangular wave at a frequency of 5 Hz. The maximum pressure change speed in the isothermal chamber is about 200 kPa/s that is the maximum value of the pressure control in the isothermal chamber. The proposed generator is thus proven to be capable of generating various flows.

Applications

The unsteady mass flow generator yields many practical applications. For example, the dynamic characteristics of an air power meter, which has an ability to measure instantaneous air power consumption and is shown in Figure 12, can be examined since an exact unsteady mass flow rate is available for test input. And the development of air power meter might contribute

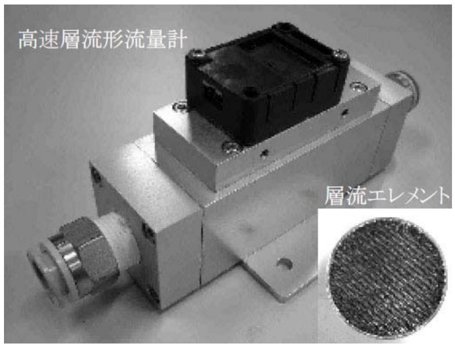

Figure .9 Photograph of quick flow sensor

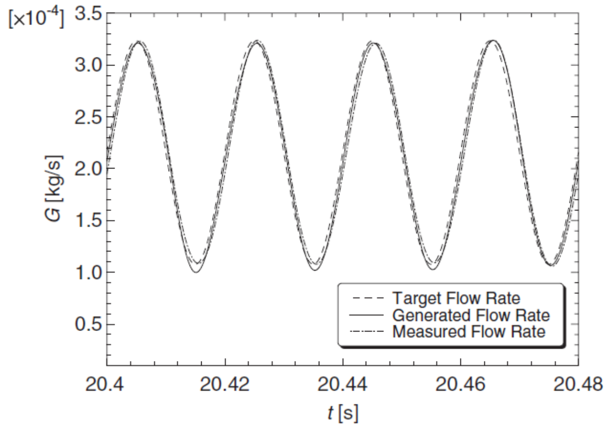

Figure .10 Oscillatory flow at a frequency of 50Hz

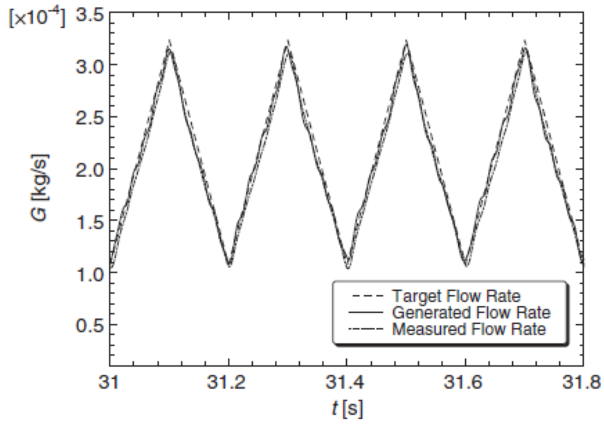

Figure .11 Triangular wave at a frequency of 5Hz

Figure .12 Photograph of air power meter largely to energy-saving researches because of a proper measurement on pneumatic energy consumption[7].

NON-CONTACT HANDLING DEVICE USING SWIRLING AIR FLOW

Usually a work piece is brought into contact with a handling device in order to be picked up and moved. Such contact methods are often accompanied by surface scratching and static electricity. Therefore, many non-contact handling approaches had been proposed and have proven effective. In this section, a new pneumatic non-contacting handling approach named vortex levitation is introduced by the authors. Vortex levitation is characterized by its low air consumption. Comparing to Bernoulli levitation, it requires less air supply flow rate while generating the same lifting force. In our research, analysis is conducted on both its static and dynamic characteristics[8,9].

Mechanism of vortex levitation

A simple structure called the vortex cup (hereafter referred to as cup) is used to generate an air swirling flow. As can be seen in Figure 13, the cup is made up of a circular cylinder and a tangential nozzle inserted above. A fillet is cut at the bottom to direct air out of the cup. Compressed air is blown through the nozzle into the cup, and then spins along the circular wall to create a negative pressure in the central area by centrifugal force. This negative pressure will be applied as a lifting force to a work piece placed under the cup, which will then pick it up hold it at an equilibrium position where the weight is balanced by the lifting force. Because air is supplied continuously, the work piece will keep levitating with a gap of hundred micrometers from the cup, through which air can be discharged into the atmosphere. For this reason, the work piece never contacts the cup.

Pressure distribution

Figure 14 shows a sketch of the cup and indicates the coordinates. The lower of Figure 14 plots the radial pressure distribution at a certain gap thicknesses for the case in which the supply flow rate is set constant. It is observed from this figure that the pressure inside the cup is distributed along the radial direction, and the pressure distribution is quite similar to a parabolic curve. Moreover, because air flows relatively slowly toward the gap entrance and then is forced into the thin gap, it is observed that pressure drops through the gap.

One more important fact is that negative pressure inside the cup is dependent on the gap between the cup and the work piece. As the gap is enlarged, pressure at the gap drops to atmospheric pressure. At the same time, the parabolic pressure distribution shifts toward the vacuum with a uniform distribution. However, once pressure in the gap becomes nearly equal to zero, the negative pressure inside the cup slowly recovers toward atmospheric pressure.

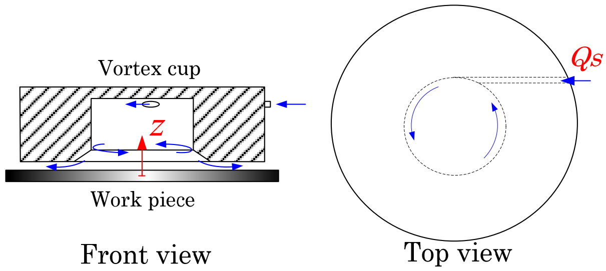

Figure .13 Sketch of vortex cup

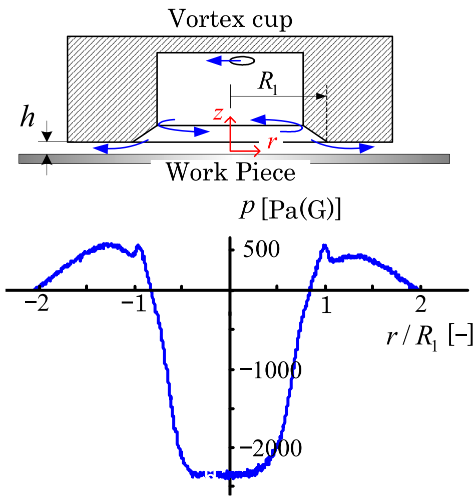

Figure .14 Pressure distribution

Lifting force and stable levitation

According to the negative pressure distribution and its change with respect to the gap thickness between the cup and the work piece, the lifting force increases as the gap is enlarged, and decreases slowly after it reaches a maximum as the gap becomes bigger and bigger. The curve shown in Figure 15 indicates the lifting force and its change. From this result, it is known that the cup can handle a work piece whose weight is less than maximum lifting force. As an example, assume a 0.2 [N] work piece is handled by the cup, which is plotted by a broken line in Figure 15. This line intersects the lifting force line at two points A and B where the weight is balanced by the lifting force. If the work piece gets closer to the cup than A, it will obviously fall back to A because the lifting force is smaller than its weight. If it comes into the region between A and B, the lifting force becomes bigger than its weight to be able to pull it back to A. However, the work piece will fall down once it gets further away than B due to the insufficient lifting force. Therefore, A is defined as a stable levitation position and B is defined as the levitation boundary position. The region from the bottom of the cup to B is called the stable levitation region.

Dynamic levitation

The experiments and analysis as stated above were conducted only in the steady state conditions. Considering its practical uses, for example, in a semiconductor production process where each wafer is handled frequently during repeated loading and unloading, efforts are obviously needed to investigate how the work piece behaves at the moments when it is picked up by the cup and when it is disturbed while levitating under the cup. Therefore, investigations on the dynamic characteristics of vortex levitation were conducted and reported. Figure 16 is an instantaneous movement of the work piece at the vertical direction when it is picked up by the cup. The vibration due to its inertia occurs and is damped to zero in several periods.

In order to clarify the reason of the damped vibration, a pressure response was measured while keeping the work piece to vibrate continuously under the cup. Pressure responses inside the cup and in the skirt are shown in Figure 16, respectively. A very thin air layer is formed between the surrounding skirt and the work piece. Air reaches a higher pressure when it approaches to the cup than when it gets away from the cup. Thus, by this means damping effect can be confirmed to result in the damped vibration.

AFTERWORD

Low noise, energy consumption assessment, energy saving non-contact handling technique, these achievements mentioned in this paper contribute toward improving environment and saving energy consumption. Their further applications can be expected in the future.

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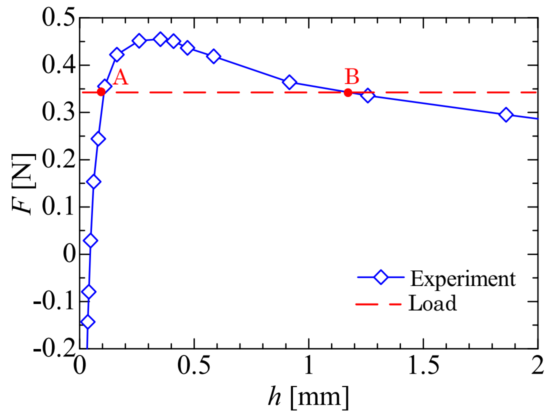

Figure .15 Lifting force

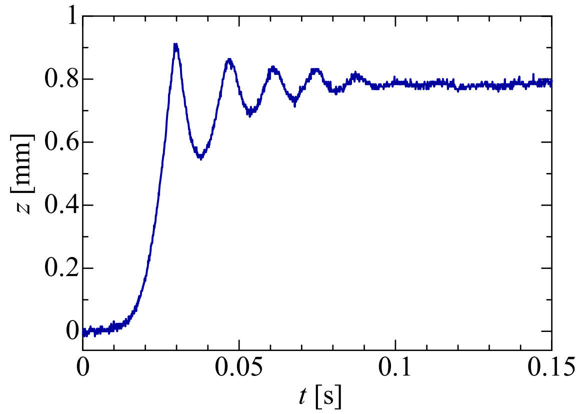

Figure .16 Instantaneous movement of work piece

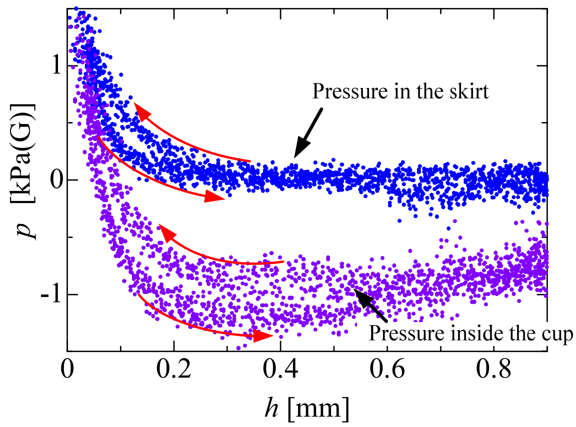

Figure .17 Pressure response

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